Maximizing the Role of Atmospheric CO_2 Observations in Shaping Carbon Cycle Science and Carbon-Climate Policy

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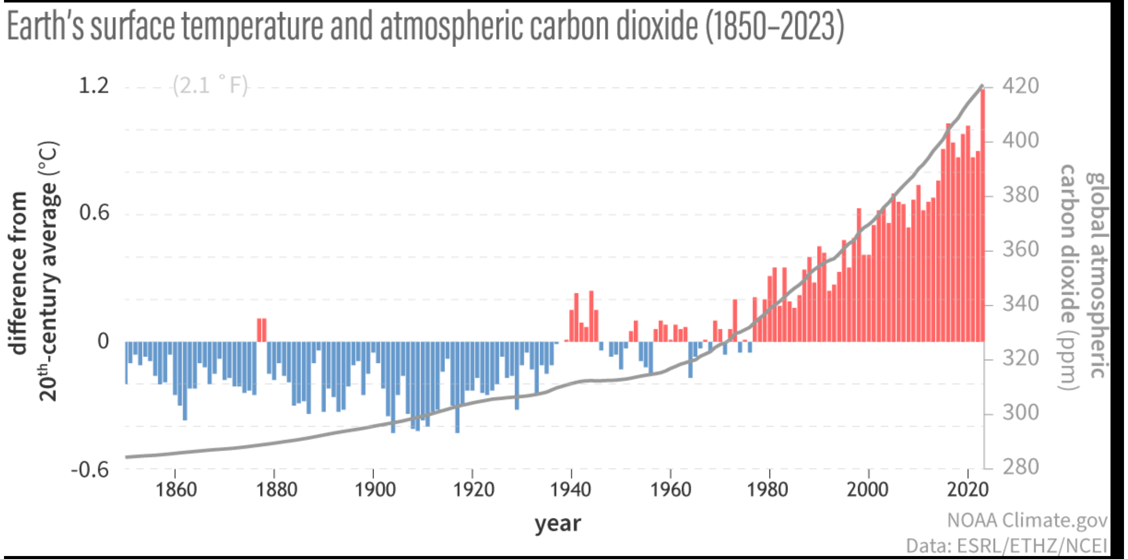
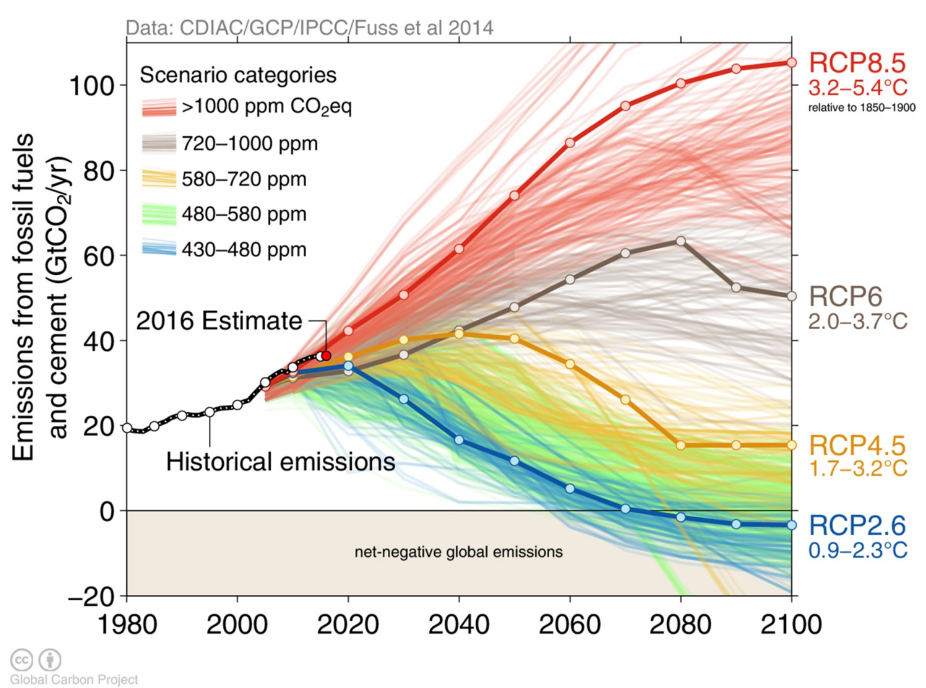
KISS workshop
Oct 7th, 2024

Increasing in Atmospheric CO_2 is the Primary Driver for Climate Change


Earth's surface temperature and atmospheric carbon dioxide (1850–2023)

NOAA Climate.gov
Data: ESRL/ETHZ/NCEI

- Year 2023 was the hottest year since 1850s;
- Atmospheric CO2 concentration has been accelerating.

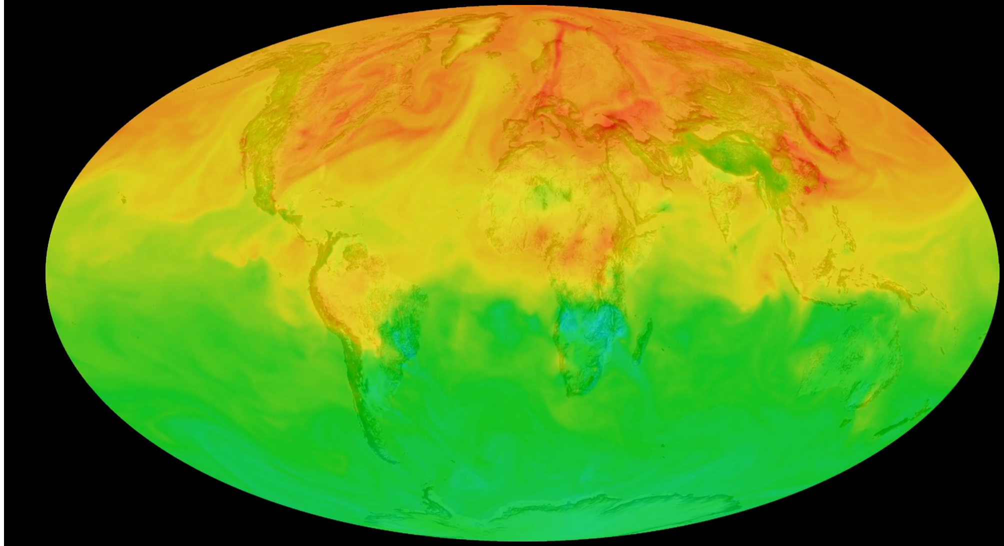

Data: CDIAC/GCP/IPCC/Fuss et al 2014

Global Carbon Project

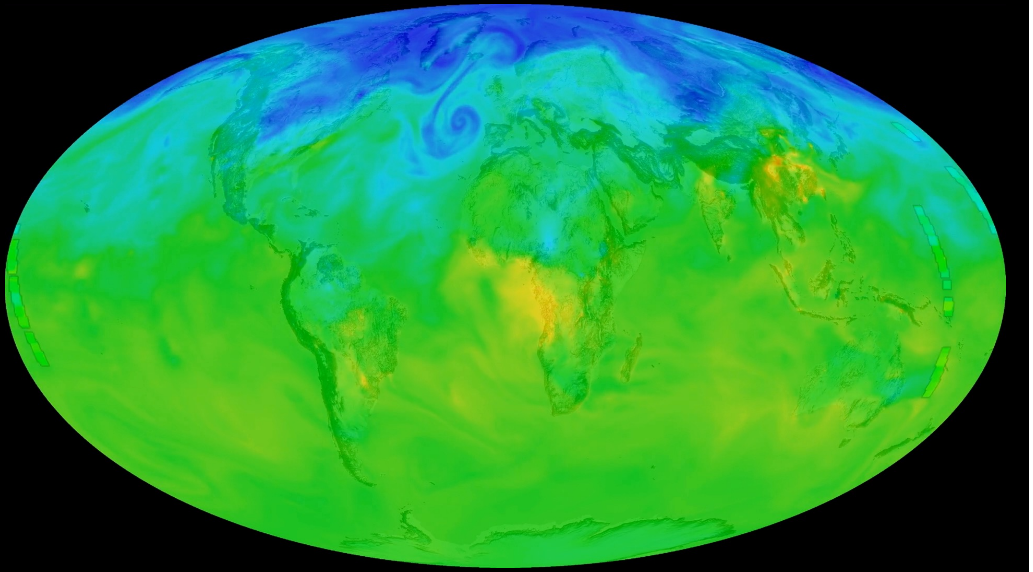
- Future climate change is closely related to the atmospheric CO_2 concentration.
- The changes of atmospheric CO_2 concentration is the net effect of sources and sinks.

The Variability of Atmospheric CO2 is Driven by Atmospheric Transport and Surface CO_2 Fluxes

6-hourly column CO2 concentration simulations



- The spatiotemporal gradient of atmospheric CO_2 concentration is the result of both atmospheric transport and surface fluxes.



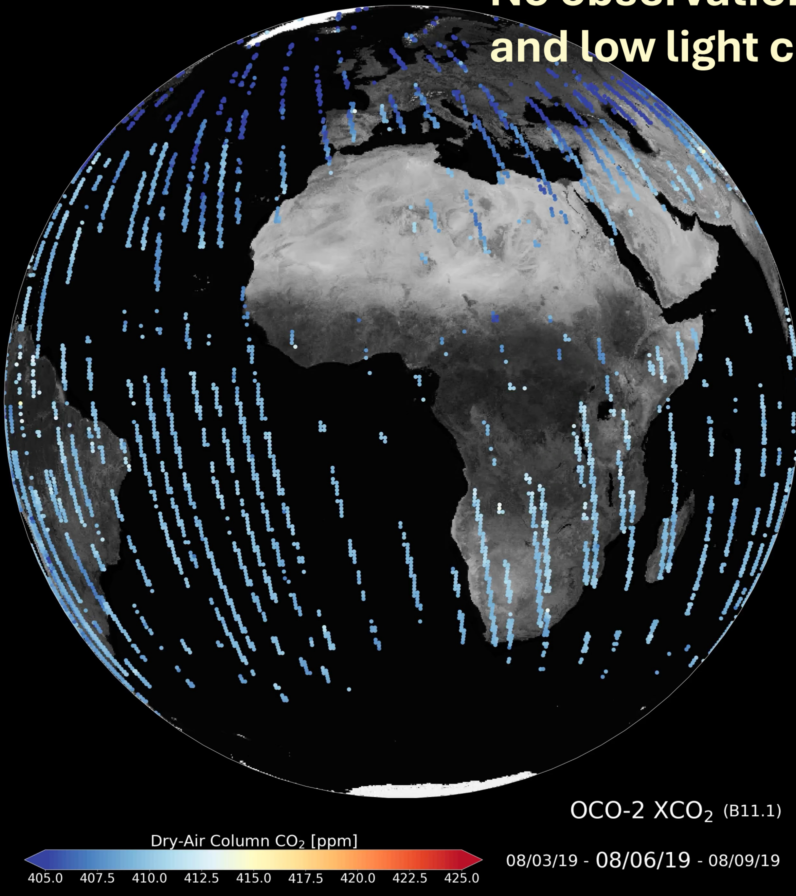
- Satellite observations (e.g., OCO-2) capture a snapshot of atmospheric CO2 concentration.

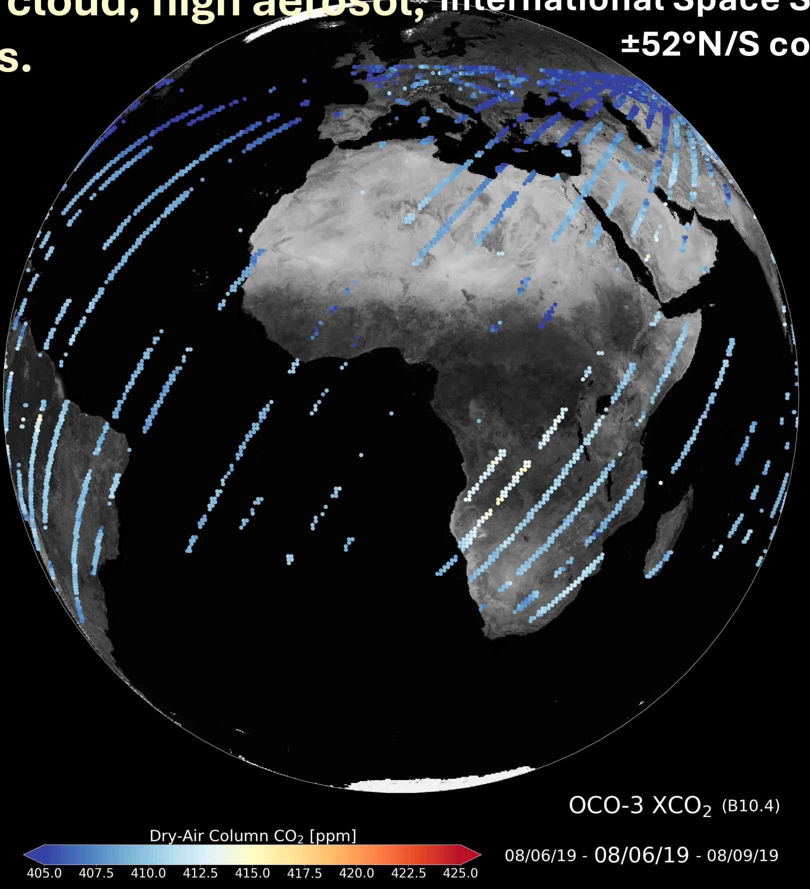
https://svs.gsfc.nasa.gov/

OCO-2 (since 09/2014):
Sun-synchronous orbit, pole-to-pole coverage
Footprint size: 1.9x2.3km^2

- **The CO2 north-south gradient is about 5-7 ppm**
- **The accuracy of XCO2 retrievals is about 1.0ppm.**
- **No observations under cloud, high aerosol, and low light conditions.**

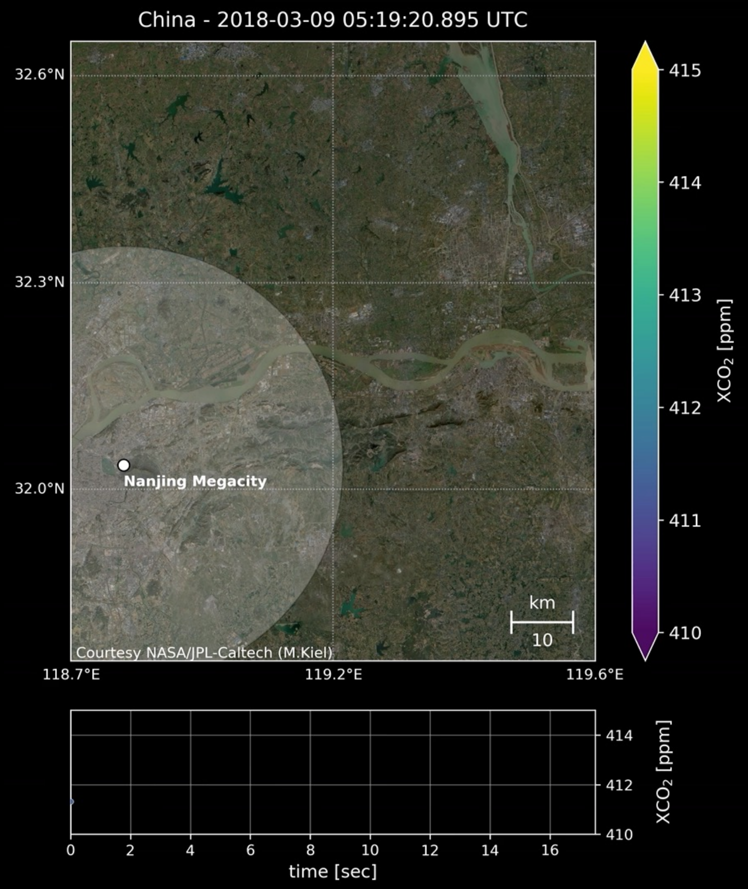
OCO-3 (since 08/2019):
International Space Station,
±52°N/S coverage



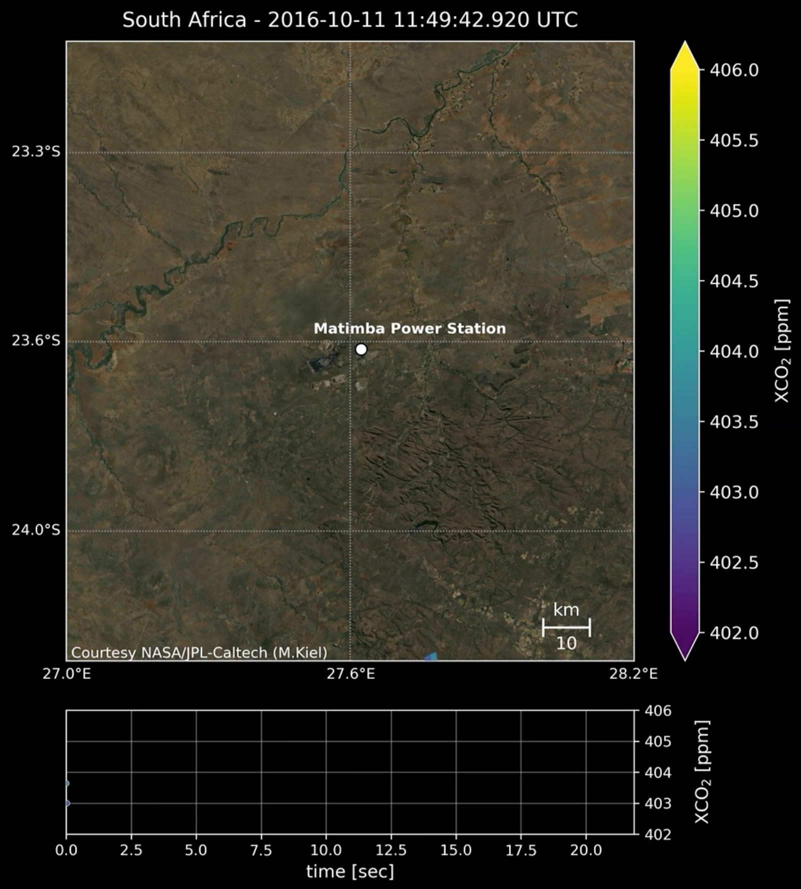


Credit: T. Kurosu

OCO-2/3 Detect CO_2 Signals from Fossil Fuel Emissions in Large Urban Areas and Power Plants


China - 2018-03-09 05:19:20.895 UTC

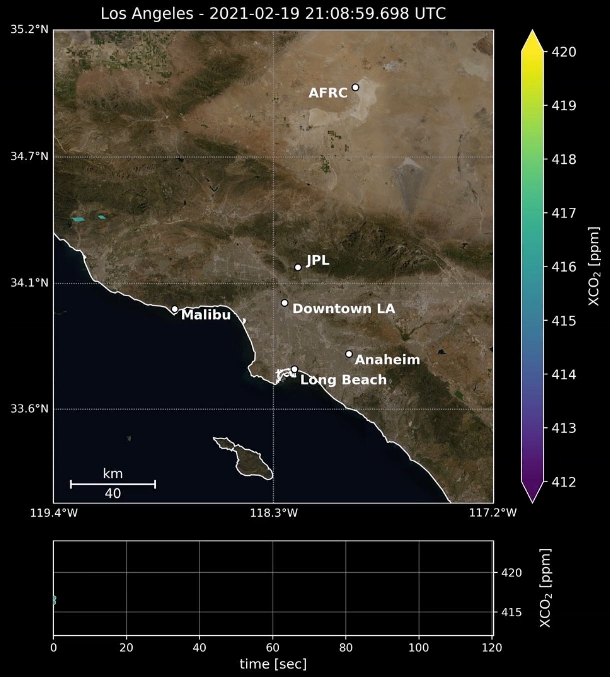
Courtesy NASA/JPL-Caltech (M.Kiel)


South Africa - 2016-10-11 11:49:42.920 UTC

Courtesy NASA/JPL-Caltech (M.Kiel)

OCO-3 (ISS) Snapshot Area Maps

CO$_2$, Belchatów Powerplant, Poland

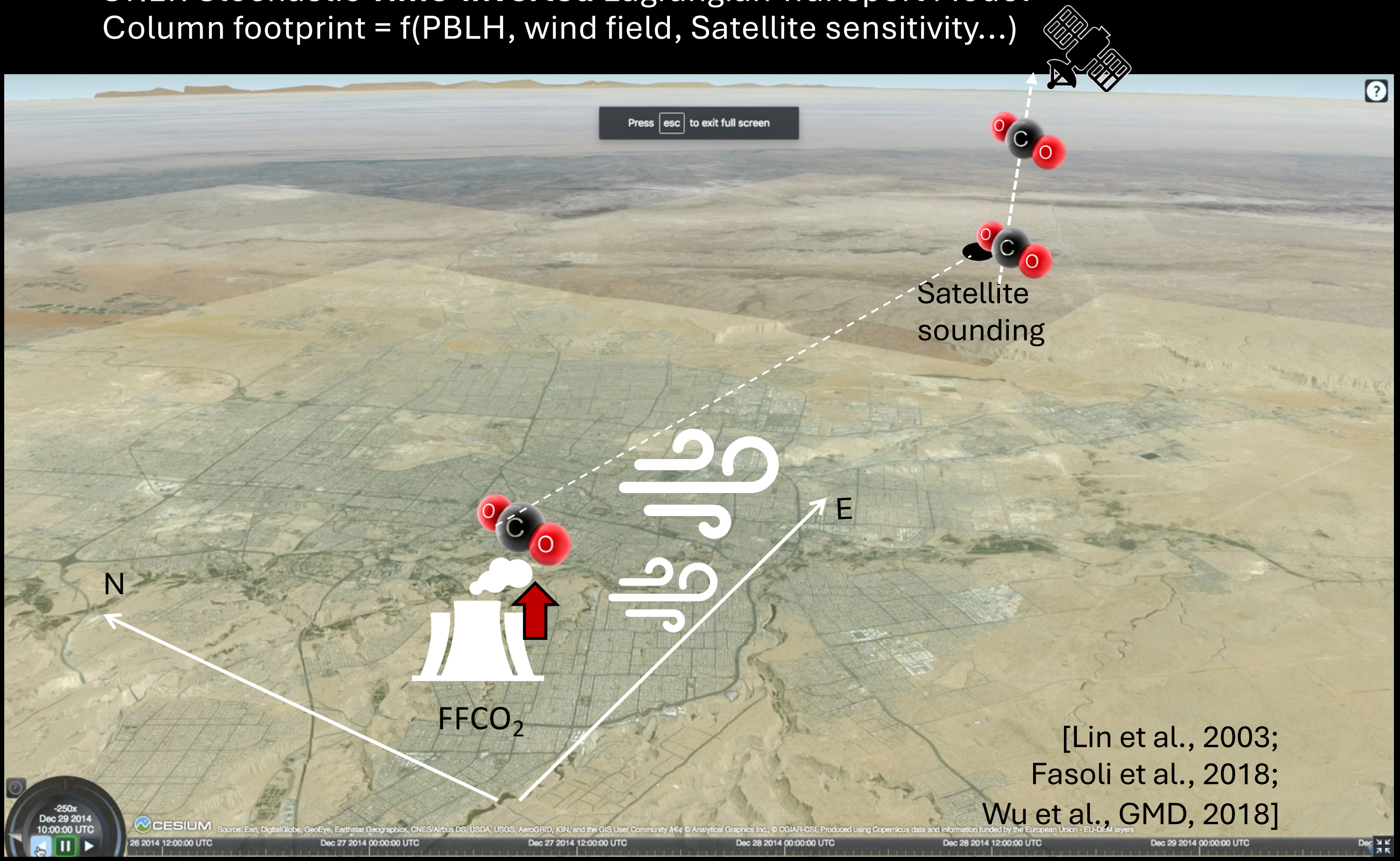


CO$_2$, Los Angeles

What are the barriers to advancing quantification of fossil fuel emissions and improving our understanding of natural carbon fluxes?

Calculating the Sensitivity of CO_2 Concentration to the Fluxes: X-STILT in Linking Concentrations to Emissions

STILT: Stochastic **Time-inverted** Lagrangian Transport Model
Column footprint = f(PBLH, wind field, Satellite sensitivity...)



[Lin et al., 2003;
Fasoli et al., 2018;
Wu et al., GMD, 2018]

Credit: D. Wu

Calculating the Sensitivity of CO2 Concentration to the Fluxes: X-STILT in Linking Concentrations to Emissions

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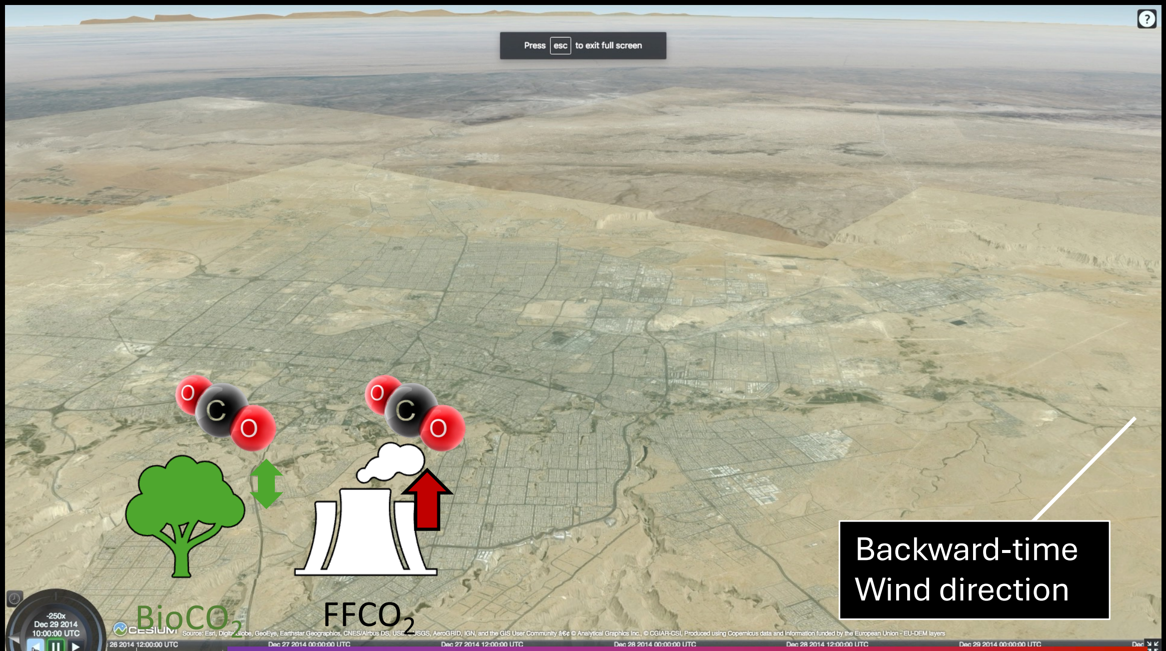
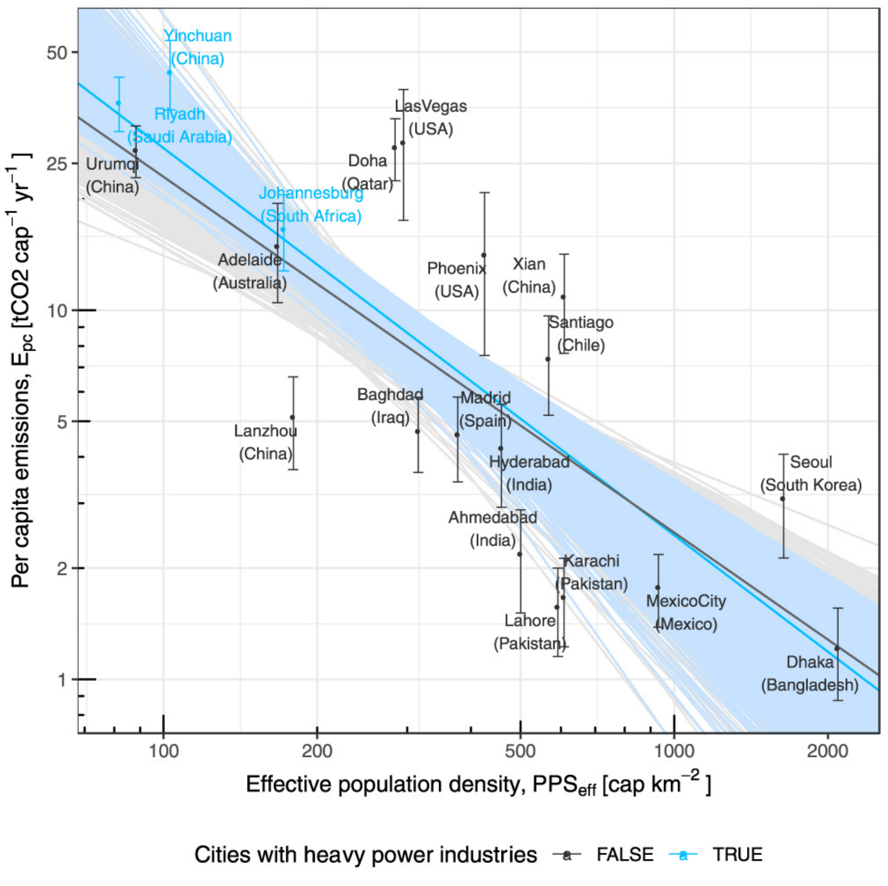


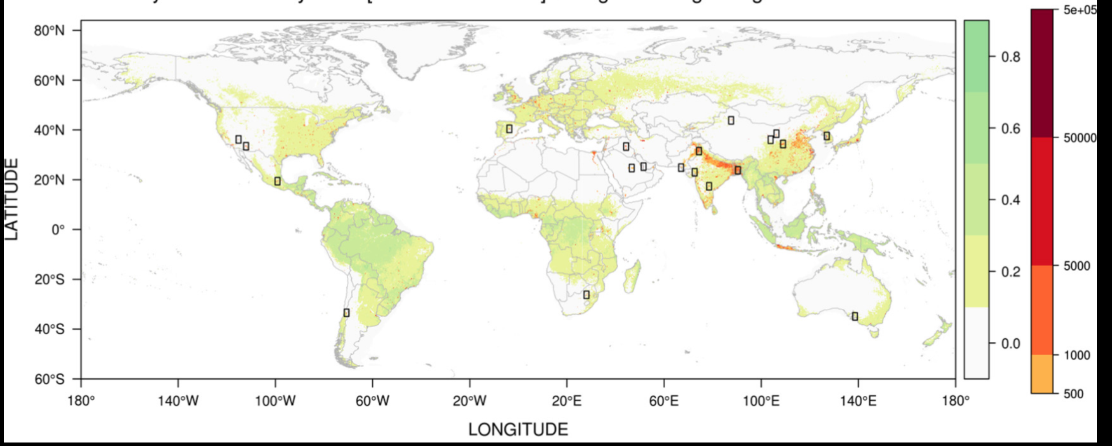
Column CO_2 Enhancements = Column footprint x $FFCO_2$ fluxes

Credit: D. Wu

Urban Emission Characteristics and Uncertainties



20 arid cities

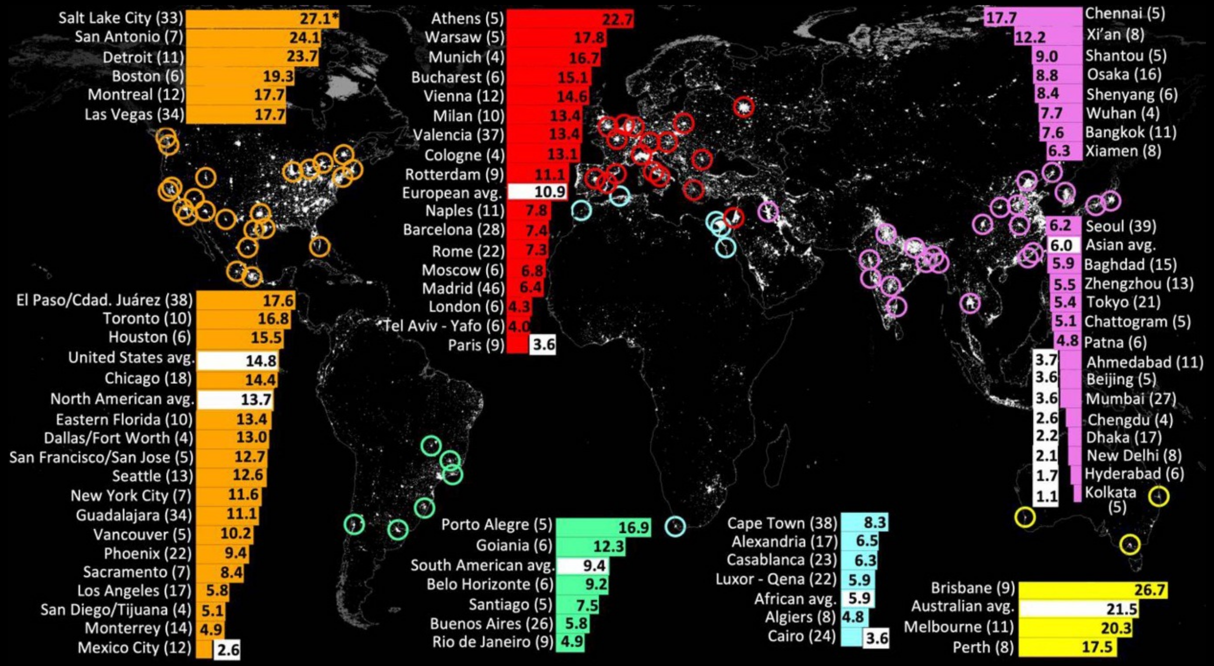


- Uncertainty sources: observational error and transport errors

Wu et al., ERL, 2020

Urban Emission Characteristics and Quantification

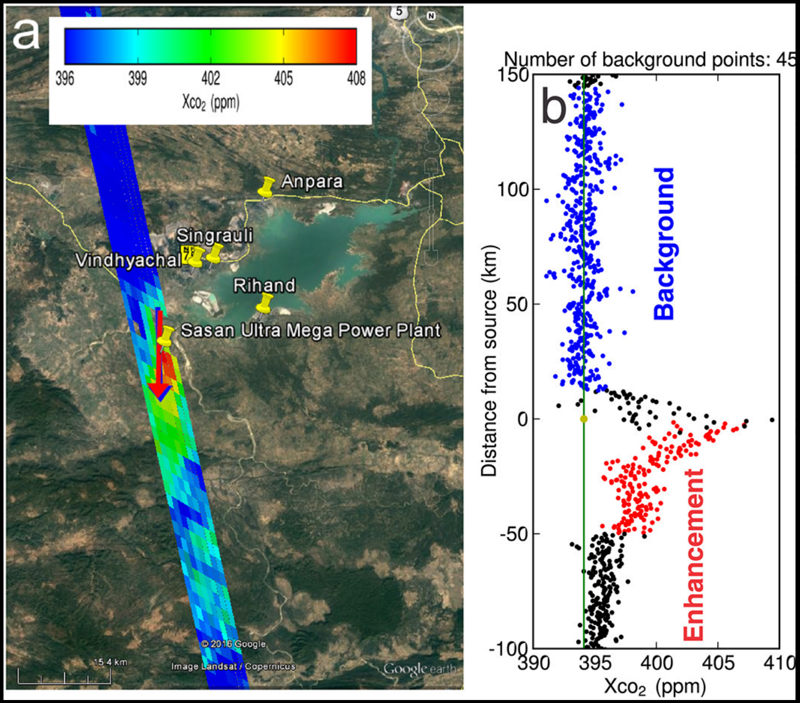
77 cities

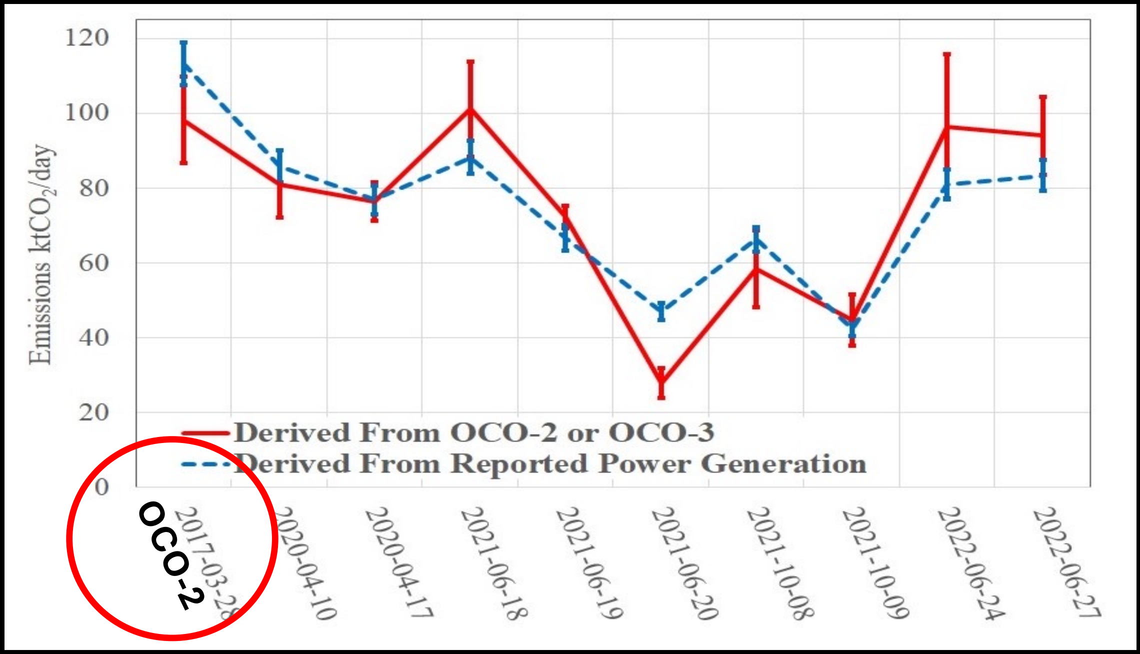


Wilmot e t al., 2024

- Captures ~16% of global carbon dioxide emissions, similar in magnitude to the total direct emissions of the United States or Europe.
- Uncertainties: aerosols and cloud coverage

Estimating Emissions from Power Stations





Nassar et al., 2017, 2023

- The OCO-2/3 observations capture a factor of two temporal variations of emissions from power stations .
- The uncertainty can be up to about 20% of emissions.

Emission Estimations of from Power Stations

$$V(x,y) = \frac{F}{\sqrt{2\pi}\sigma_y(x)u} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y(x)}\right)^2}$$

$$\sigma_y(x) = a\cdot\left(\frac{x}{x_o}\right)^{0.894}$$

Gaussian plume model

Nassar et al., 2017

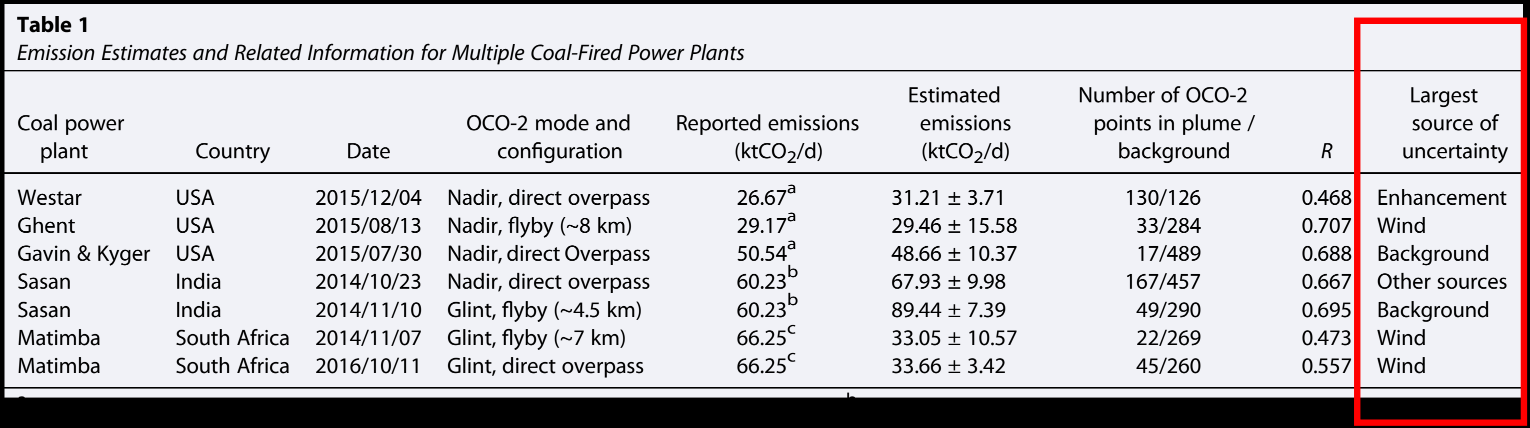


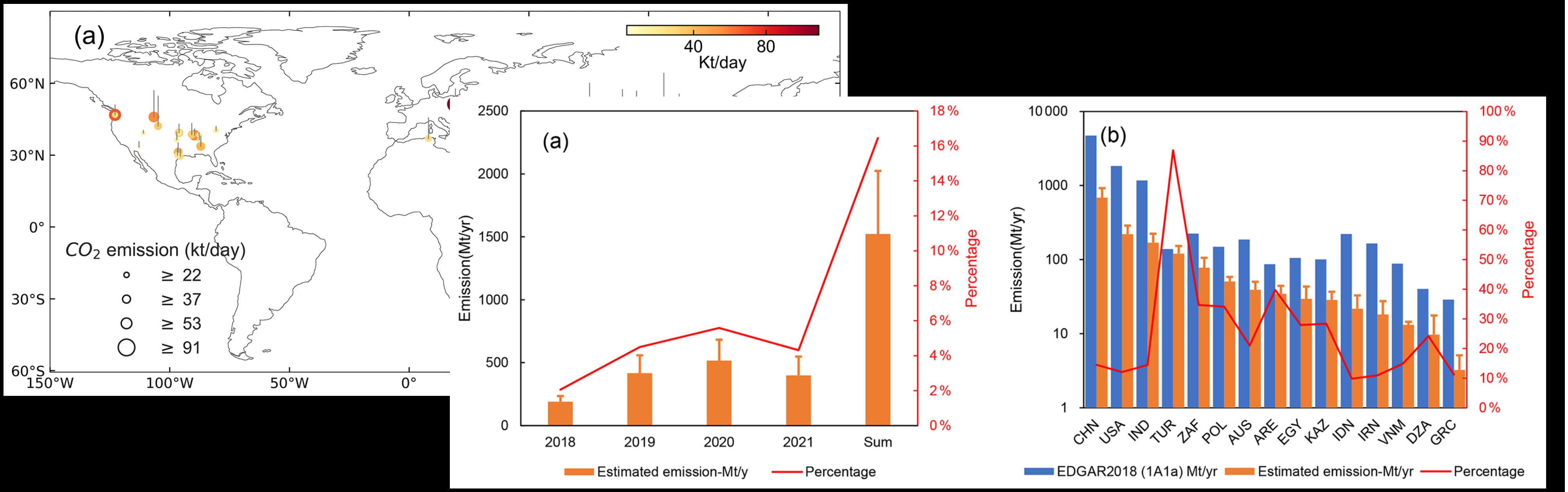
Table 1

Emission Estimates and Related Information for Multiple Coal-Fired Power Plants

Coal power plant	Country	Date	OCO-2 mode and configuration	Reported emissions ($ktCO_2/d$)	Estimated emissions ($ktCO_2/d$)	Number of OCO-2 points in plume / background	R	Largest source of uncertainty
Westar	USA	2015/12/04	Nadir, direct overpass	26.67[a]	31.21 ± 3.71	130/126	0.468	Enhancement
Ghent	USA	2015/08/13	Nadir, flyby (~8 km)	29.17[a]	29.46 ± 15.58	33/284	0.707	Wind
Gavin & Kyger	USA	2015/07/30	Nadir, direct Overpass	50.54[a]	48.66 ± 10.37	17/489	0.688	Background
Sasan	India	2014/10/23	Nadir, direct overpass	60.23[b]	67.93 ± 9.98	167/457	0.667	Other sources
Sasan	India	2014/11/10	Glint, flyby (~4.5 km)	60.23[b]	89.44 ± 7.39	49/290	0.695	Background
Matimba	South Africa	2014/11/07	Glint, flyby (~7 km)	66.25[c]	33.05 ± 10.57	22/269	0.473	Wind
Matimba	South Africa	2016/10/11	Glint, direct overpass	66.25[c]	33.66 ± 3.42	45/260	0.557	Wind

- Uncertainty in wind observations is one of the leading sources of uncertainty in power plant emission estimations.

About 10% of Emissions from Isolated Power Stations were Captured by OCO-2/3 over Four Years



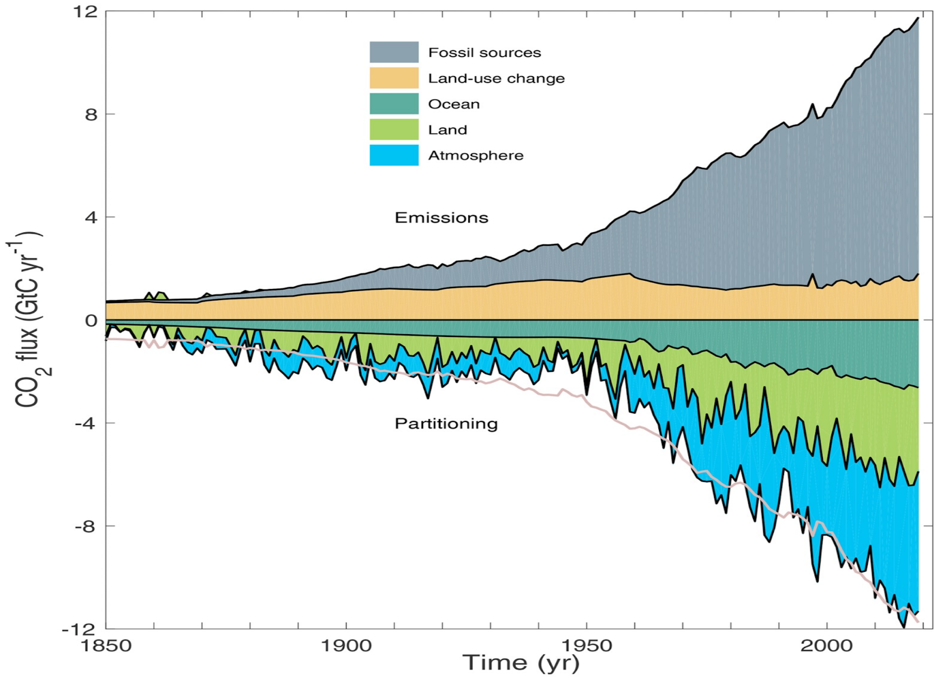
- The success of OCO-2/3 in observing anthropogenic emissions inspired a fleet of future satellite missions, such as GOSAT-GW and CO2M.

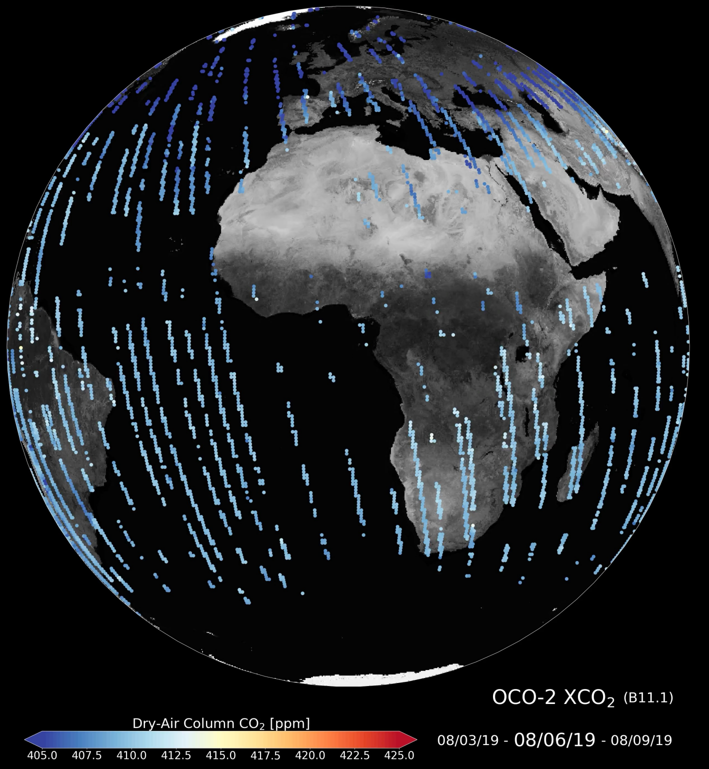
Lin et al., ACP, 2023

Maximizing the Impact of GHG Observations on Fossil Fuel Emission Estimation

- **OCO-2/3 observations demonstrate the feasibility to use space-borne observations to quantify emissions from urban domes and power stations.**
- Reduce uncertainties in transport (winds, PBL, dynamics, and etc.)
- Increase observational coverage (e.g., GOSAT-GW, CO2M, Carbon-I, EMIT, Carbon Mapper etc.).
  - Regions with persistent cloud and aerosols would be still challenging.
- Multi-species to learn sectorial information.
- Computational speed (e.g., ML)

About Half of the CO2 Anthropogenic Emissions are Absorbed by Land and Ocean

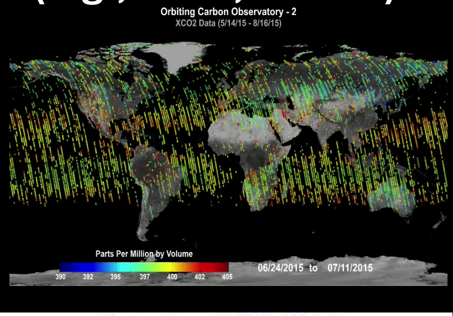




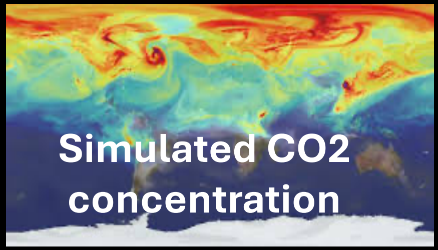
Friedlingstein et al., 2020

Inferring Natural Carbon Fluxes with Atmospheric CO2 Observations

GHG observations (e.g., flask, OCO-2)



Atmosphere Transport Model

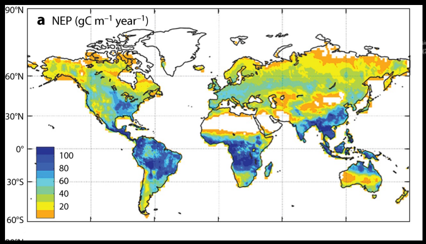


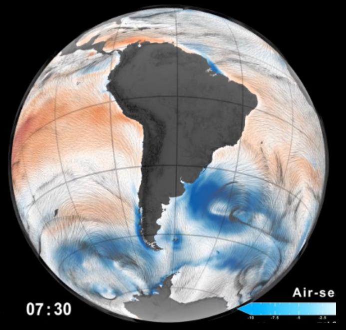
Simulated CO2 concentration

Atmospheric inverse model

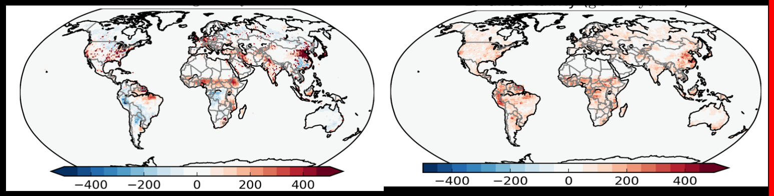
$$J(x) = (x - x^b)^T B^{-1}(x - x^b) + \sum_{i=1}^{n} (y - h(x))_i^T R^{-1}(y - h(x))$$

Bottom-up models and uncertainties





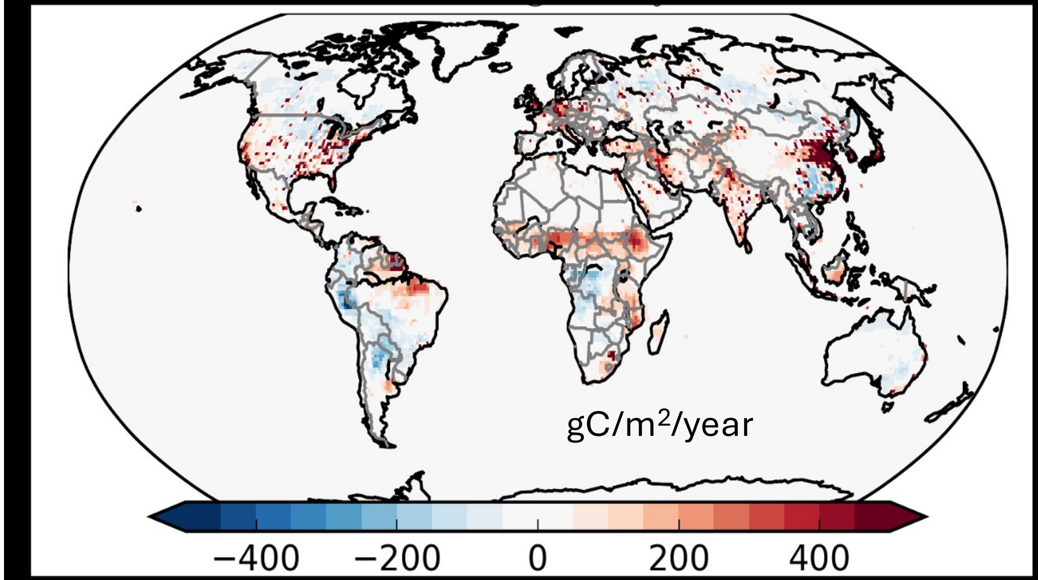
Posterior fluxes (CO2, CO, CH4) and uncertainties



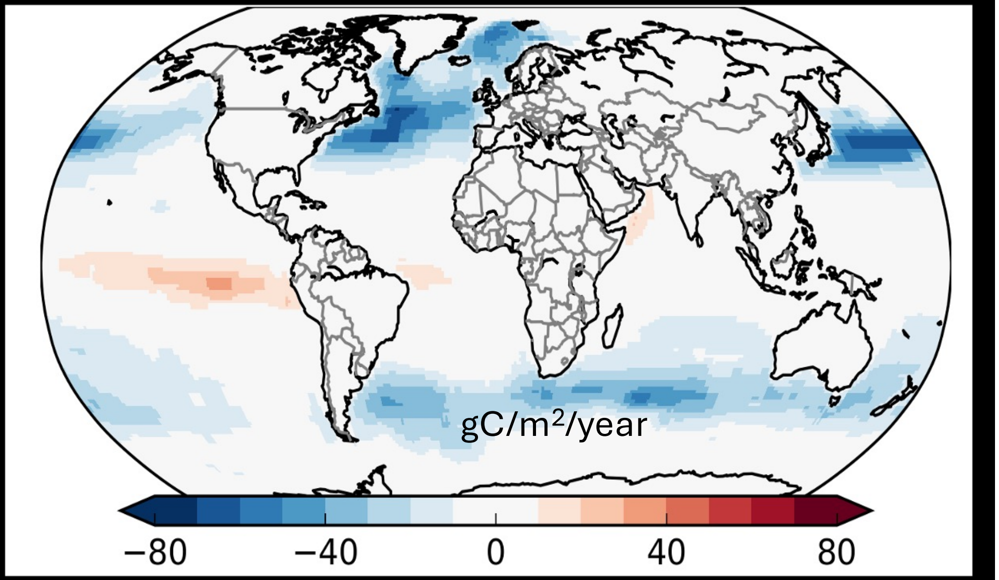
Science and decision support

The Spatial Distributions of CO_2 Sources and Sinks over Land and Ocean

Fossil Fuel + Terrestrial biosphere fluxes



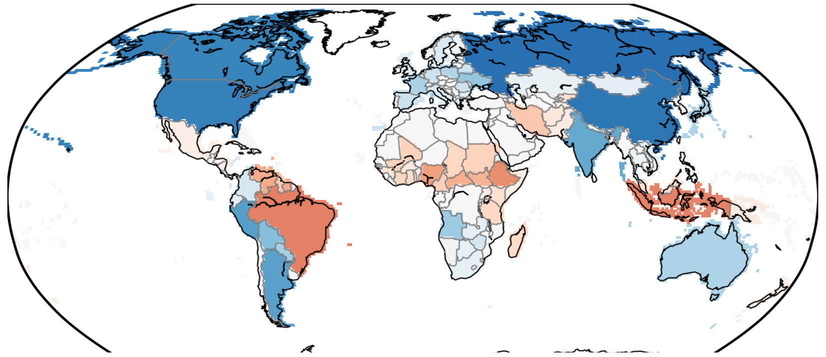
Ocean fluxes



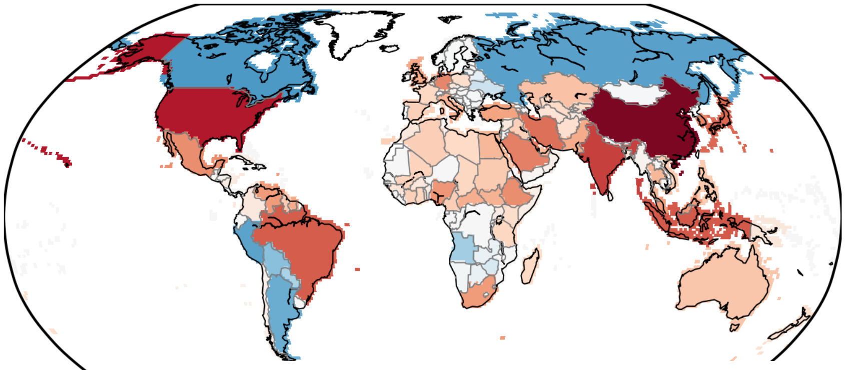
- Annual mean fluxes averaged over 2015-2020;
- It is the average over 13 top-down inversion models that have different assumptions of prior fluxes, prior flux uncertainties. These models use different transport models and inversion methodologies.

Byrne et al., ESSD 2022,

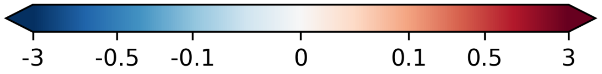
Country-scale Carbon Budget

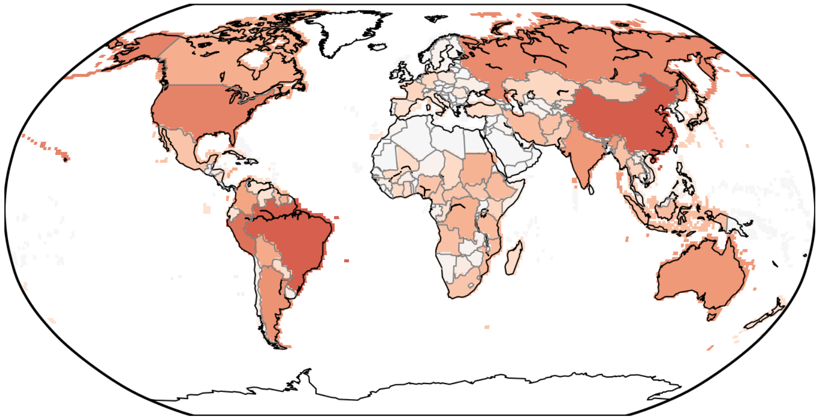


Natural land carbon flux (GtC/year)



Fossil + natural carbon flux (GtC/year)





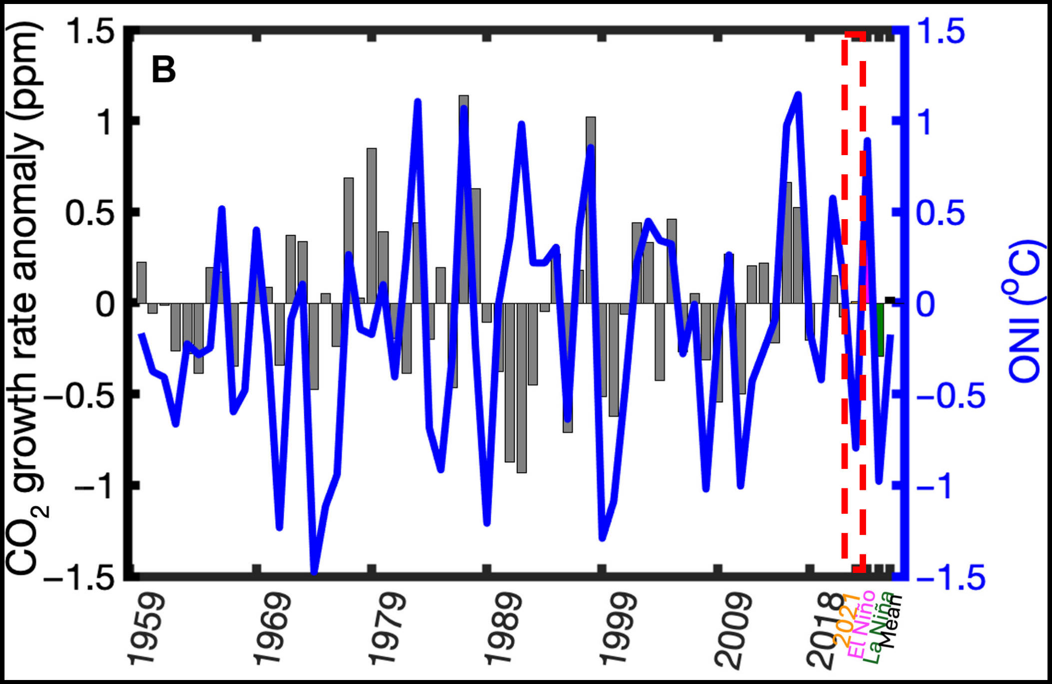
Uncertainties (GtC/year)

- Uncertainties of net carbon exchange at country scale are dominated by the uncertainty in natural carbon fluxes;
-
- Uncertainties are large over small tropical countries;
- Uncertainties are the spread among 13 models, so it includes uncertainties from transport, priors, observations, inversion methodology, fossil fuel, etc.

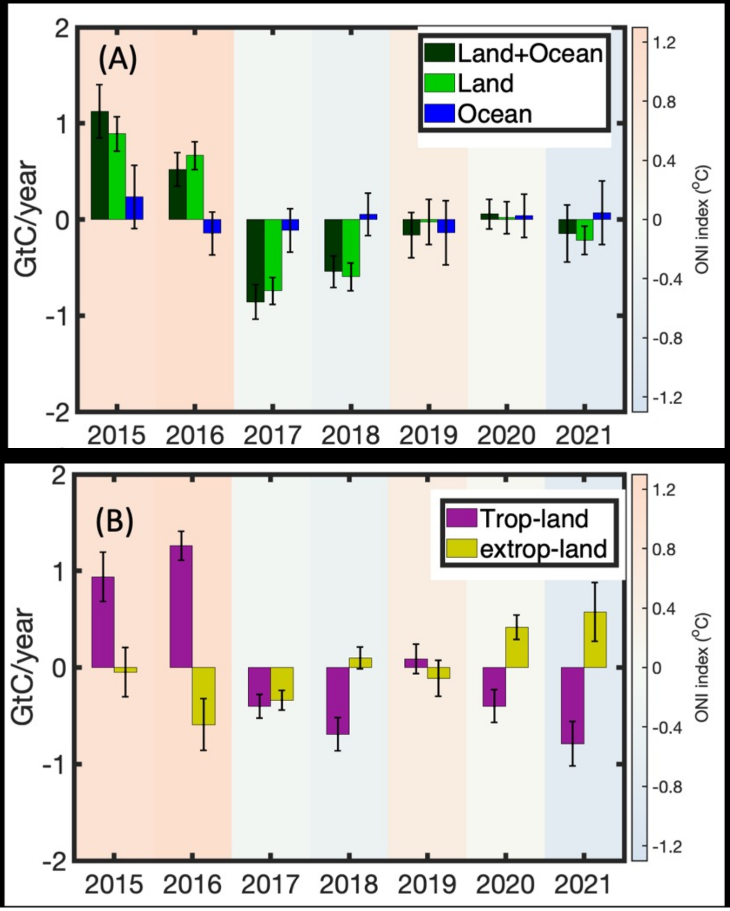
Negative: sink;
Positive: source.

Byrne et al.,ESSD 2022,

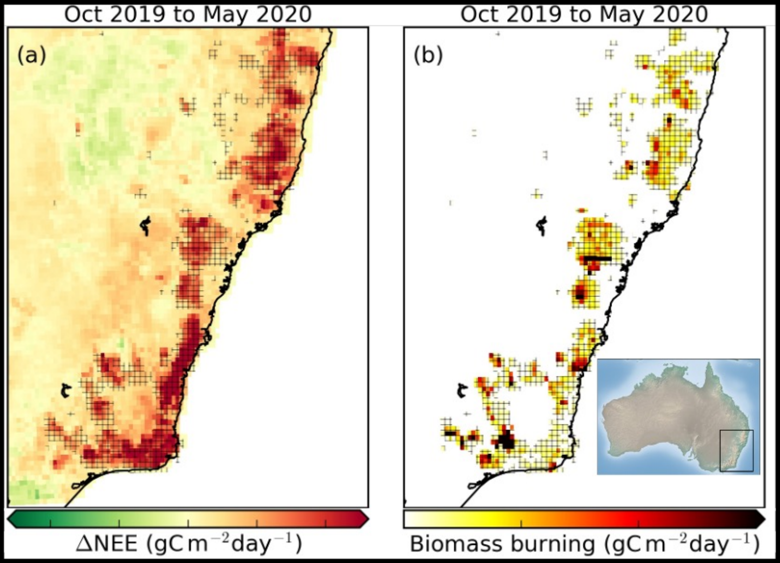
Providing Insights on the Interannual Variations of Natural Carbon Cycle

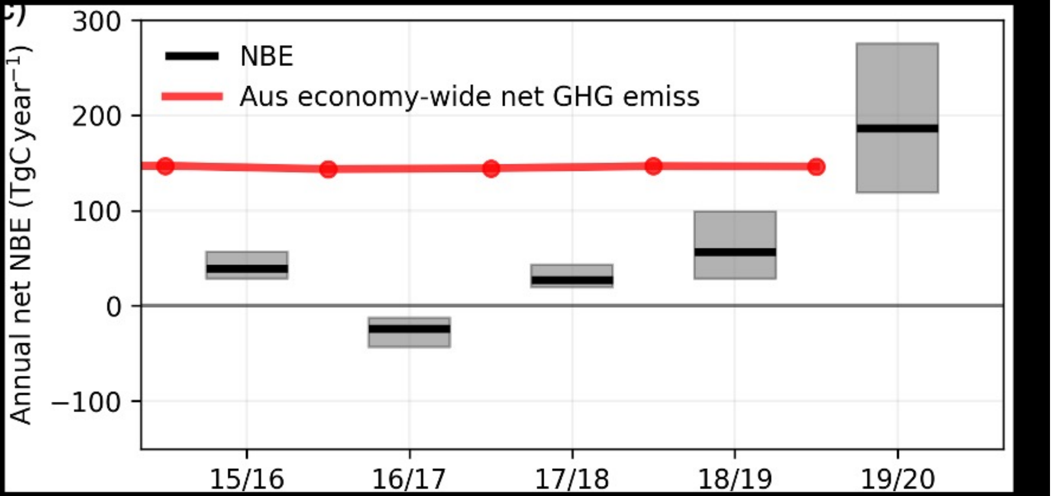


Liu et al., *Science Advances*, 2024



Detecting the Impact of Extreme Climate Events on Natural Carbon Cycle

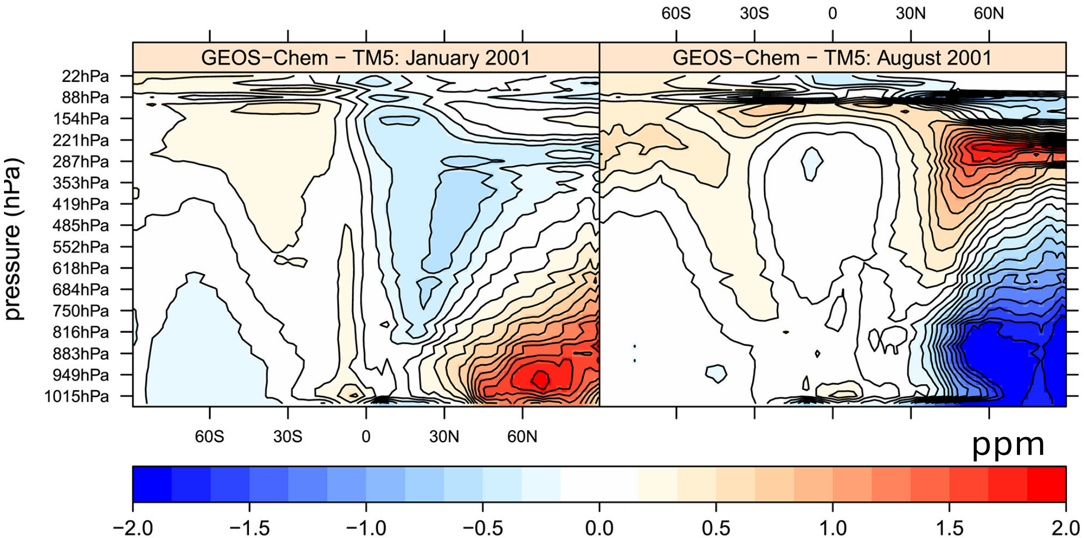




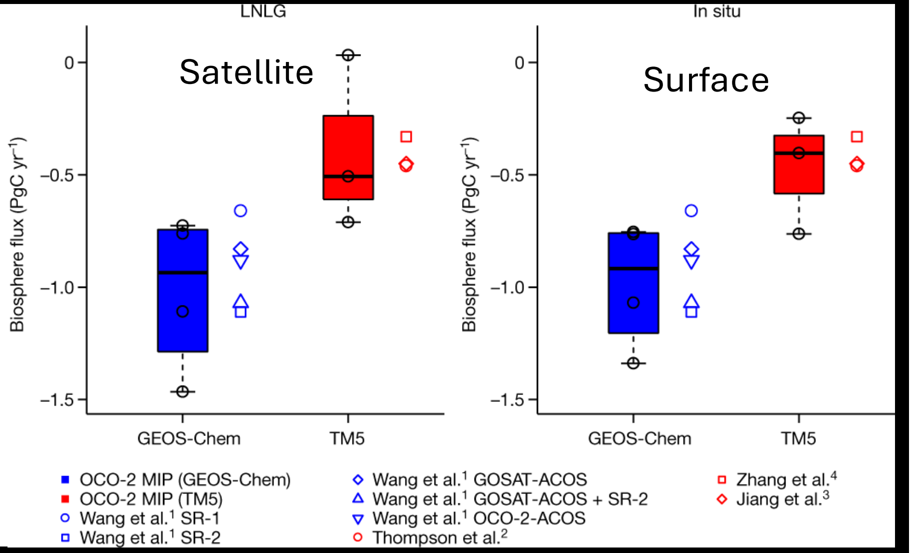
Byrne et al., AGU-Advances, 2021

- OCO-2 + TROPOMI CO to constrain both reduction of sink due to drought and C release from biomass burning;
- Dense X_{CO2} observations from OCO-2 enable quantification of impact of extreme climate events on regional carbon cycle;
- The net carbon release due to drought and fire during Oct 2019- May 2020 is larger than annual Australian fossil fuel emissions;
- **Extreme climate events play outsized role in the global carbon cycle changes; global CO_2 observation coverage is critical to continue monitor the impact of ever-increasing extreme climate events on carbon cycle.**

Sensitivity of Spatial Flux Distributions to the Atmospheric Transport



Chinese Natural Carbon Sink

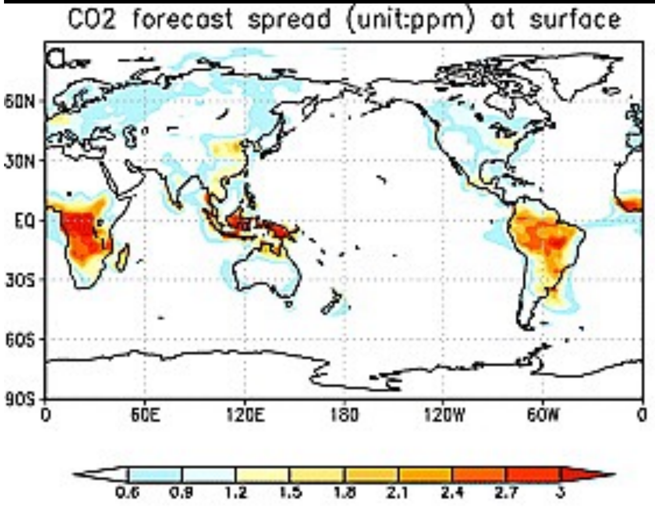


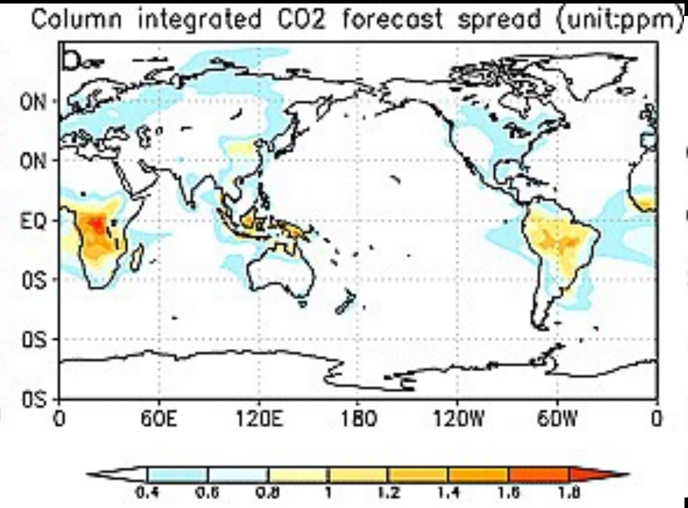
- Same surface flux forcing for both TM5 and GEOS-Chem model.
- The vertical transport of GEOS-Chem is more sluggish.

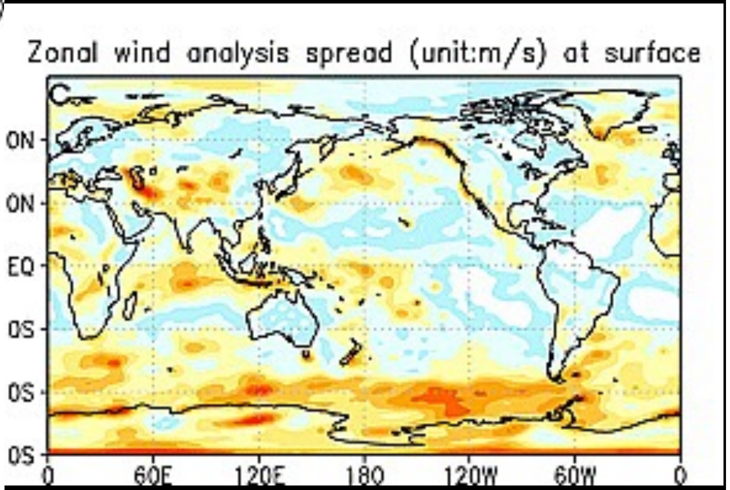
Schuh et al., 2019, 2022

Non-negligible Impact of Uncertainties in Reanalysis on Simulated CO_2 Concentration

Averaged over Feb







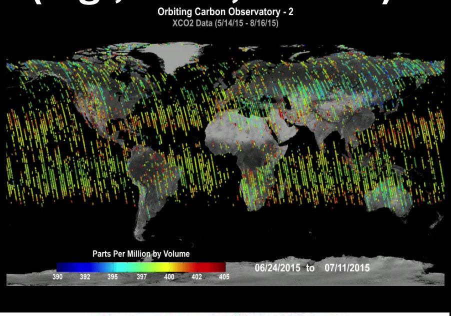
An order of a few meter per second

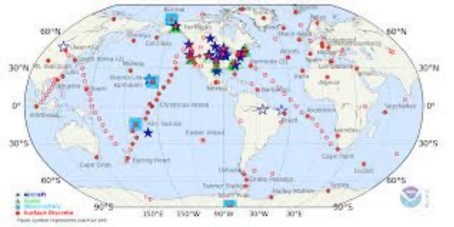
- The impact of uncertainties in reanalysis on CO2 concentration can be more than 1.0ppm.

Liu et al., GRL, 2011

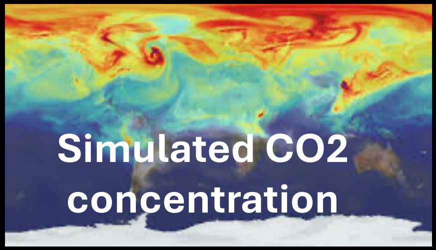
Inferring Natural Carbon Fluxes with Atmospheric CO2 Observations

GHG observations (e.g., flask, OCO-2)





Atmosphere Transport Model



Atmospheric inverse model

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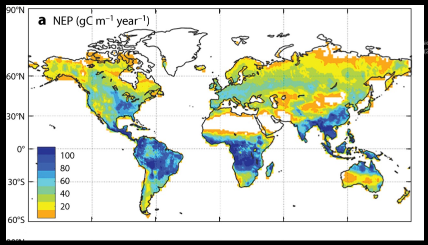
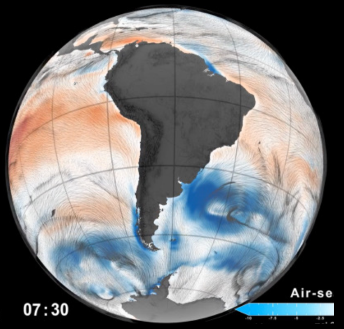
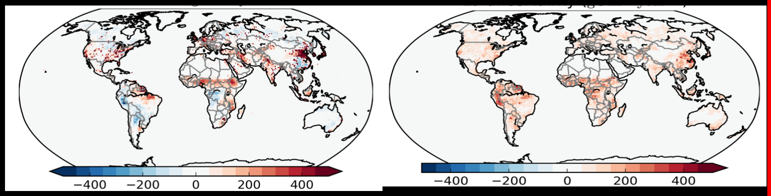
Bottom-up models and uncertainties



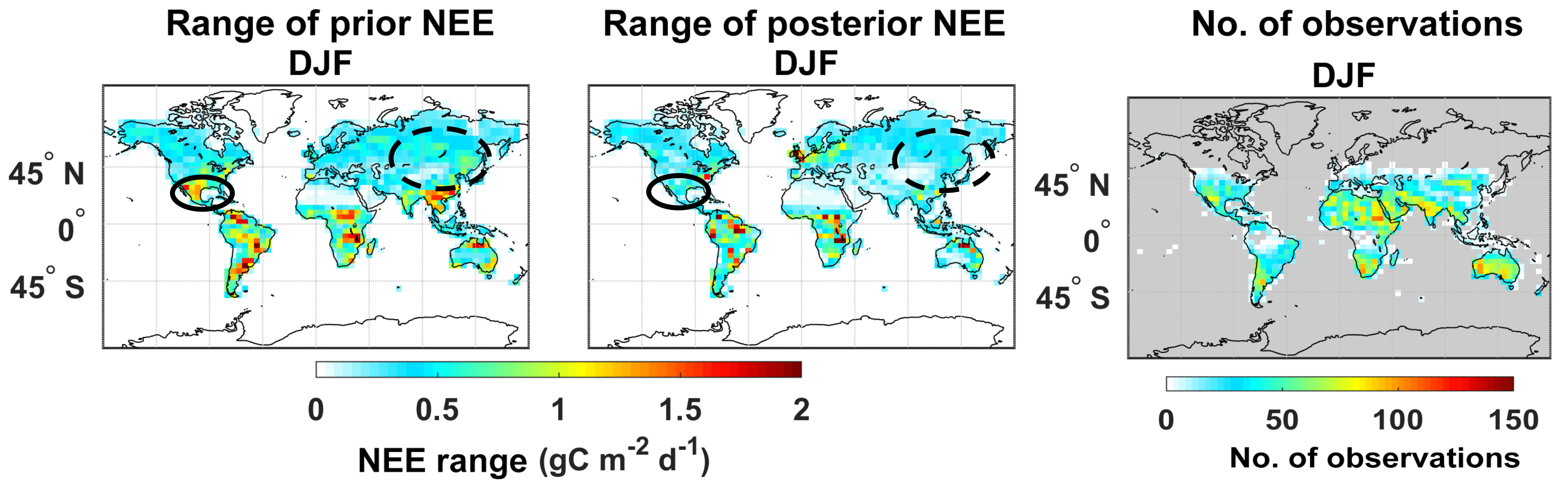


Posterior fluxes (CO2, CO, CH4) and uncertainties



Science and decision support

Sensitivities of Posterior Fluxes to Assumed Prior Fluxes and their Uncertainties



Range of prior NEE DJF

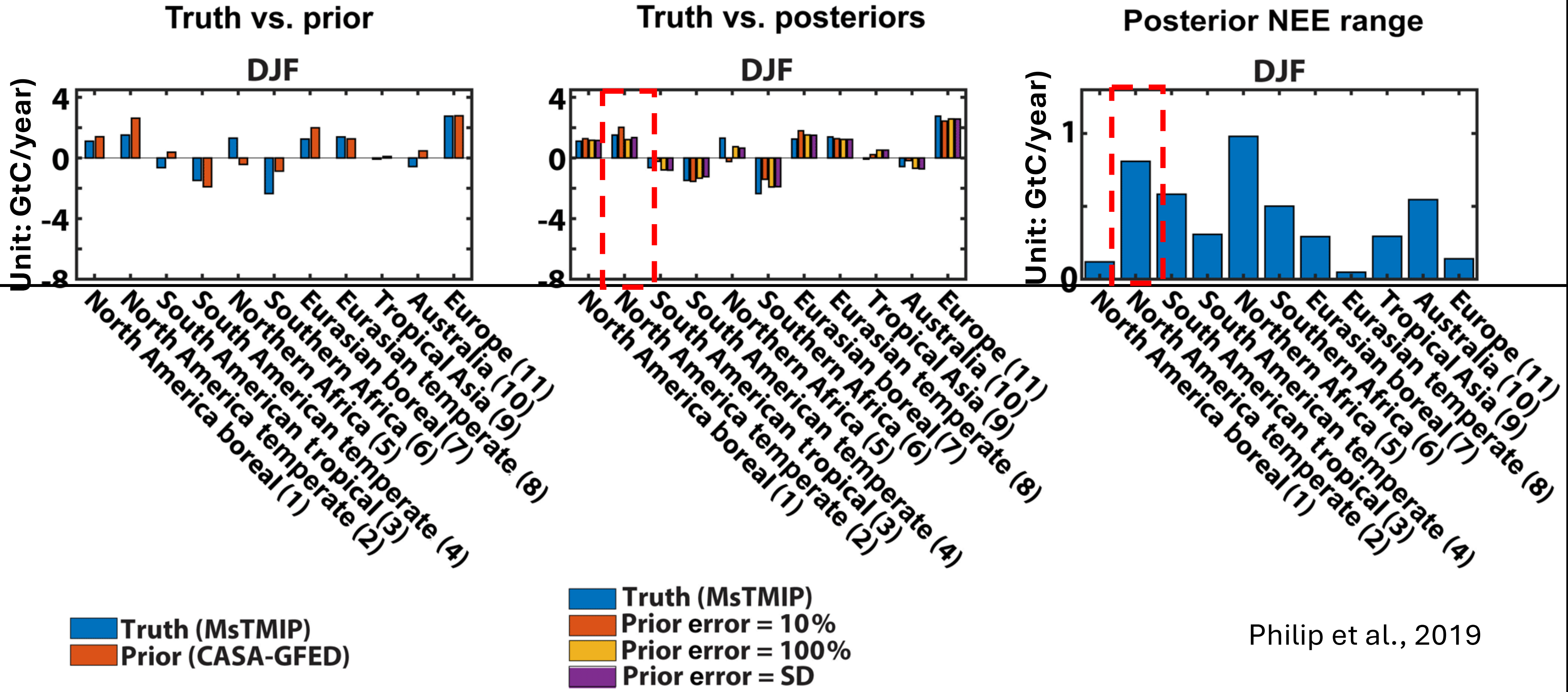
Range of posterior NEE DJF

No. of observations DJF

- Prior fluxes: NASA-CASA; CASA-GFED, LPJ
- Over regions where the observation coverage is dense, the range of posterior fluxes have been reduced.

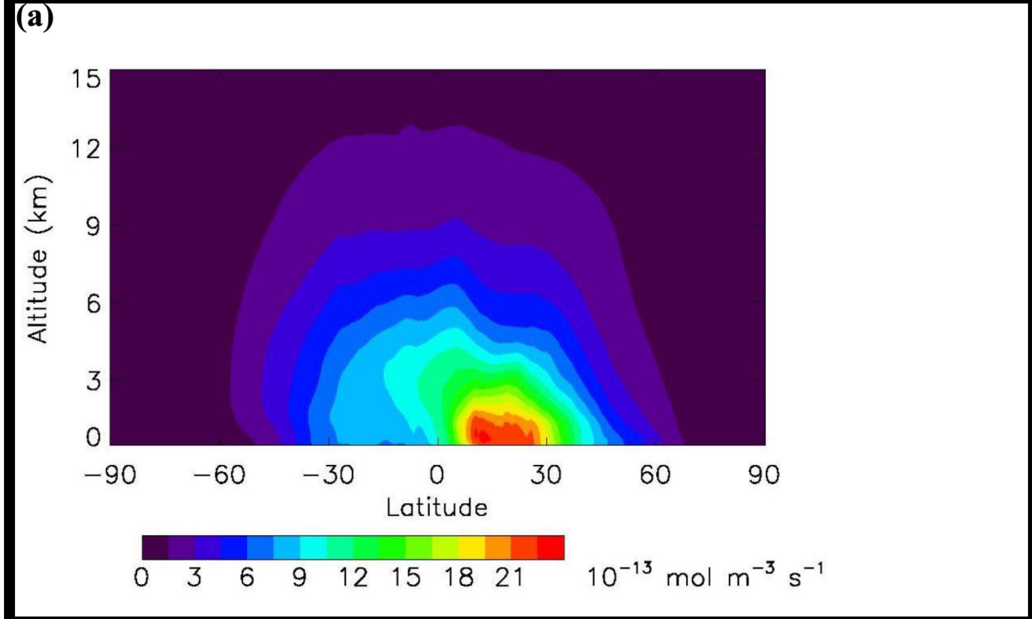
Philip et al., 2019

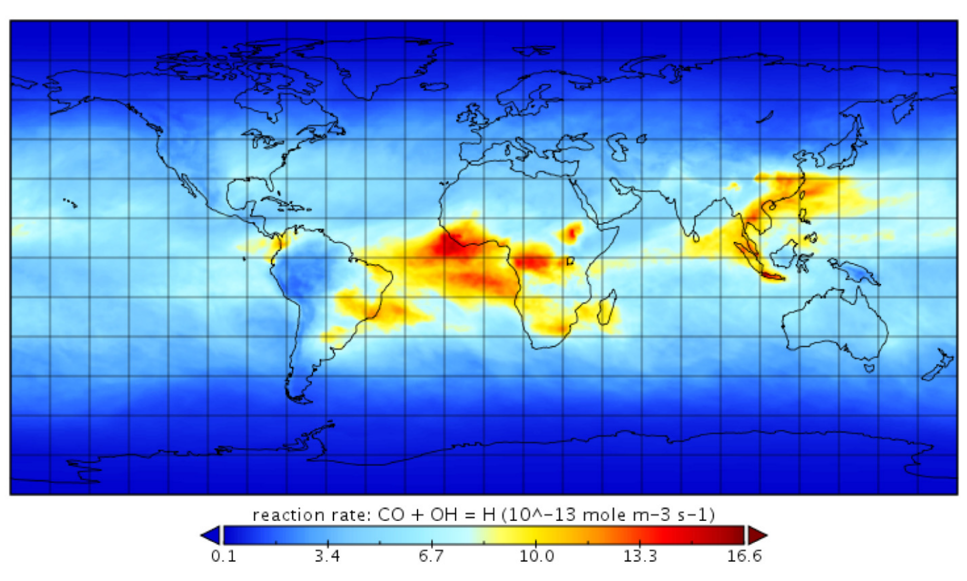
The Assumed Prior Flux Uncertainties have Relatively Larger Impact over Regions with Observations



Philip et al., 2019

3D-Production of CO_2 from Chemical Reactions (CO, CH4, and NMVOCs)

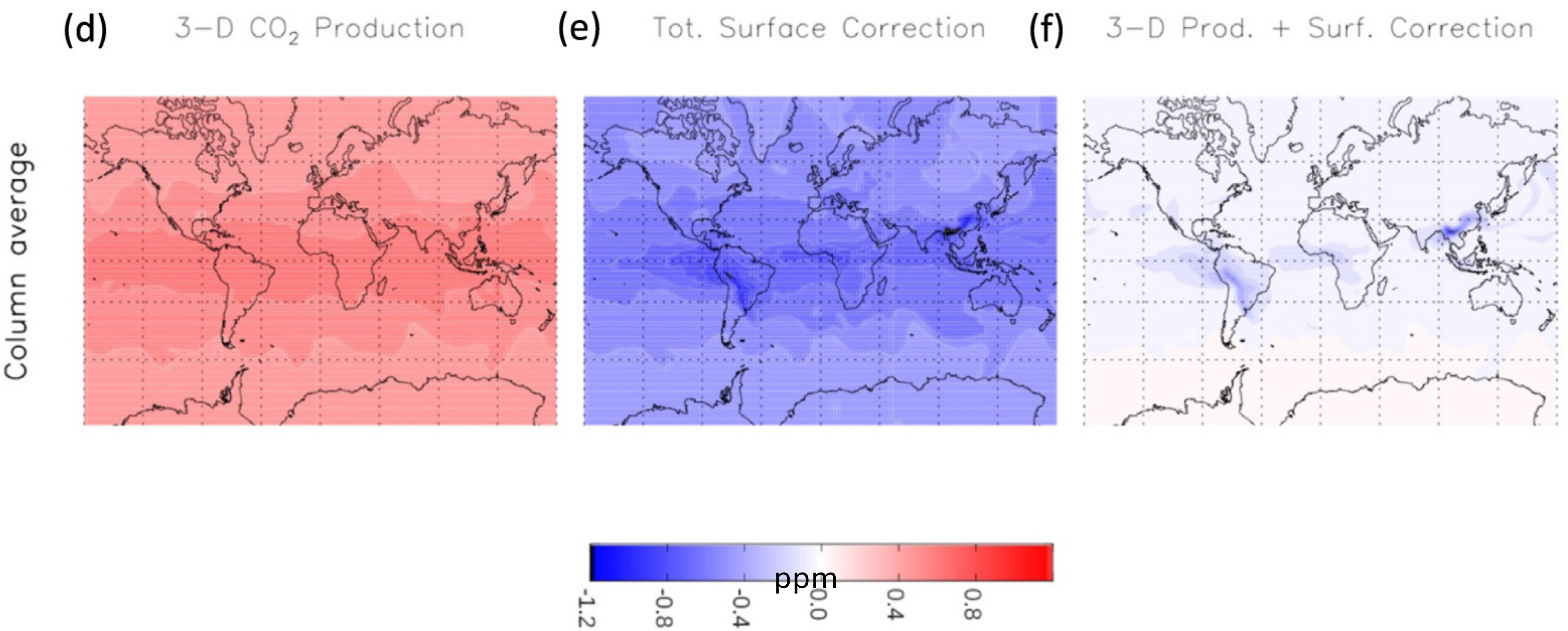




- Chemical production is higher over the tropics where biomass burning are
- The total magnitude of 3D-CO2 production is about 1.1GtC with uncertainty.
- Uncertainty source: OH, NMVOC, CO etc.

Wang et al., *ERL*, 10.1088/1748-9326/ab9795, 2020

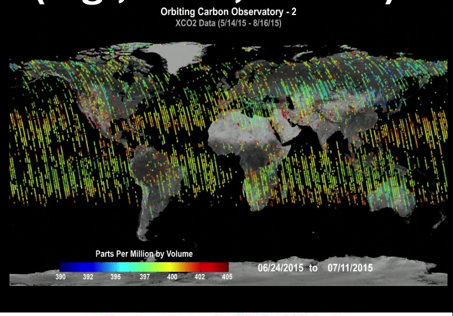
Non-negligible Impact on Column CO2 Concentrations over the Tropics



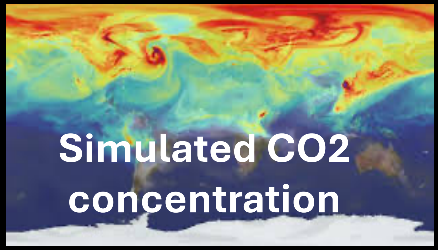
Wang et al., *ERL*, 10.1088/1748-9326/ab9795, 2020

Inferring Natural Carbon Fluxes with Atmospheric CO2 Observations

GHG observations (e.g., flask, OCO-2)



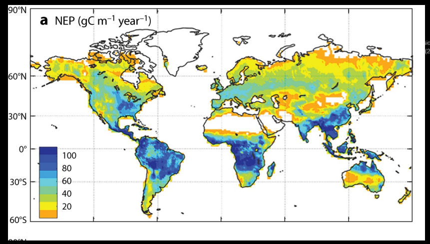
Atmosphere Transport Model

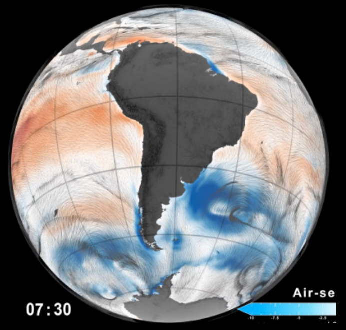


Atmospheric inverse model

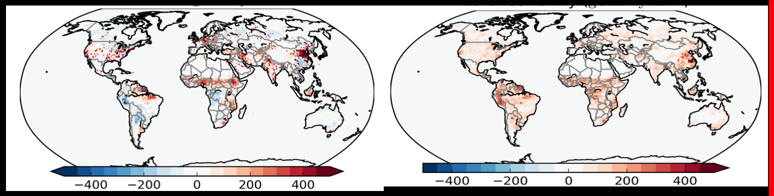
$$J(x) = (x - x^b)^T B^{-1} (x - x^b) + \sum_{i=1}^{n} (y - h(x))_i^T R^{-1} (y - h(x))$$

Bottom-up models and uncertainties



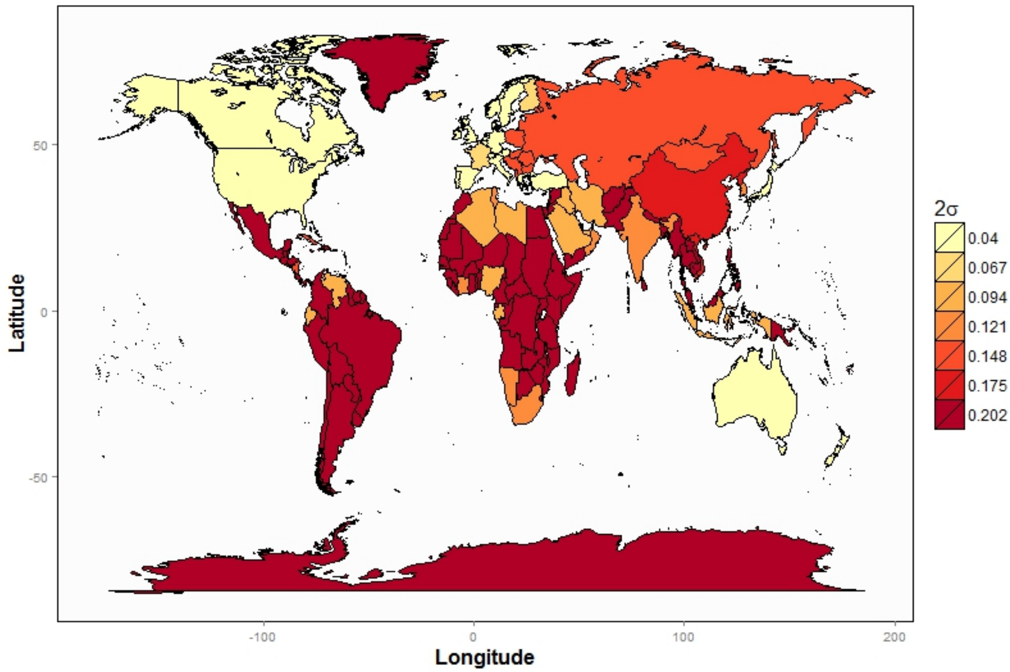


Posterior fluxes (CO2, CO, CH4) and uncertainties

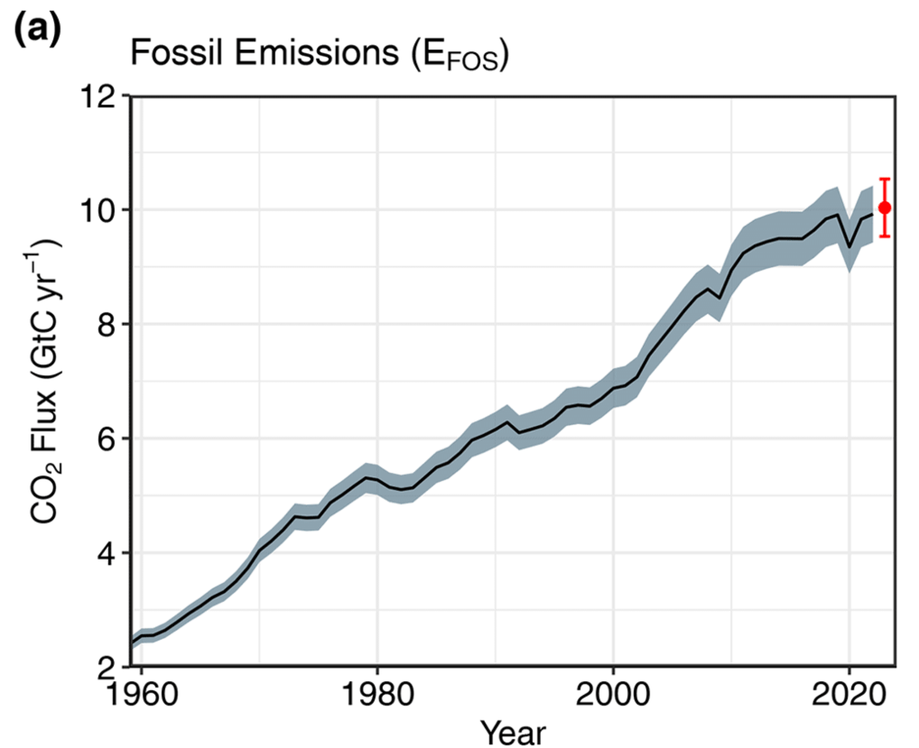


Science and decision support

Fossil Fuel Emission Uncertainties



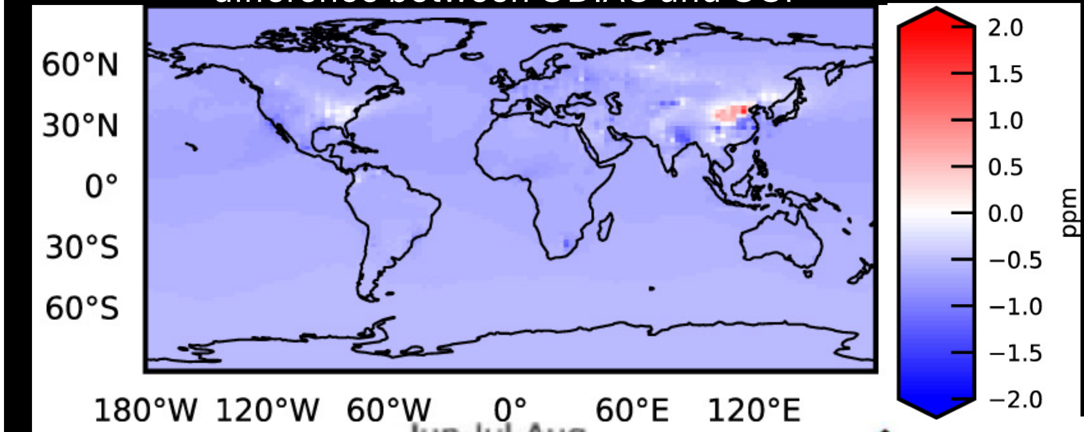
Hogue et al., 2016



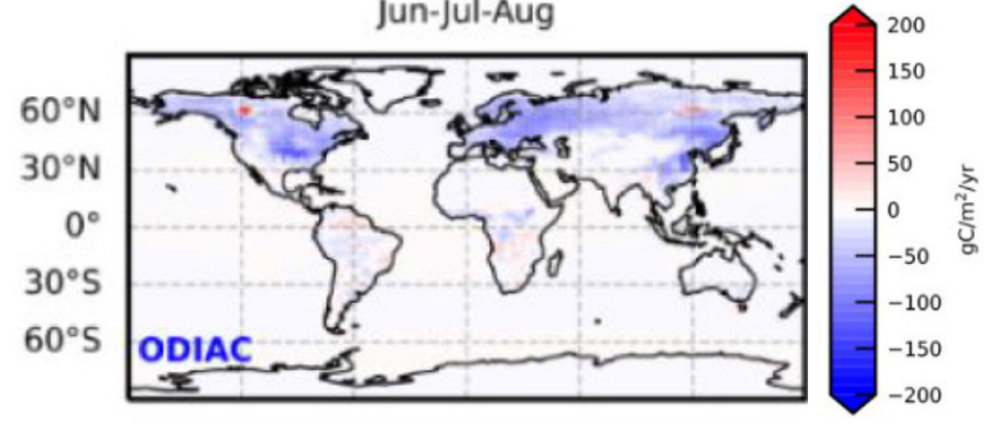
Friedlingstein et al., ESSD, 2024

Impact of Fossil Fuel Emission Uncertainties on Natural Carbon Flux Estimation

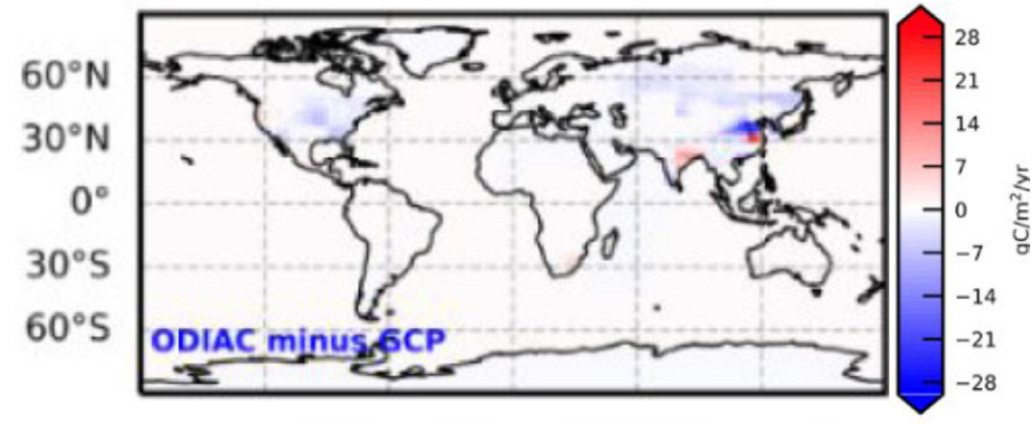
Column CO2 signal in July due to the difference between ODIAC and GCP



- Fossil fuel emissions and natural carbon fluxes offset each other.

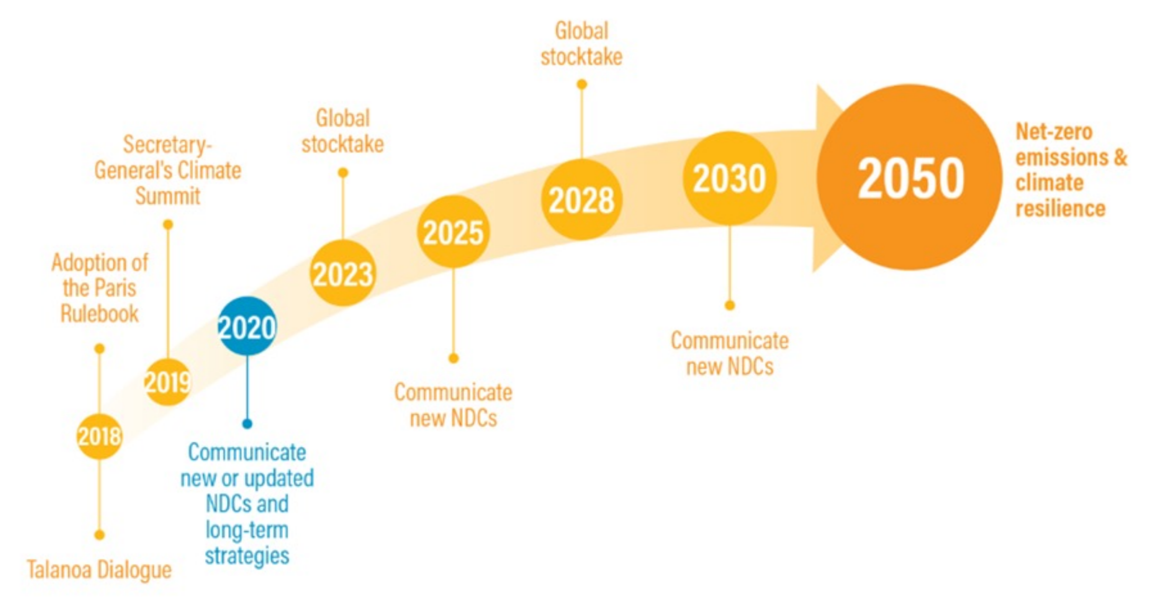


Biosphere flux estimation differences between ODIAC and GCP



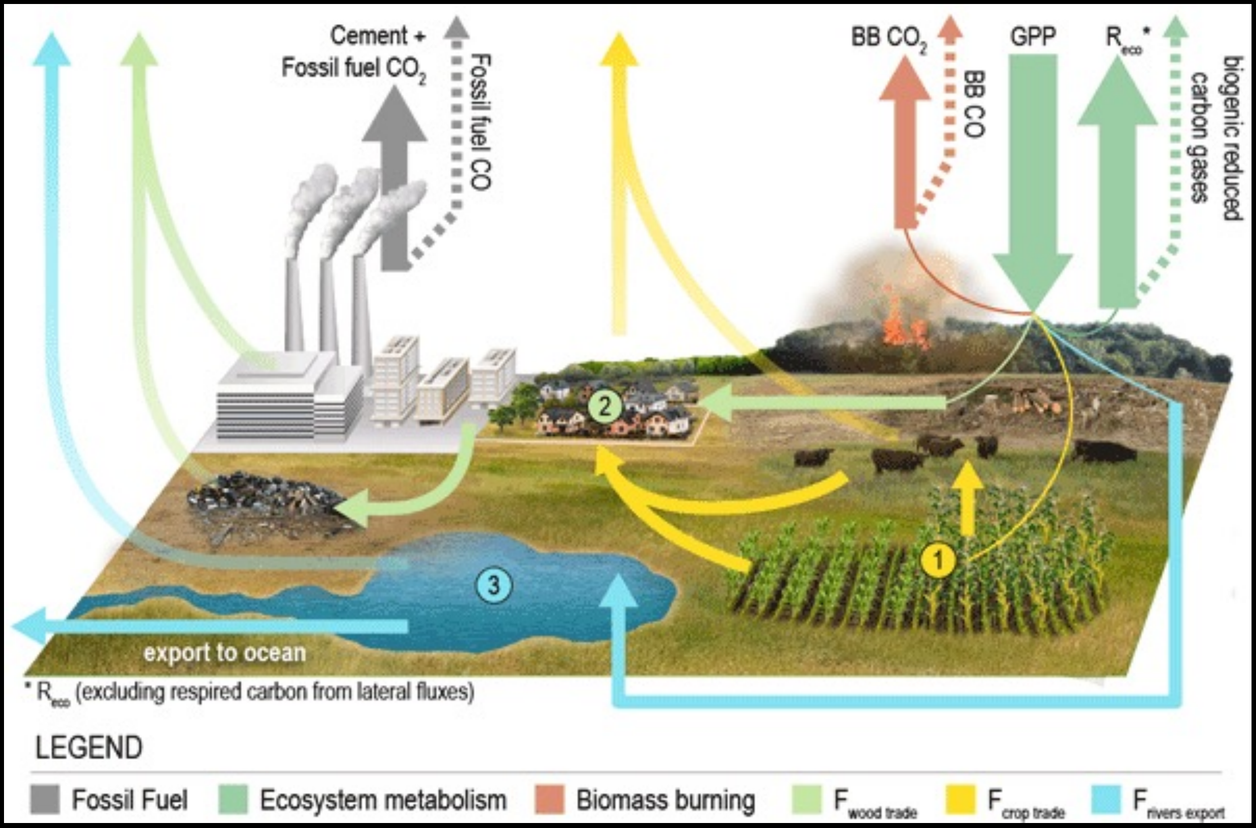
Oda et al., ERL, 2023

Global Stocktake: A Process to Achieve Carbon Neutrality



- Countries are required to submit the national GHG inventories (NGHGI) under the IPCC guideline;
- Annex-I countries report annual emissions and removals;
- The GHGI are based on emission factors and activity data or process-based models.
- National GHG inventories (NGHGI) only reports CO_2 emissions and removals from managed land.
-

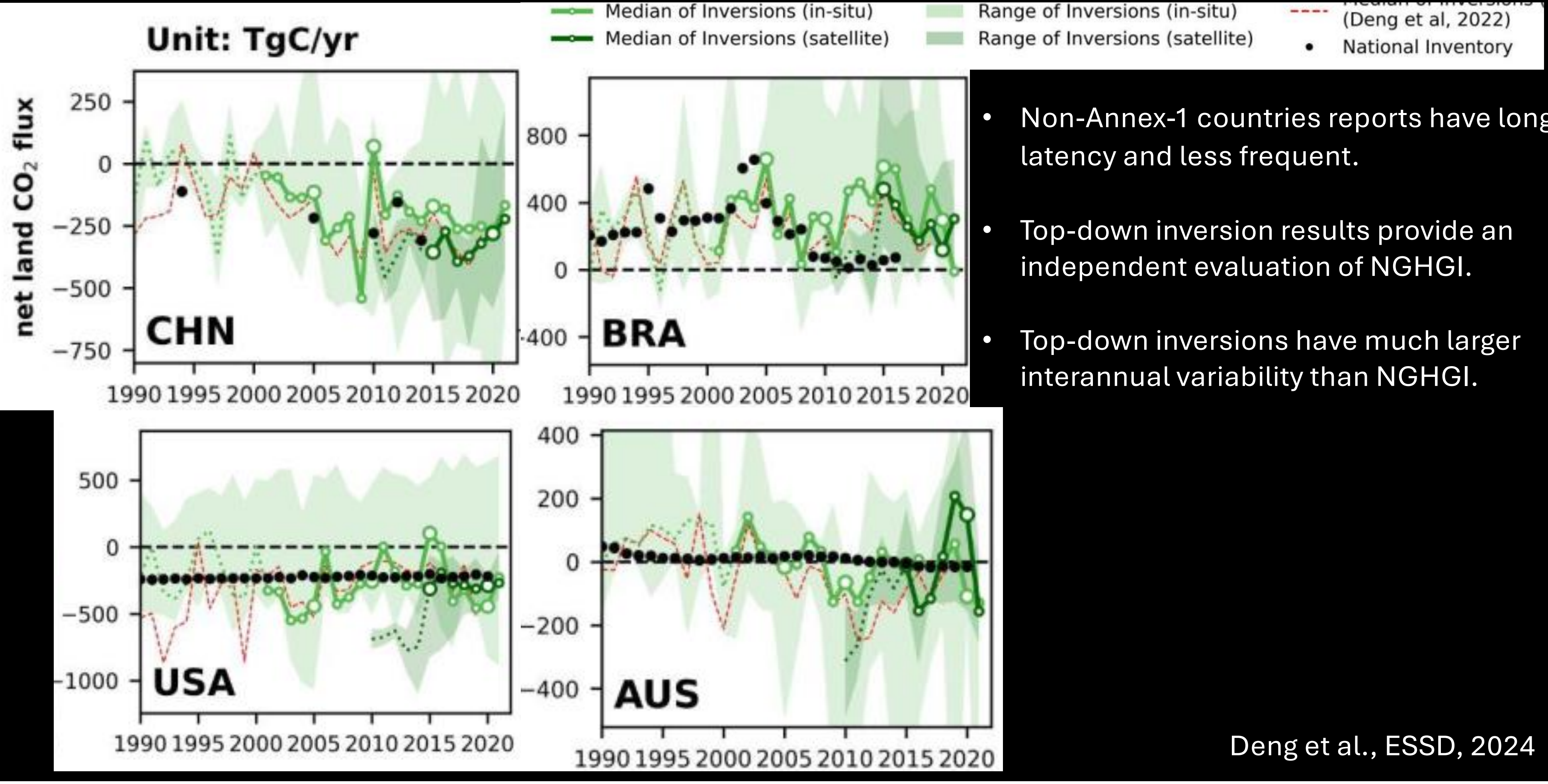
Use of Top-Down Flux inversion Results to Inform NGHGI: Accounting for Lateral Transport and Harvest



- Net carbon fluxes from atmospheric CO2 flux inversion quantifies vertical carbon exchange between atmosphere and surface.
- National GHG inventories (NGHGI) only reports CO_2 emissions and removals from managed land.
- Comparison between top-down and NGHGI needs to account for lateral transport, crop and wood harvest and trade.

Byrne et al., ESSD, 2022

The Agreement between Top-Down Inversions and NGHGI Varies across Countries



- Non-Annex-1 countries reports have long latency and less frequent.
- Top-down inversion results provide an independent evaluation of NGHGI.
- Top-down inversions have much larger interannual variability than NGHGI.

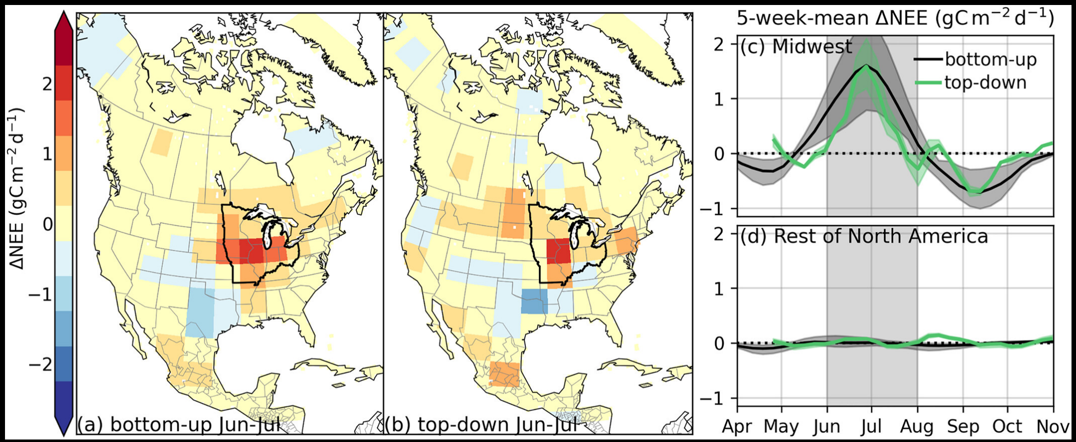
Deng et al., ESSD, 2024

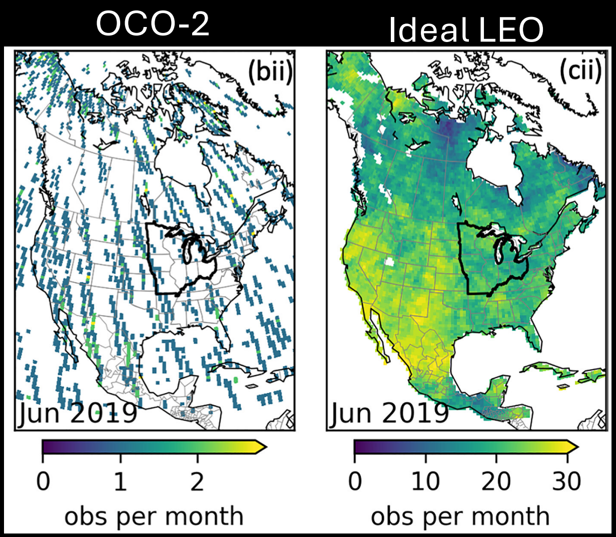
Maximizing the Impact of GHG Observations on Natural Carbon Flux Estimation and Climate Policy

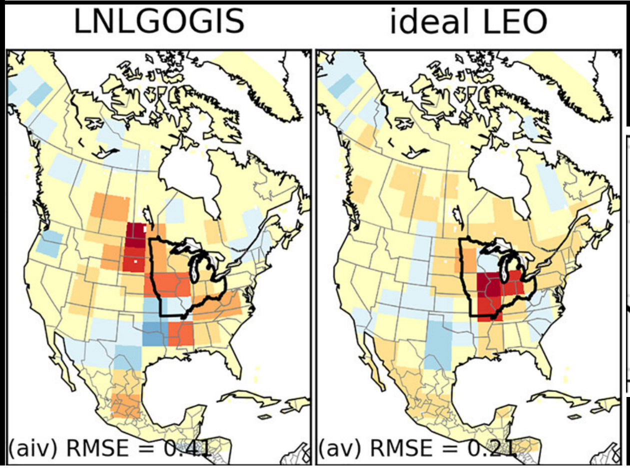
- **Observations from OCO-2/3 have advanced our understanding of the response of regional carbon fluxes to natural climate perturbations and large -scale distributions of sources and sinks.**
- Reduce uncertainties in transport (dynamics, reanalysis etc.)
- Better characterize uncertainties in prior fluxes and transport.
- Increase observational coverage (e.g., GOSAT-GW, CO2M).
- 3D-CO2 sources
- Leverage fossil fuel emission estimation capability in natural carbon flux estimation.
- Better characterize lateral transport and crop/wood harvest to support NGHGI.

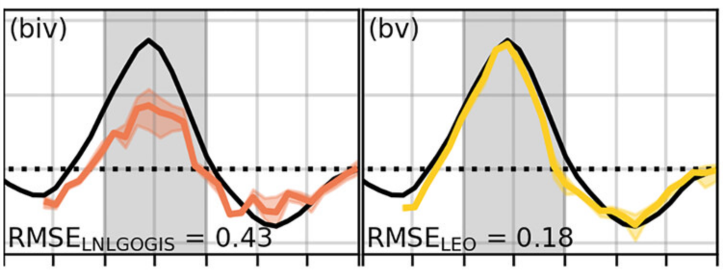
Increasing Observation Coverage to Better Quantify the Impact of Extreme Climate Events

The impact of 2019 mid-west flood









OSSE

- Bottom-up: based on greenness and SIF observations

Byrne et al., JGR-Atmospheres, 2024