Unweaving the webs of carbon

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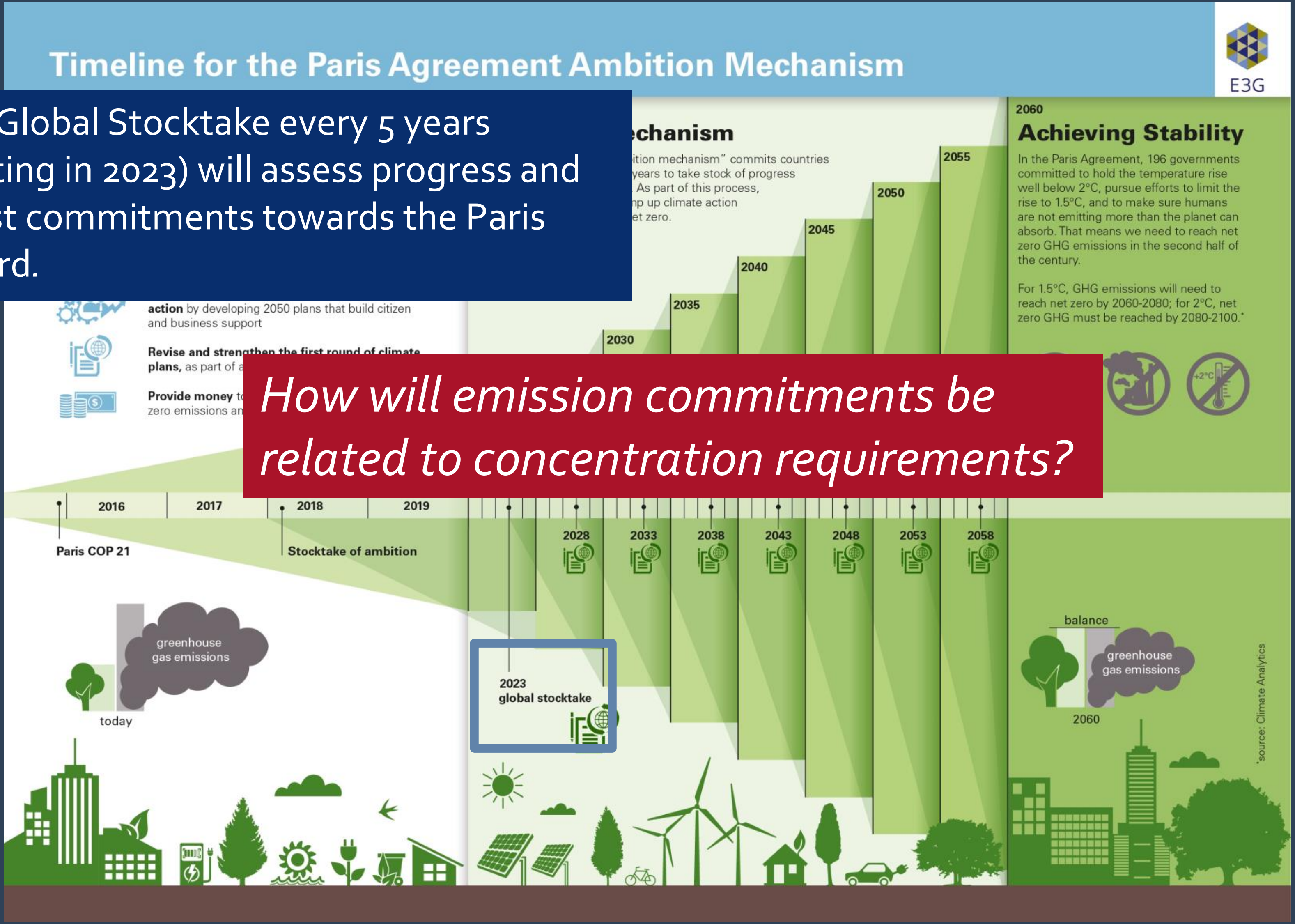
The Global Stocktake

The Global Stocktake every 5 years (starting in 2023) will assess progress and adjust commitments towards the Paris Accord.

How will emission commitments be related to concentration requirements?

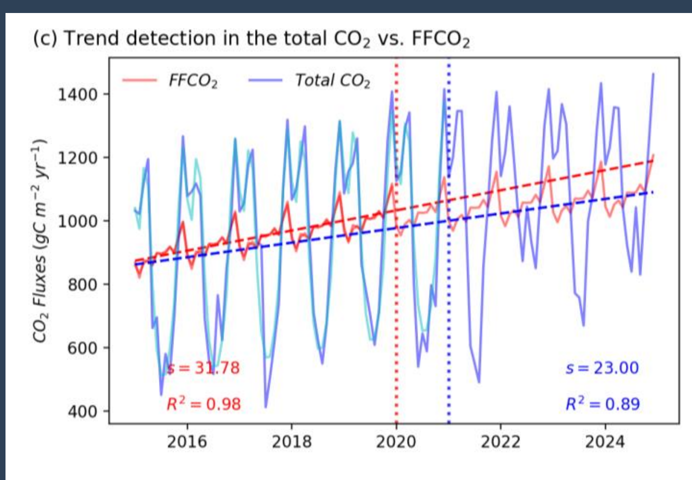


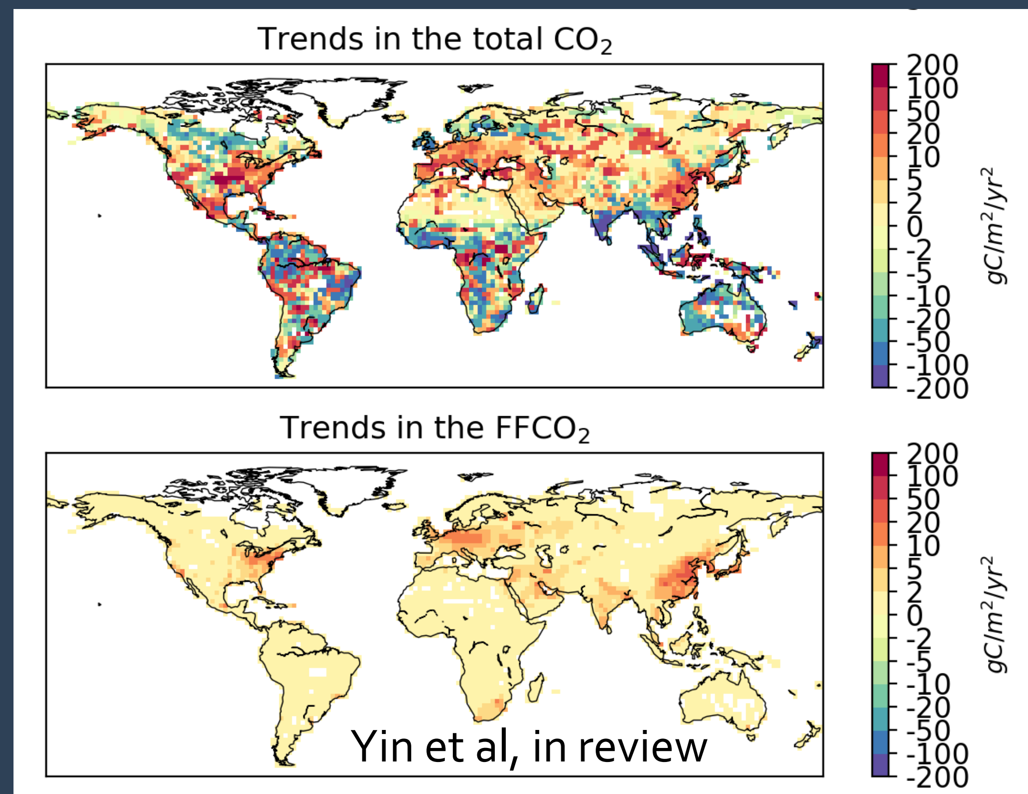
The gap between fluxes and concentrations

In an ideal system, the time-to-detection of total CO2 flux trends for many parts of the world is within 10-15 years (2-3 stocktakes). But, the relationship between those trends and FF trends is complex

In China, about 20% of total CO2 trends is within 25% of the underlying FFCO2 trends

Both anthropogenic and natural processes drive trends at stocktake scales





Confounding variables: Carbon-climate feedbacks

A steep road to climate stabilization

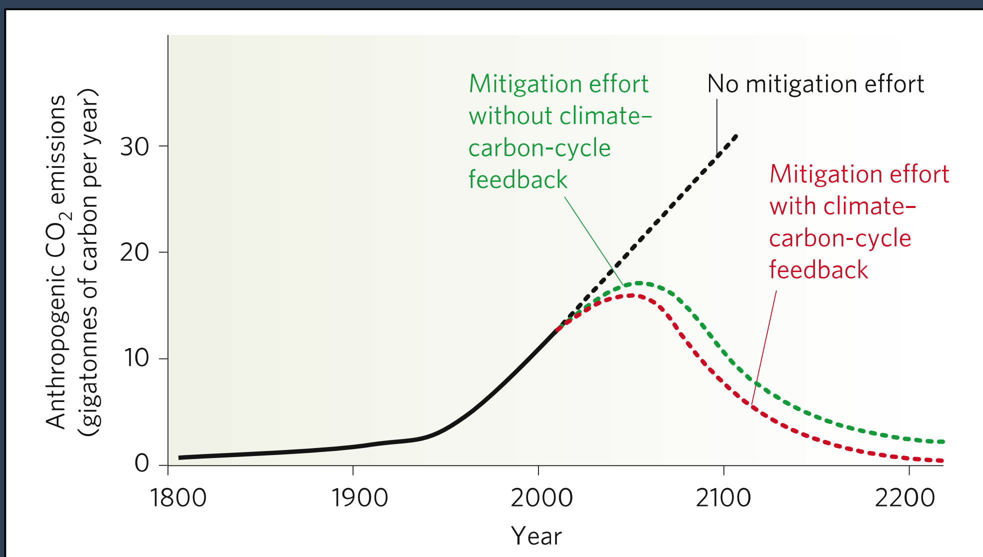
Pierre Friedlingstein

The only way to stabilize Earth's climate is to stabilize the concentration of greenhouse gases in the atmosphere, but future changes in the carbon cycle might make this more difficult than has been thought.

nature geoscience FOCUS | PROGRESS ARTICLES
PUBLISHED ONLINE: 17 NOVEMBER 2009 | DOI: 10.1038/NGEO689

Trends in the sources and sinks of carbon dioxide

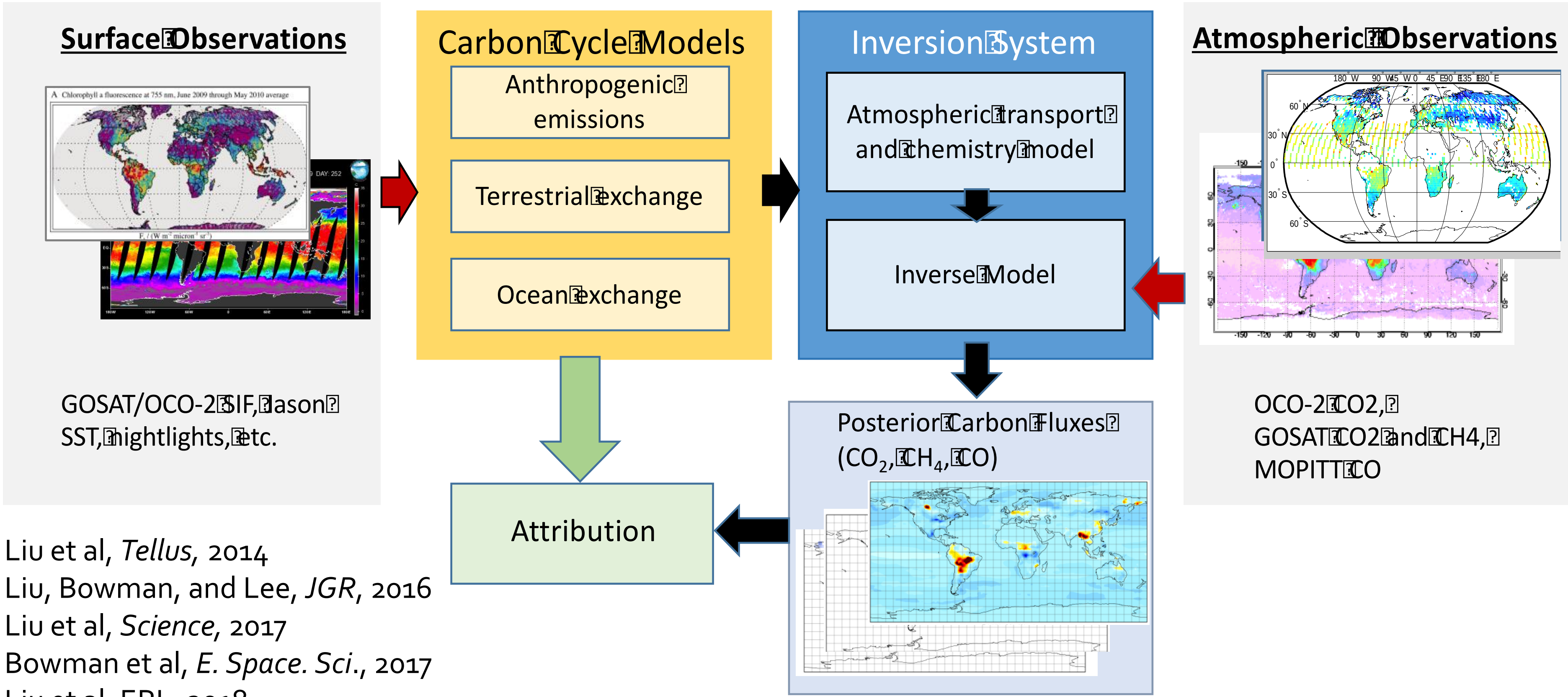
Corinne Le Quéré, Michael R. Raupach, Josep G. Canadell, Gregg Marland *et al.**



"major gaps remain….in our ability to link anthropogenic CO_2 emissions to atmospheric CO_2 concentration on a year-to-year basis…. and adds uncertainty to our capacity to quantify the effectiveness of climate mitigation policies."

Both fossil fuel FFCO2 (forcing) and net CO2 (forcing and feedbacks) trends are important.
How are they related globally?

Prototype Carbon Cycle Assimilation Systems: CMS-Flux

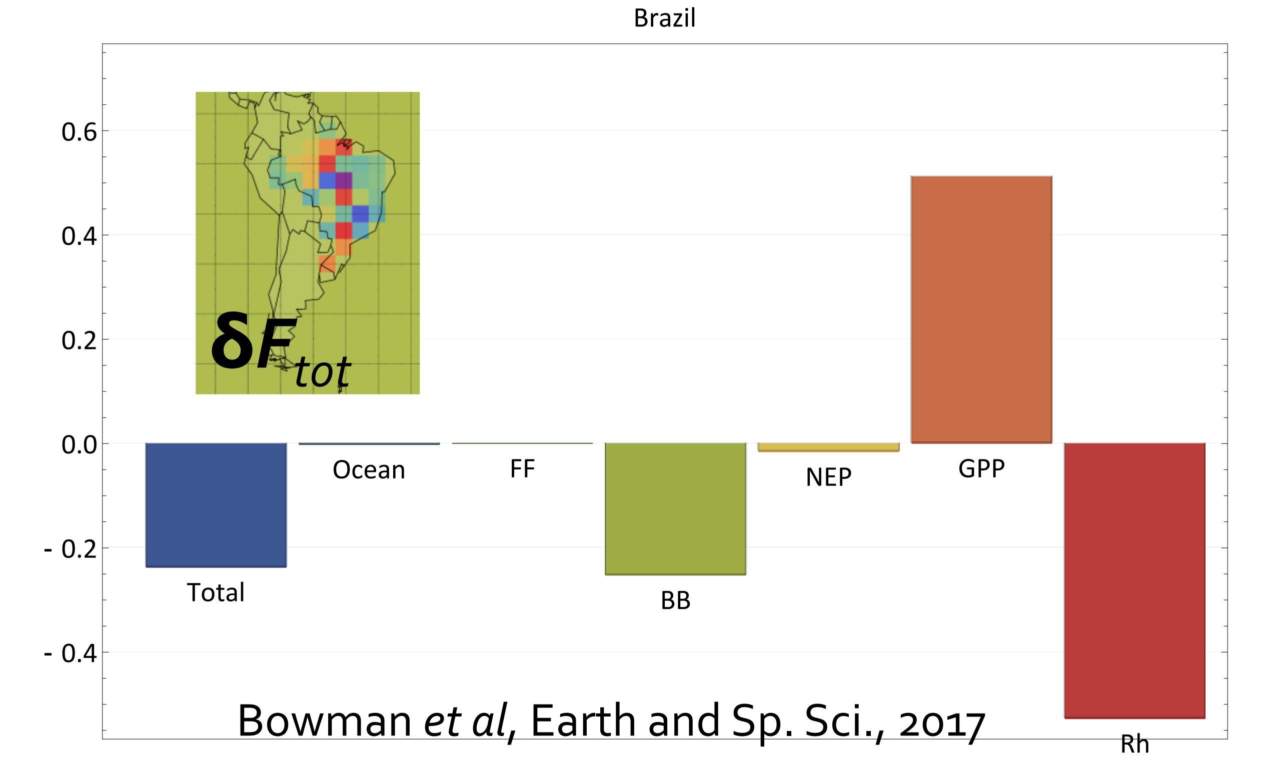


Liu et al, *Tellus*, 2014
Liu, Bowman, and Lee, *JGR*, 2016
Liu et al, *Science*, 2017
Bowman et al, *E. Space. Sci.*, 2017
Liu et al, ERL, 2018

The NASA Carbon Monitoring System Flux (CMS-Flux) attributes atmospheric carbon variability to spatially resolved fluxes driven by data-constrained process models across the global carbon cycle.

Brazilian carbon balance, 2010-2011

- The Modoki El Nino from 2010-2011 led to historic droughts in Brazil
- CMS-Flux results indicate that the change in total flux was driven by biomass burning.
- Brazil was the largest contributor to the global biomass burning anomalies
- Productivity increases were offset by equivalent and respiration.



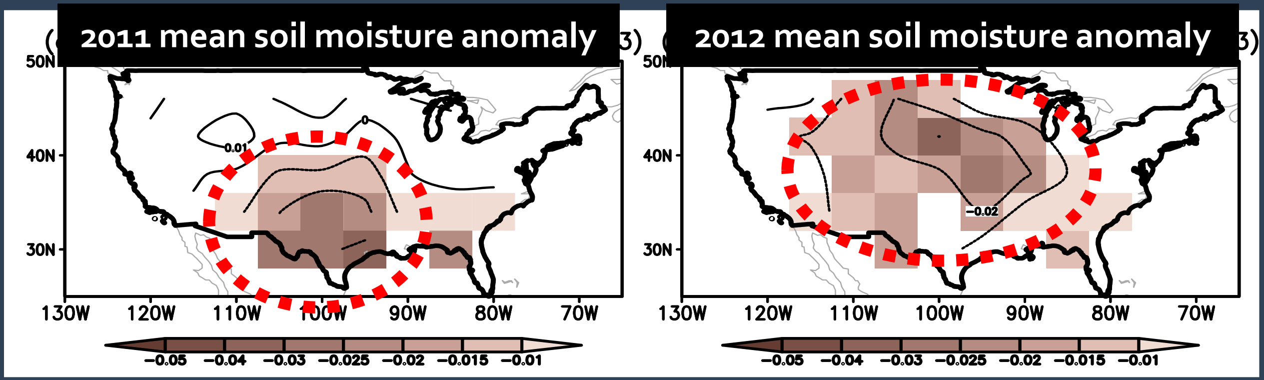
$$F^{\uparrow}(x,y,t) = F_F + F_O + F_{BB} + \underbrace{(R - GPP_{SIF})}_{-F_{NEP}} + F_{chem}$$

Net flux into the atmosphere is positive PgC

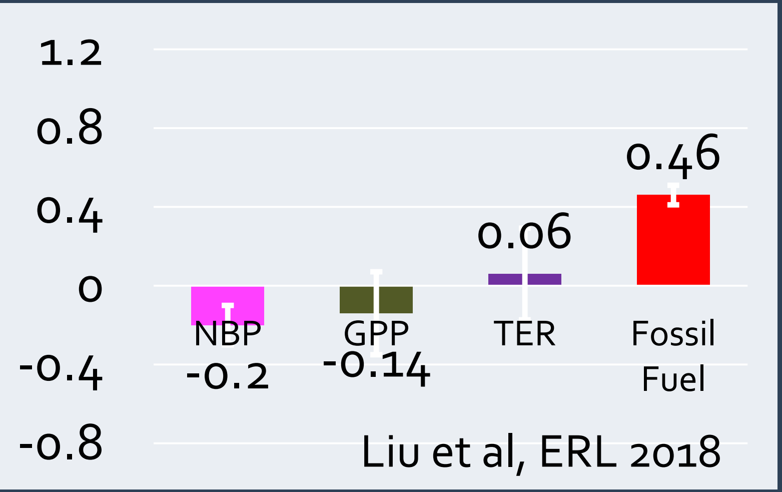
Impact of drought during 2011 and 2012 on NBP anomalies

The 2011 dry spell in Texas was the worst one-year period of drought since 1895, and the area span of 2012 summer drought was comparable to the dust bowl era.

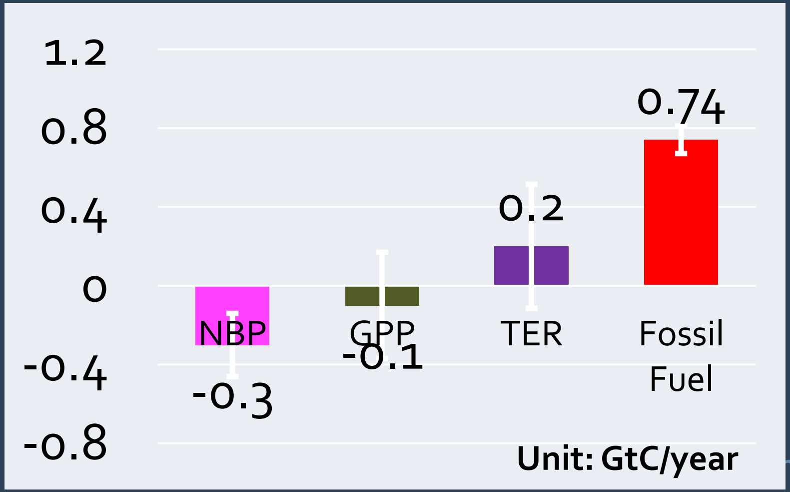
The NBP reduction due to the drought was more than 40% of the regional fossil fuel emissions



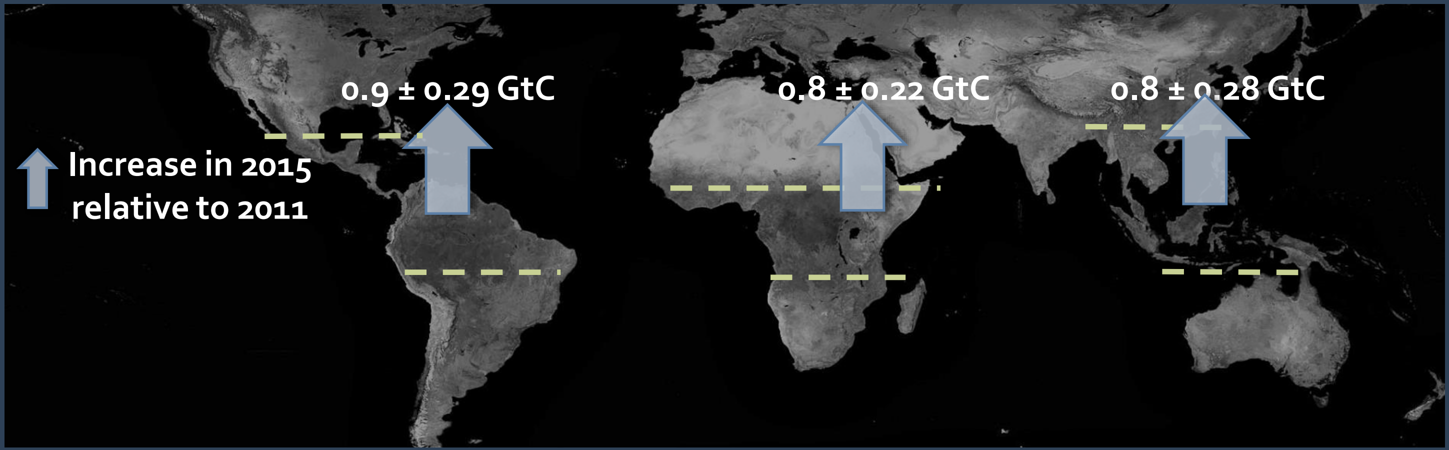
2012 NBE seasonal anomalies consistent with flux towers results in Wolf et al, 2016)



Liu et al, ERL 2018



A Tale of 3 continents: the 2015 El Nino



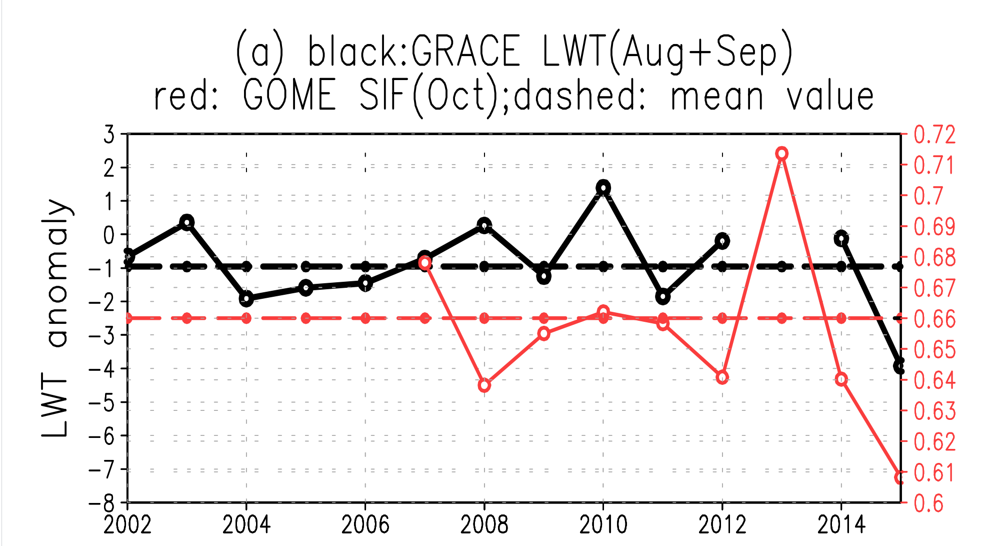
Liu et al, Science, 2017

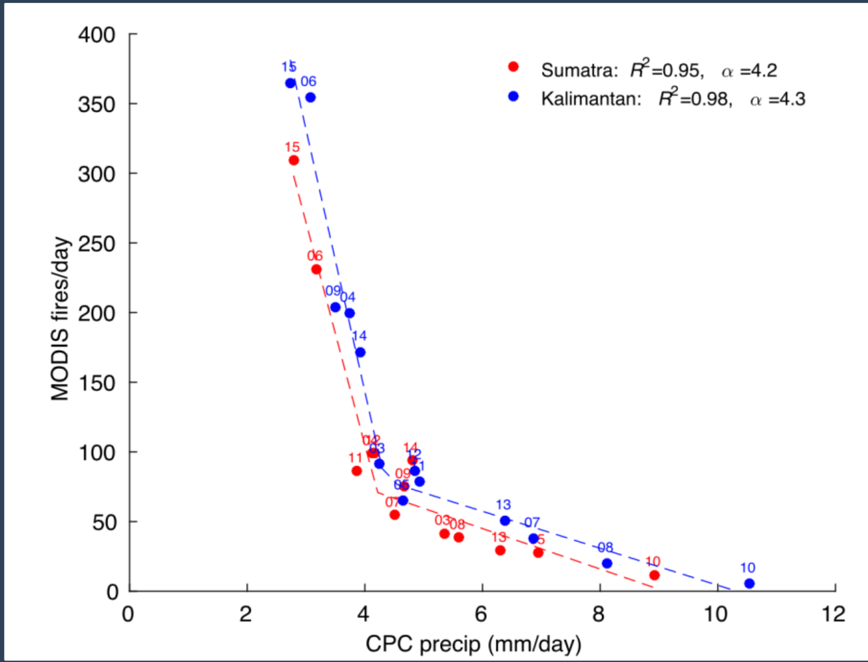
The Tropics released 2.5 ± 0.34 Gt more carbon into the atmosphere in 2015 than in 2011.

Tipping points: the hydrological context

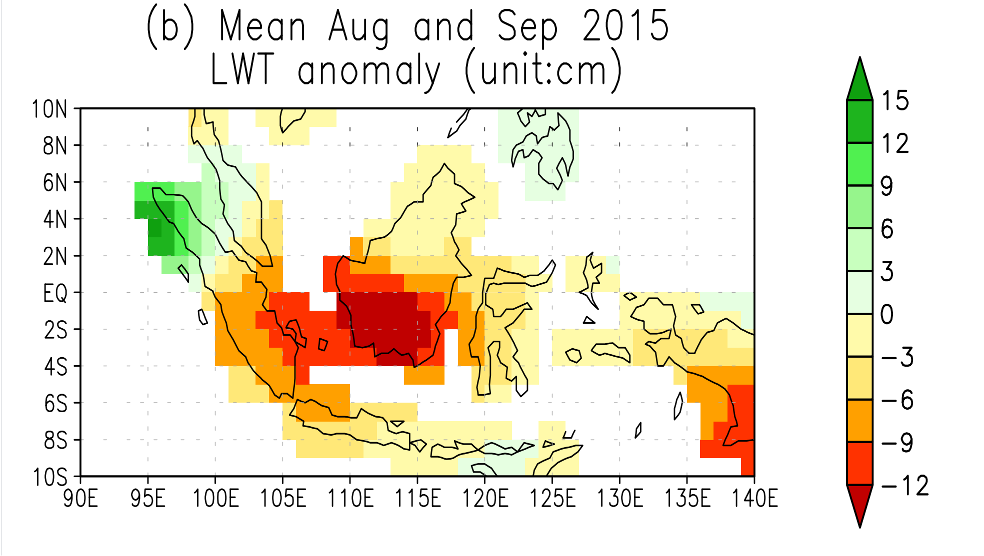
Centered on Kalimantan, GRACE gravity data shows a liquid water equivalent thickness (LWT) anomaly of -4 cm, 4x larger than then decadal mean anomaly.

Field et al, 2016 PNAS reported a non-linear relationship between firecounts and precipitation below 4 mm/day

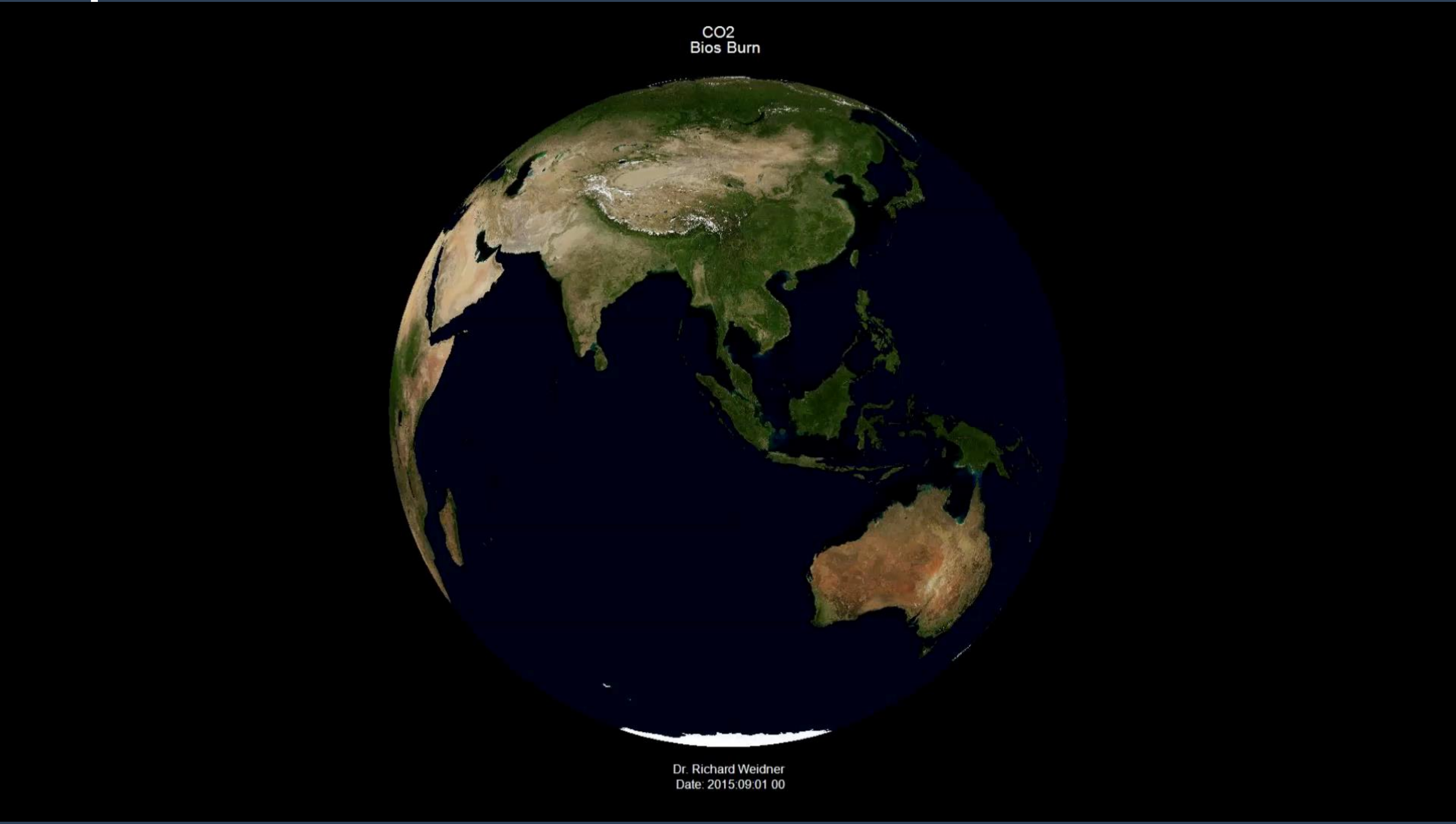




Fields et al, 2016 (PNAS)



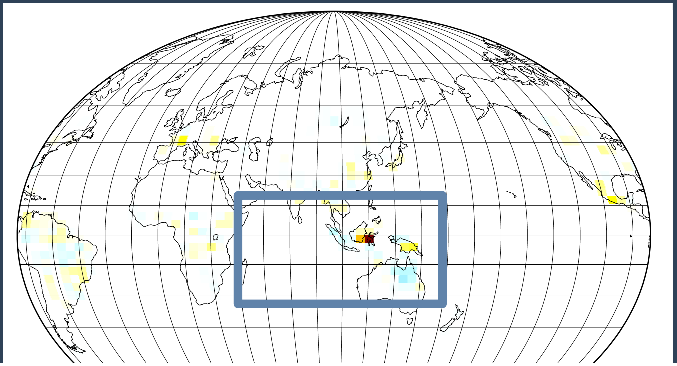
Atmospheric signature of Indonesian carbon in 2015

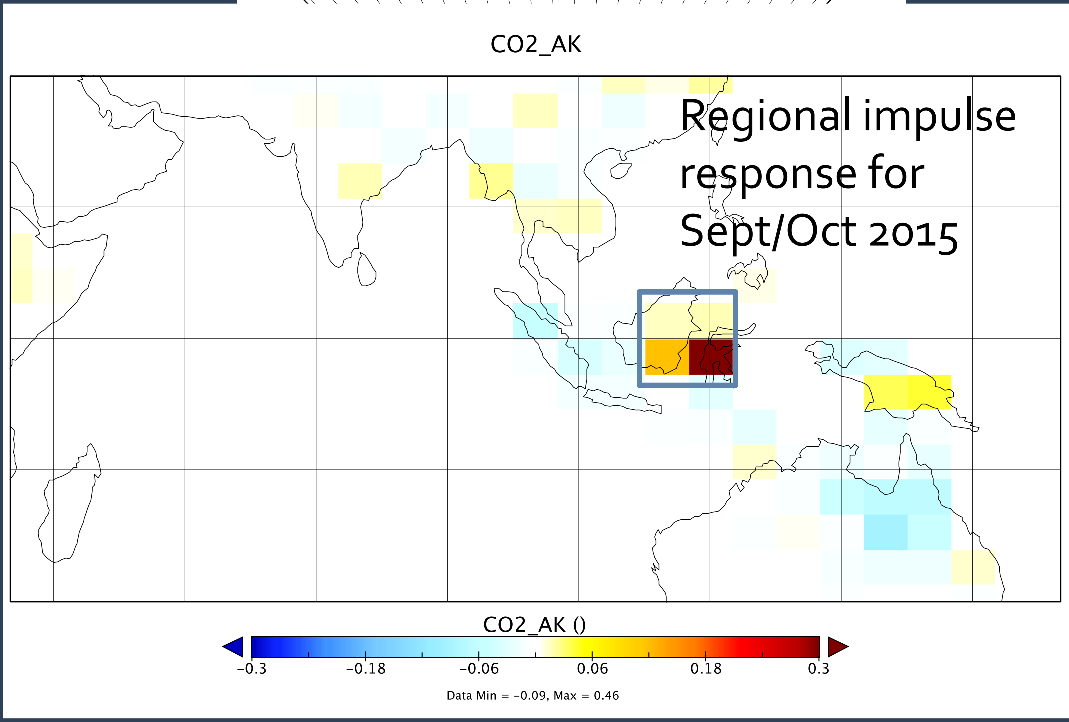


Resolving Indonesian Flux

The sensitivity of the CMS-Flux Indonesian flux estimate to the true flux is defined by the impulse response (IR):

$$\frac{\partial \hat{\mathbf{x}}}{\partial [\mathbf{x}]_{i \in L}}$$





The IR response shows the fractional change in the OCO-2-constrained global flux if the *true* flux increased by 100%.

The IR can be approximated following techniques in Bousserez and Henze, 2018, which synthesize advances in probabilistic matrix decomposition and estimation techniques

The high values over Indonesia and Borneo (and weaker responses elsewhere) show that the the peak biomass burning in Sept/Oct 2015 is well resolved by CMS-Flux.

Validation of carbon fluxes

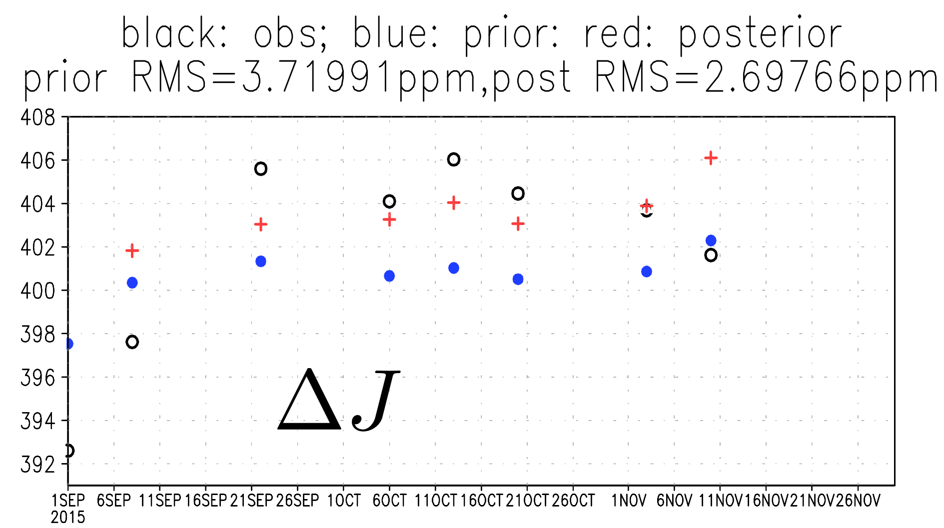
Direct validation of large-scale fluxes is difficult. Posterior CO2 can be compared to independent data. How do they relate to fluxes? Following Liu and Bowman, 2016 (GRL)

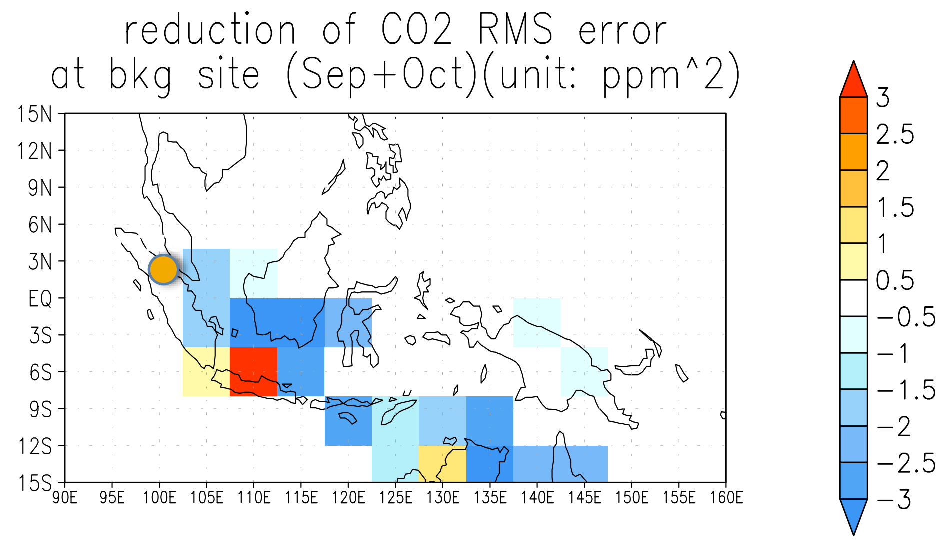
$$J_{prior}(\mathbf{x}_a) = ||CO2_{prior} - CO2_{site}||^2$$

$$J_{post}(\hat{\mathbf{x}}) = ||CO2_{post} - CO2_{site}||^2$$

$$\Delta J = J_{post} - J_{prior}$$

$$\nabla_{\mathbf{x}}(\Delta J)$$

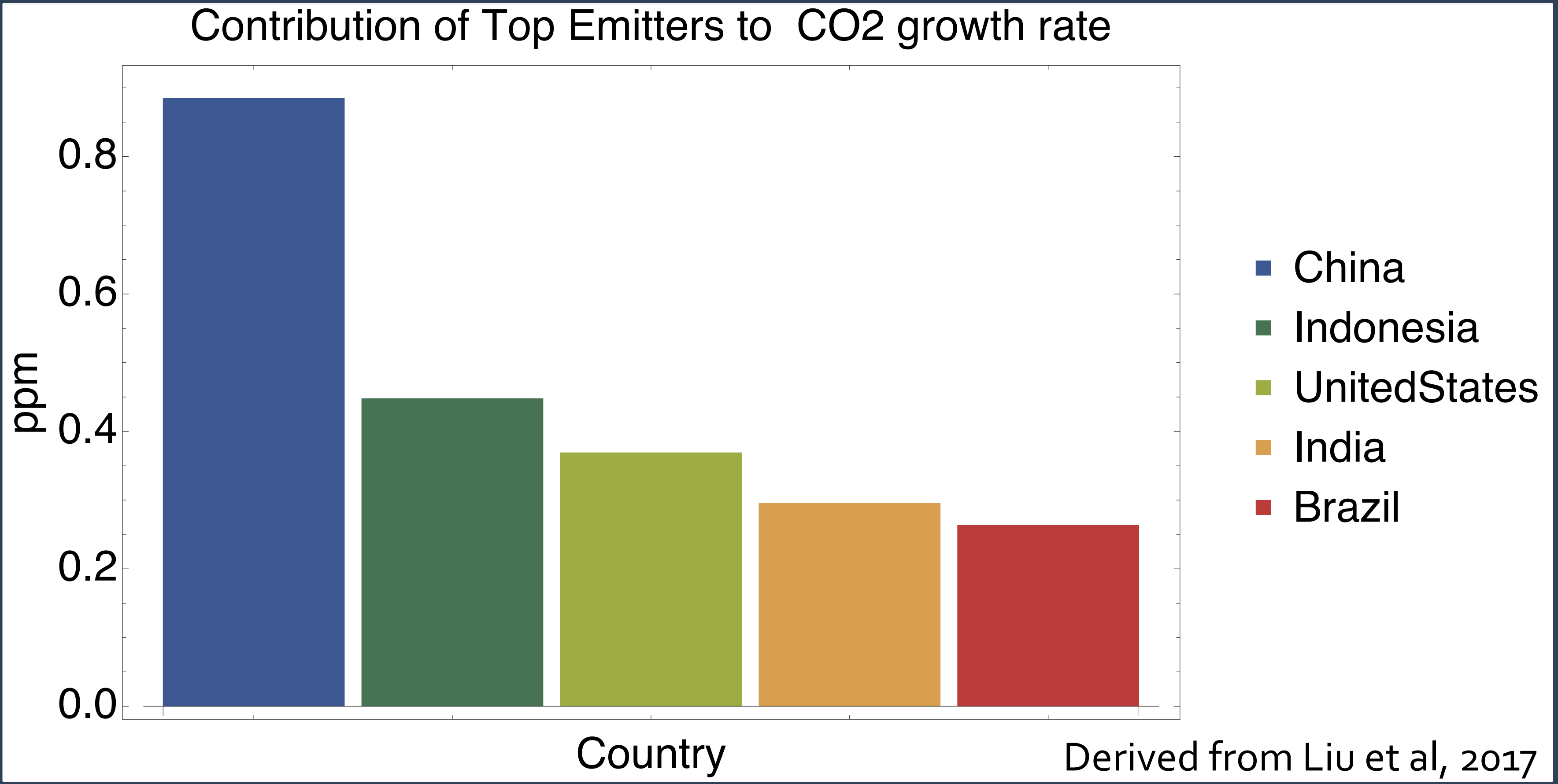




Fluxes in S. Kalimantan improved agreement with the background site by >3ppm² or ~5% of total improvement.

Underestimate w.r.t. site suggests fluxes are likely underestimated.

Contributions to the CO_2 growth rate



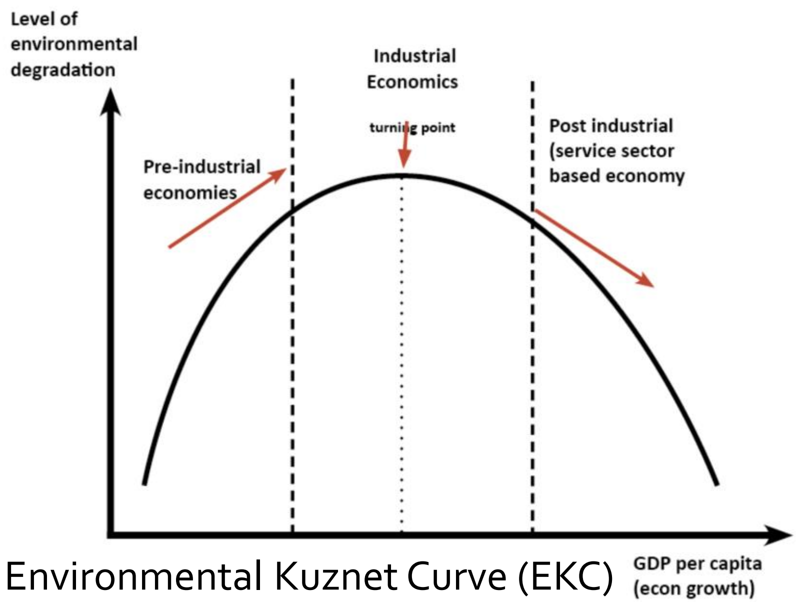
CMS-Flux was used to show that China was the highest and Indonesian region was the 2nd highest contributor (0.45 ppm) to total flux of the record CO_2 growth rate in 2015.

Both those were due to different drivers.

The ties that bind: air quality and carbon

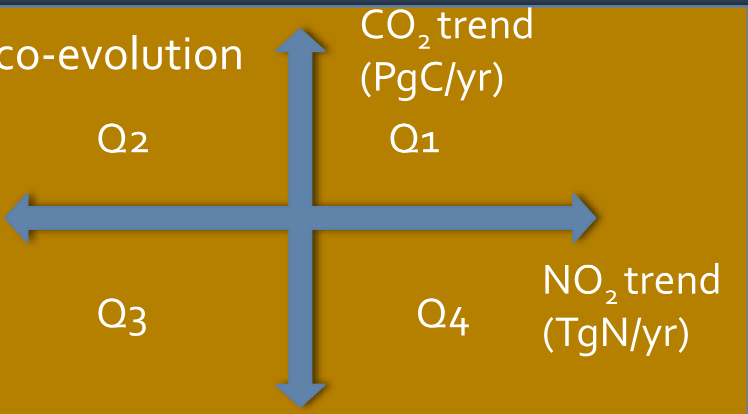
The primary environmental concern in most developing countries is air quality, not carbon.

How will changes in air quality mitigation impact carbon emissions? Do they have similar or conflicting environmental Kuznet curves?



Environmental Kuznet Curve (EKC)

AQ/Carbon co-evolution



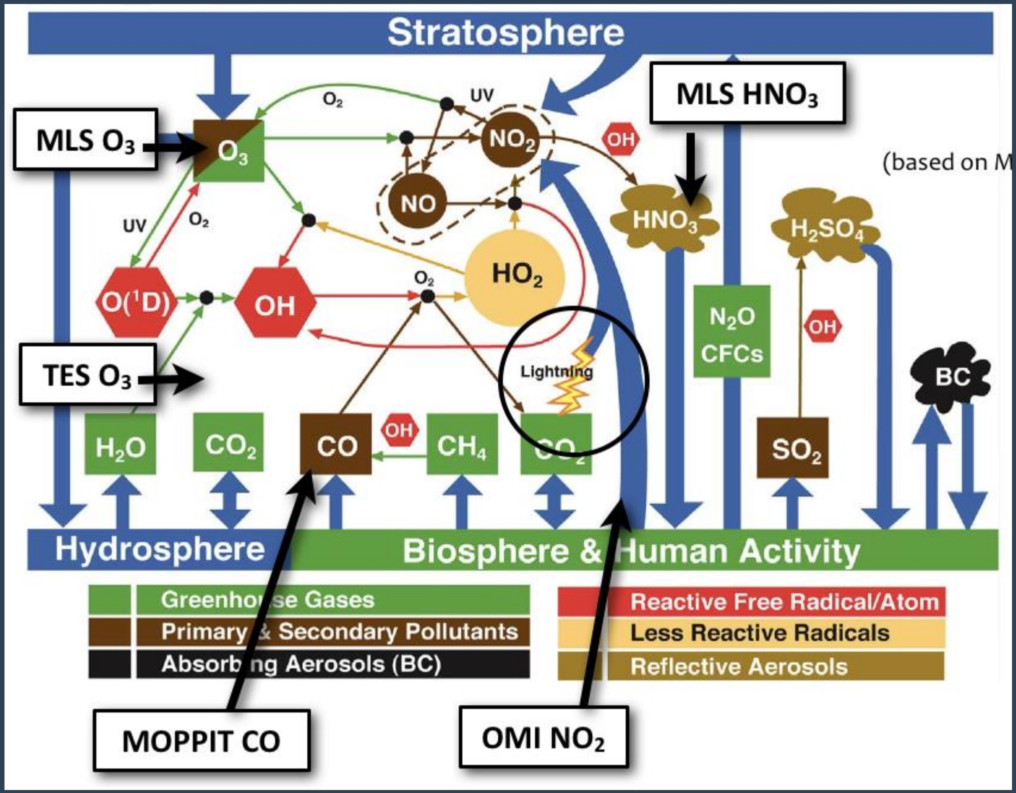
Q1: Business as usual (BAU)
Q2: AQ-only (CO_2 lock-in?)
Q3: AQ/Carbon (renewables)
Q4: Carbon-only

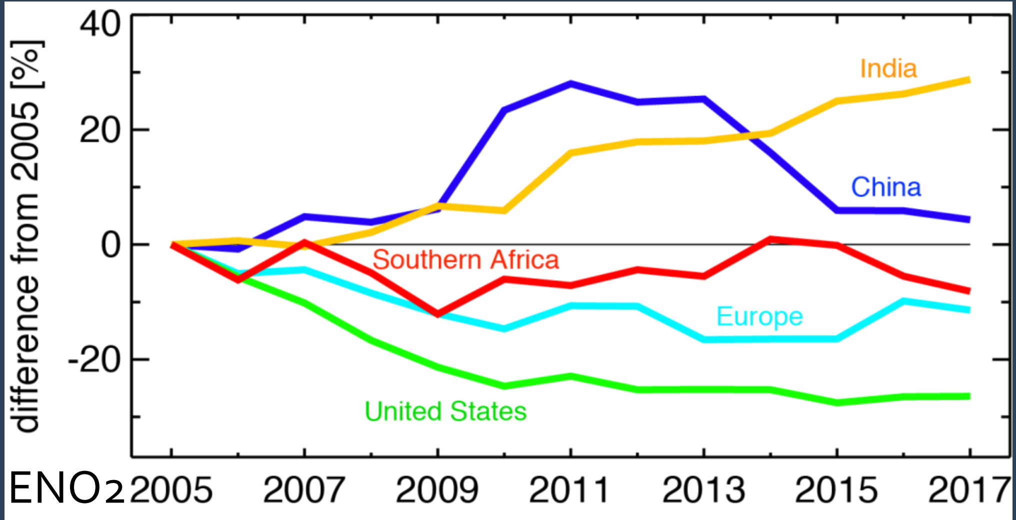
https://www.economicshelp.org/blog/14337/environment/environmental-kuznets-curve/

JPL/JAMSTEC chemical reanalysis

The tropospheric chemistry reanalysis (TCR-2) assimilated data from multiple satellites (Miyazaki et al, 2012-2019).
Migration towards AIRS/OMI O3 (Miyazaki et al, 2019) and TROPOMI data streams in progress.

NOx emissions have been computed from 2005-2017 at 1x1 grid resolution.

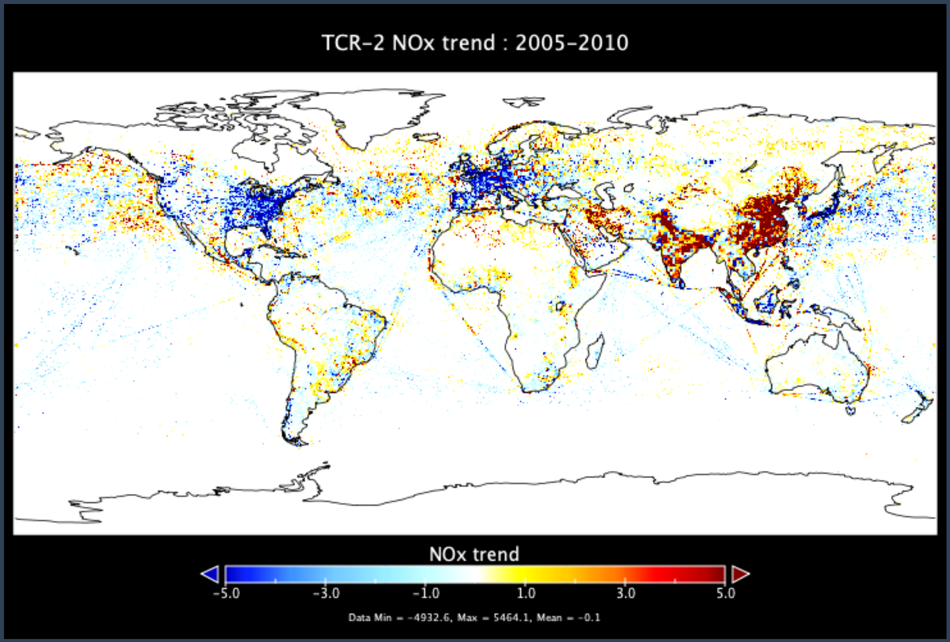


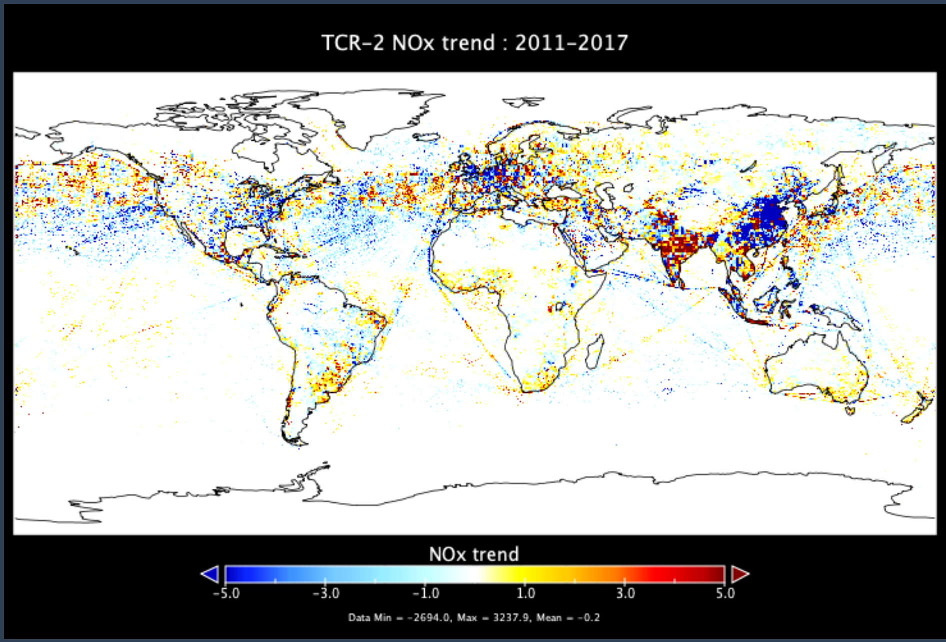


ENO2

gov

The Changing Landscape of Emissions



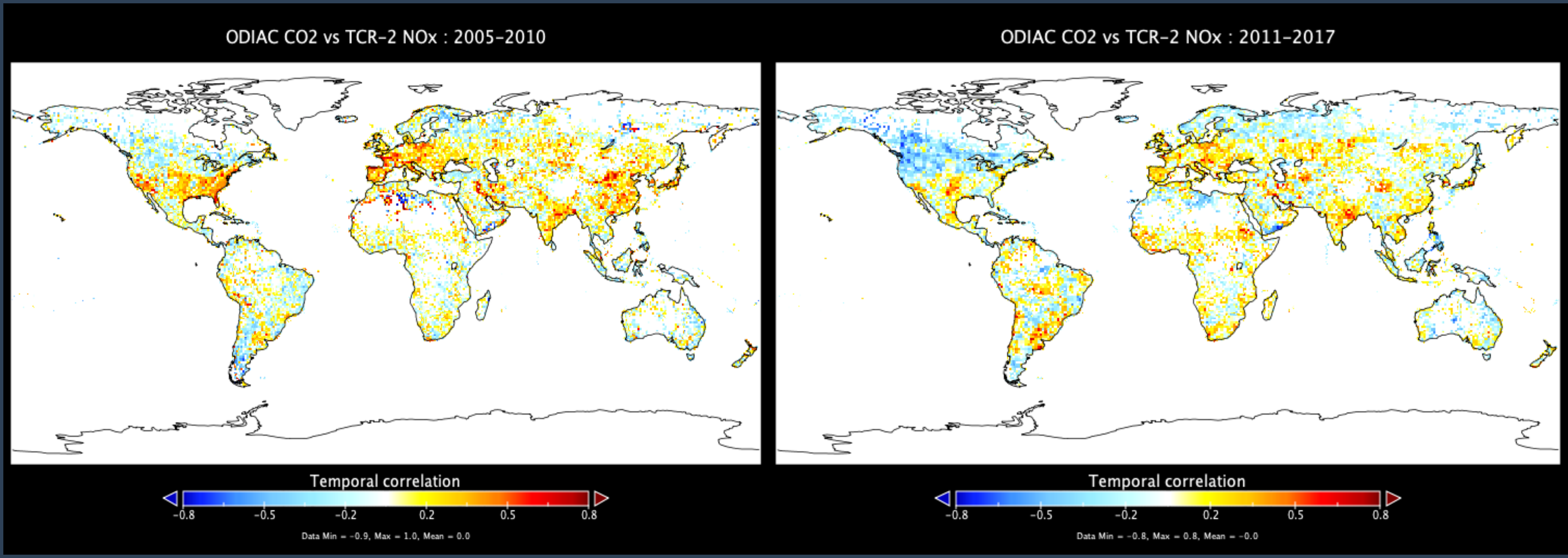


The JPL/JAMSTEC multi-constituent data assimilation analysis (TCR-2) shows rapid changes in Chinese NOx emissions—within one stocktake.

These results also show a slow-down in US emissions as reported in Jiang *et al*, PNAS (2018).

What do these changes imply about the carbon footprint?

Changing landscape of correlations



There is a substantial change in CO_2:NO_2 correlations between between 2005-2010 and 2011-2017 from ODIAC and TCR-2.

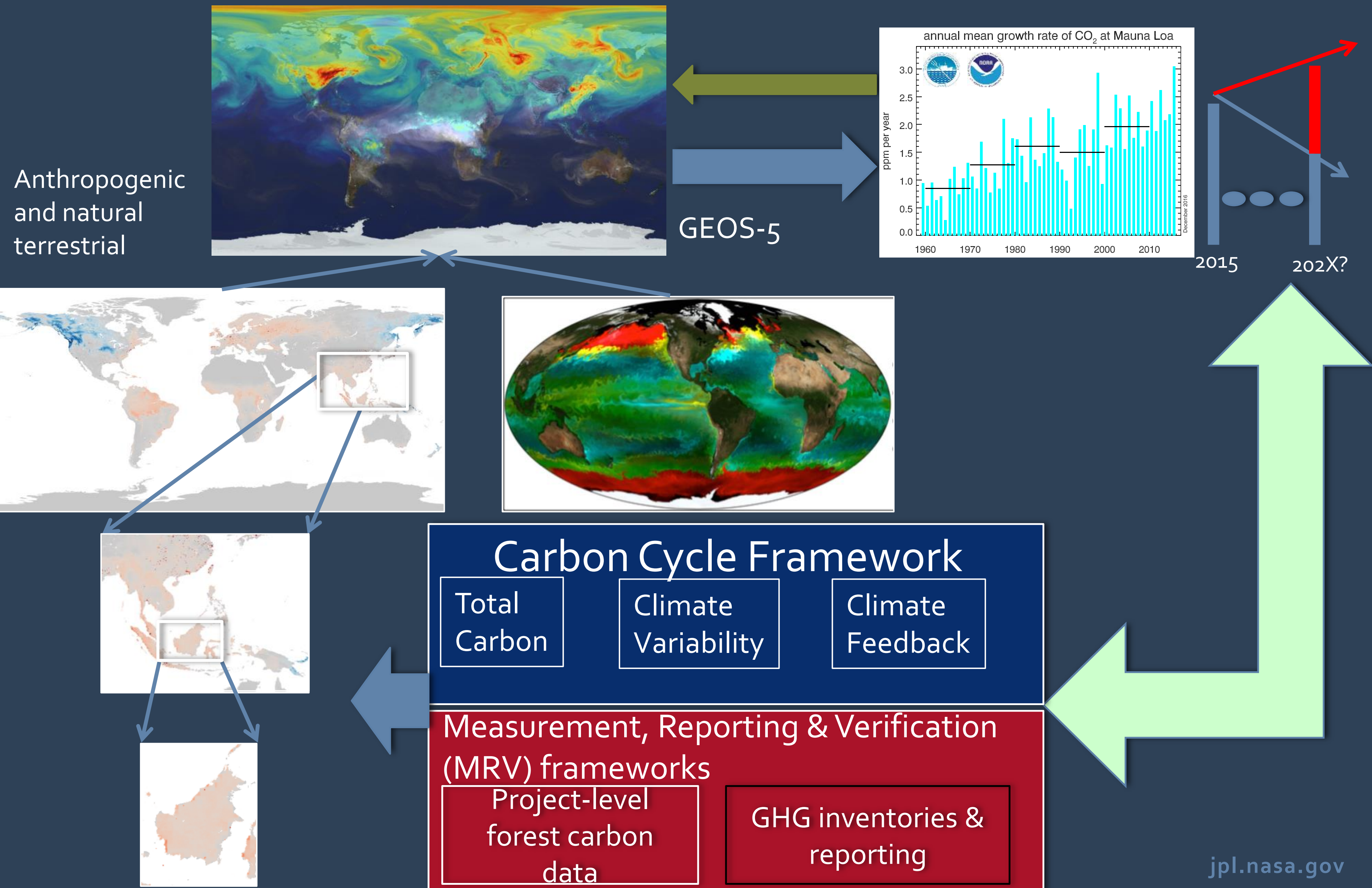
Nation	2005-2010 (R)	2011-2017 (R)
US	0.55	0.11
Europe	0.36	0.25
India	0.20	0.36
China	0.36	-0.34

This suggests that either CO_2 predictions have degraded (NA and Europe) or emission factors are dynamic.
A changing GHG/AQ Kuznet process?

Conclusions

- The bidecadal stocktake requires a link between
  - net CO_2 flux ← → Concentrations (what the climate sees)
  - $FFCO_2$ ← → Emissions (what carbon mitigation sees)
- Only atmospheric-based systems, not the UNFCCC inventories, can make that link.
- Trends at stocktake scales will be a mixture of anthropogenic and carbon processes
  - Attribution of decadal oceanic carbon trends need to considered (ECCO-Darwin)
  - The predictability of the carbon cycle is important (CARDAMOM)
- CMS-Flux results show the intimate relationship between hydrological and carbon cycles that will impact those trends
- Exploitation of the full carbon and air quality constellation at multiple scales is critical to advance the objectives of the Paris accord and guide observing system requirements.

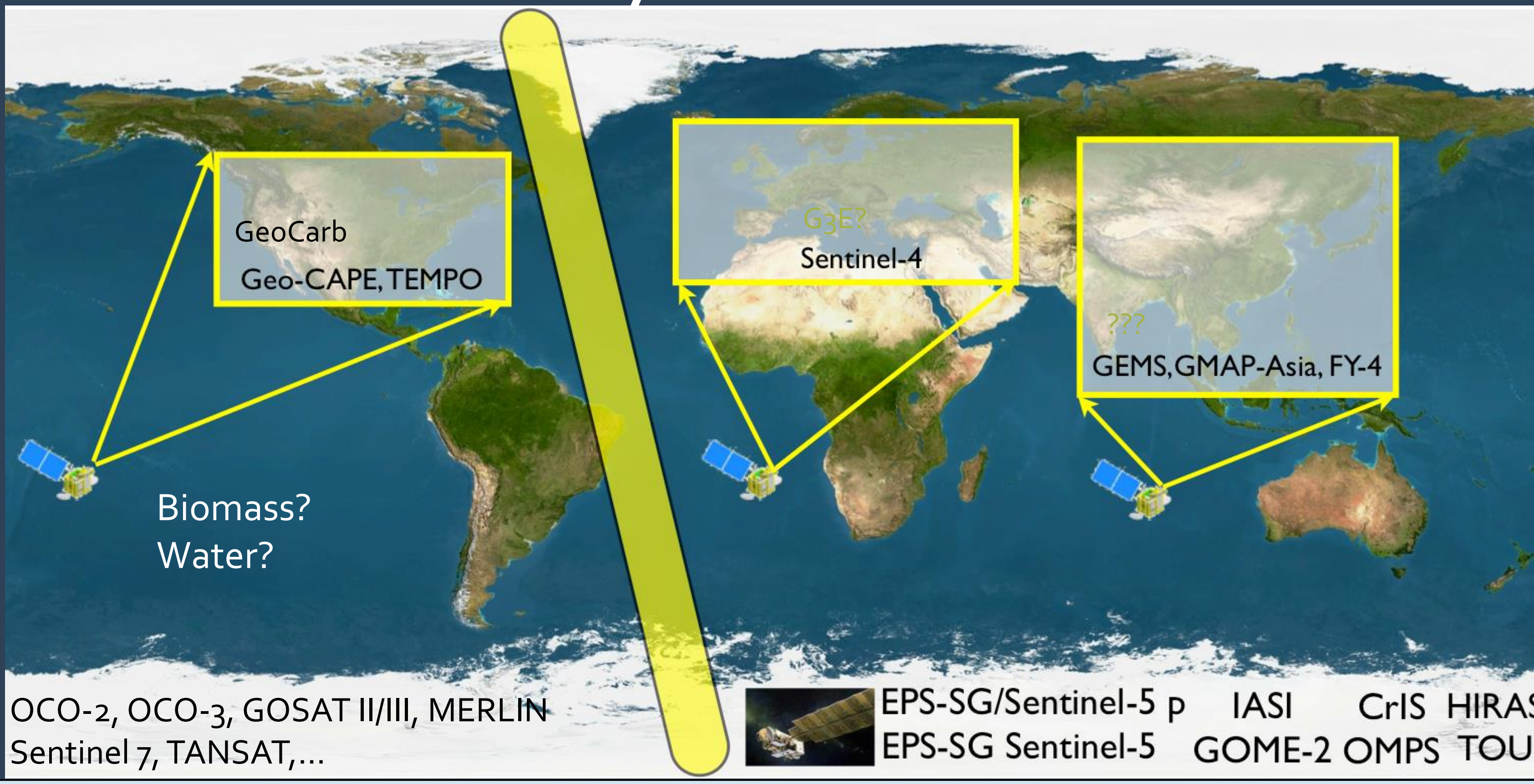
Carbon-Climate Framework



jpl.nasa.gov

Toward an Air Quality-Carbon-Climate

Bowman et al, Atm.Env. 2013



- LEO:
  - IASI+GOME-2, AIRS+OMI, CrIS+OMPS could provide UV+IR ozone products for more than a decade.
  - Combined UV+IR ozone products from GEO-UVN and GEO-TIR aboard Sentinel 4 (Ingmann *et al*, 2012 Atm. Env.)
  - Sentinel 5p (TROPOMI) will provide column CO and CH_4.
  - OCO-2+AIRS, GOSAT II (IR+NIR) could provide vertical discrimination.
- GEO
  - TEMPO, Sentinel-4, and GEMS, would provide high spatio-temporal air quality information.
  - GeoCarb and G3E could provide geo-carbon information.

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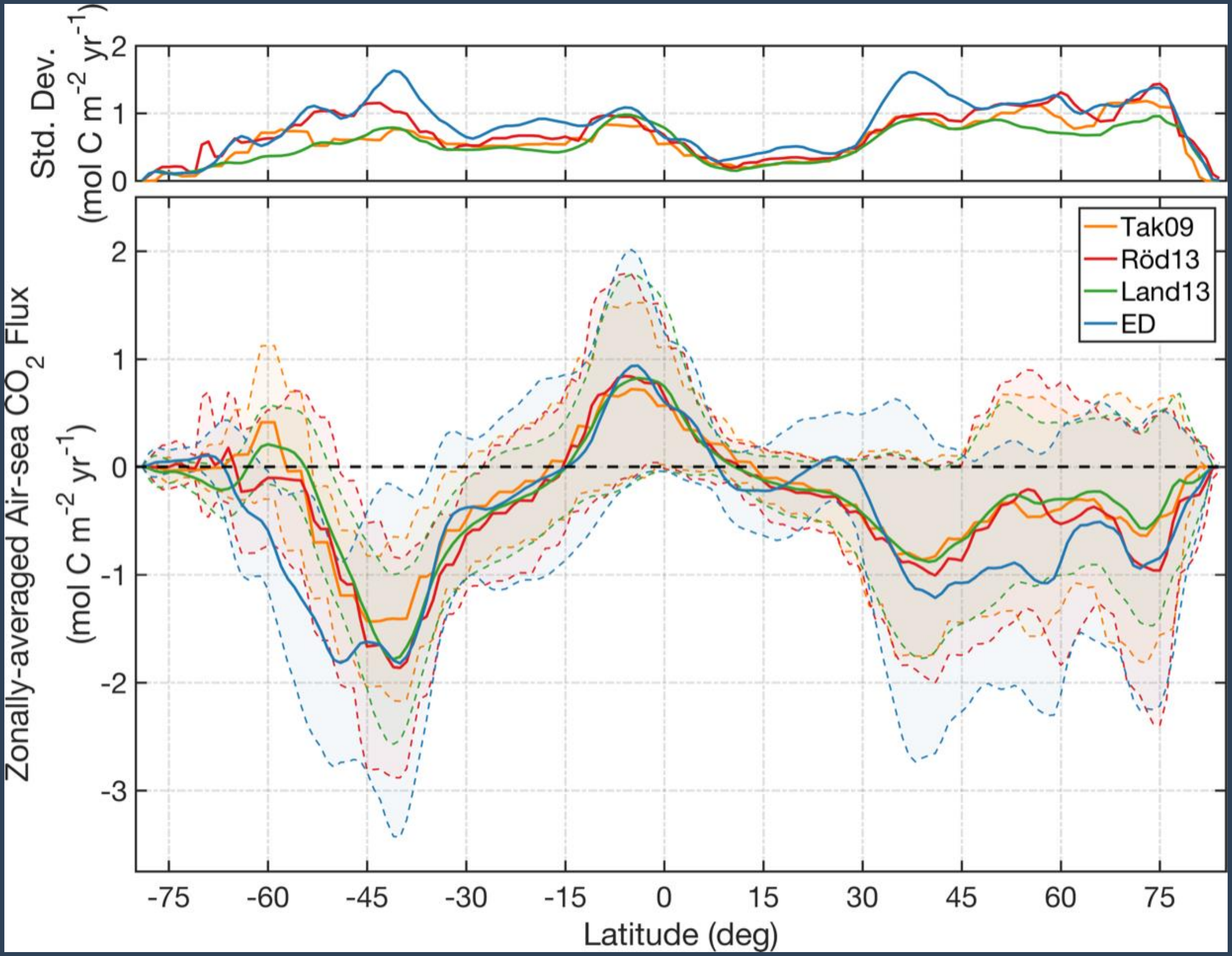
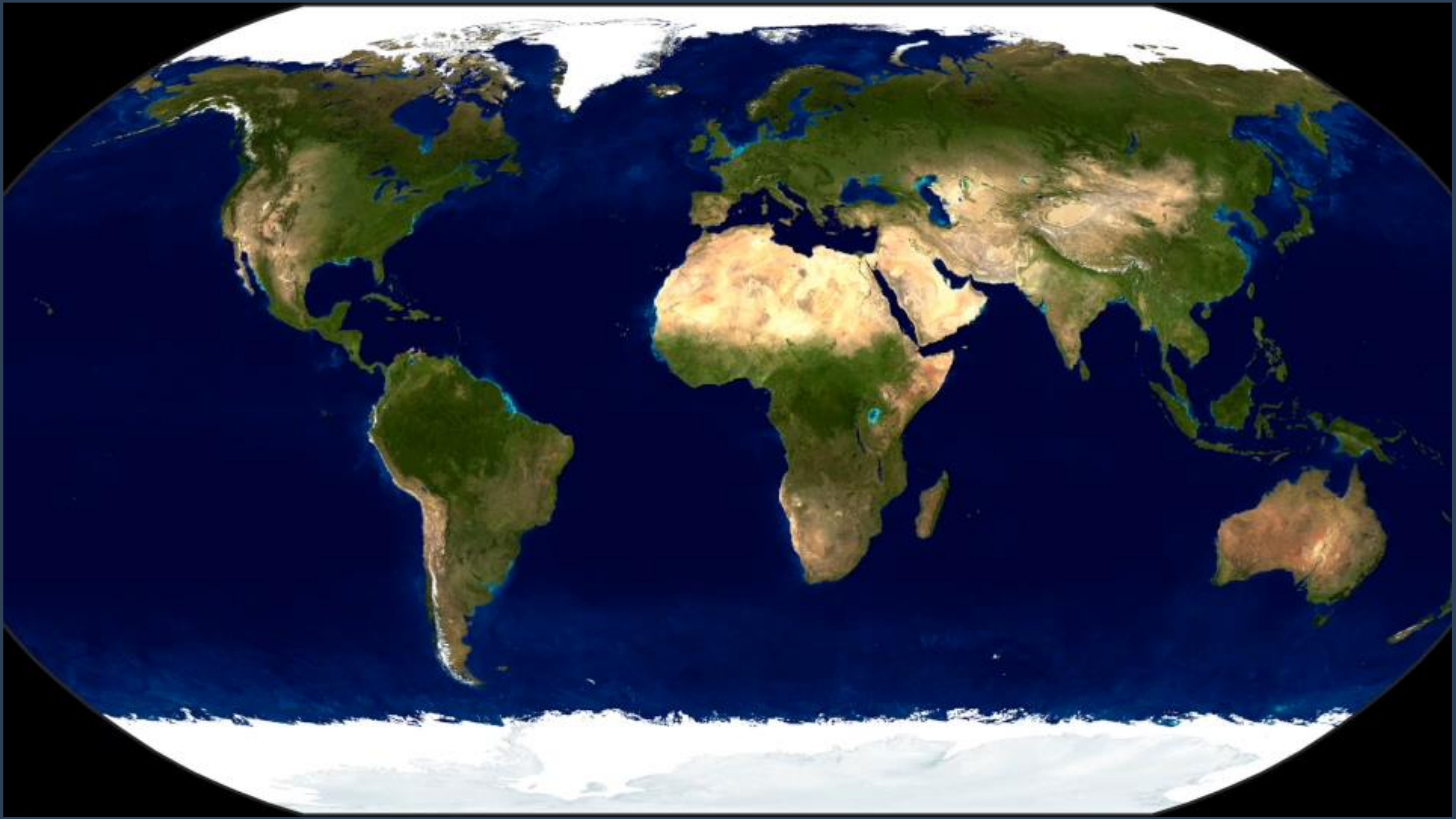
ECCO-Darwin evaluation



From emissions to concentrations

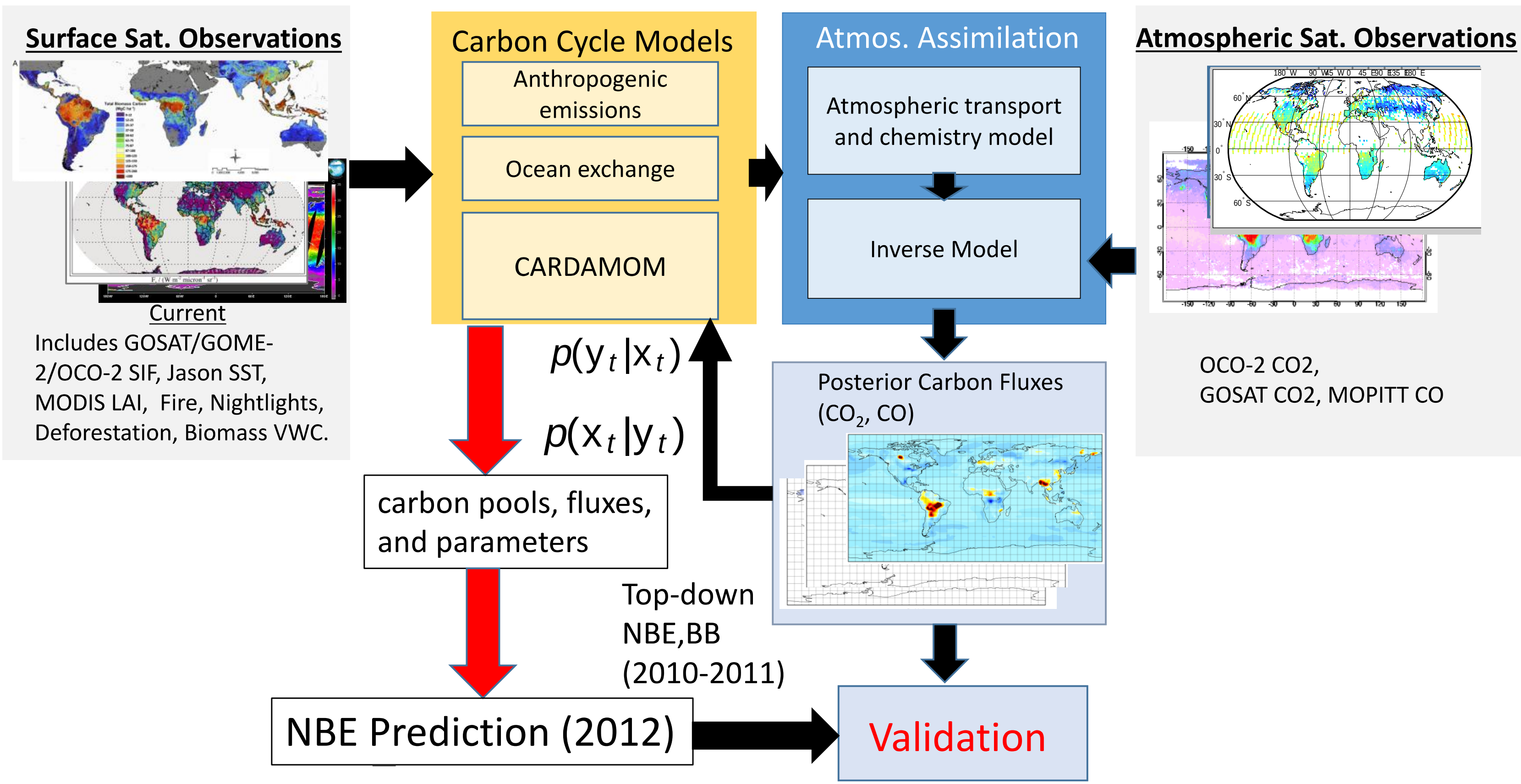
GEOS-Chem High Performance, C360



Courtesy, Sebastian Eastham, MIT

Towards carbon cycle prediction

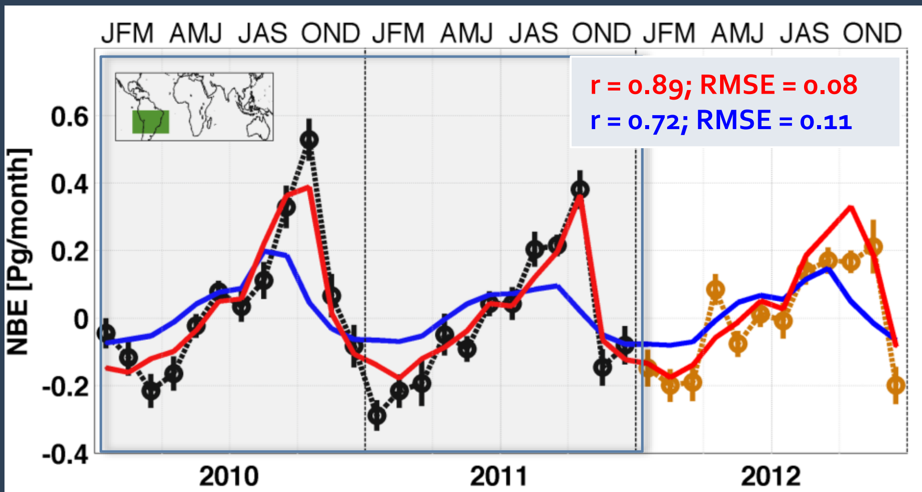
Carbon Cycle Data Assimilation System (CMS-Flux)



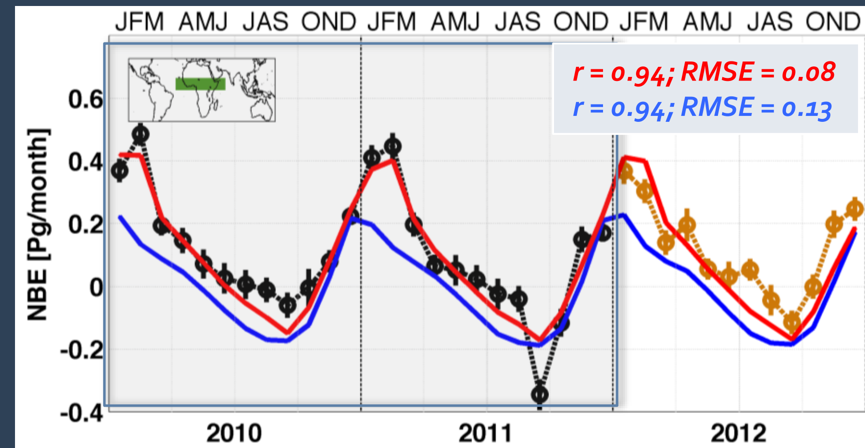
$$p(z_{t+\boxtimes}|y_t) = \quad p(z_{t+\boxtimes}|x_t)p(x_t|y_t)dx$$

Results: 2012 NBE prediction

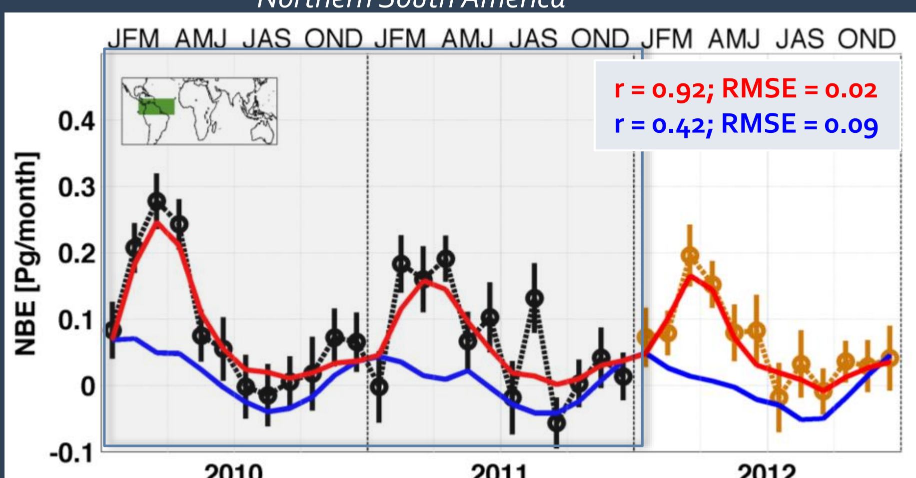
Southern South America



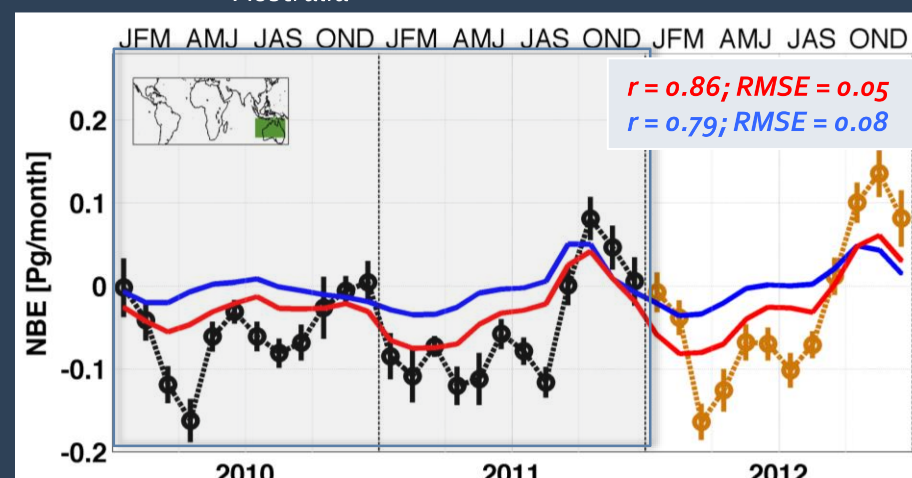
Northern Sub-Saharan Africa



Northern South America



Australia



BLACK = CMS-Flux NBE (assimilated);
ORANGE = CMS-Flux NBE (witheld)

CARDAMOM (NBE constrained)
CARDAMOM (Baseline)

Regional variations in trends

There is a wide intra-regional range of TTD with the Middle East having the lowest range 5 years (5-10 1st and 3rd quartile), though Europe and China TTD 3rd quartile is within 20 years.

For, FFCO2 trends greater than 5 gC/m²/yr², ~1/3 corresponding net CO2 trends agree to within 25%.

Similarly in China, ~20% of the net CO2 trends agree to within 25%.

In the Middle East, over 70% of net CO2 trends is within 25%