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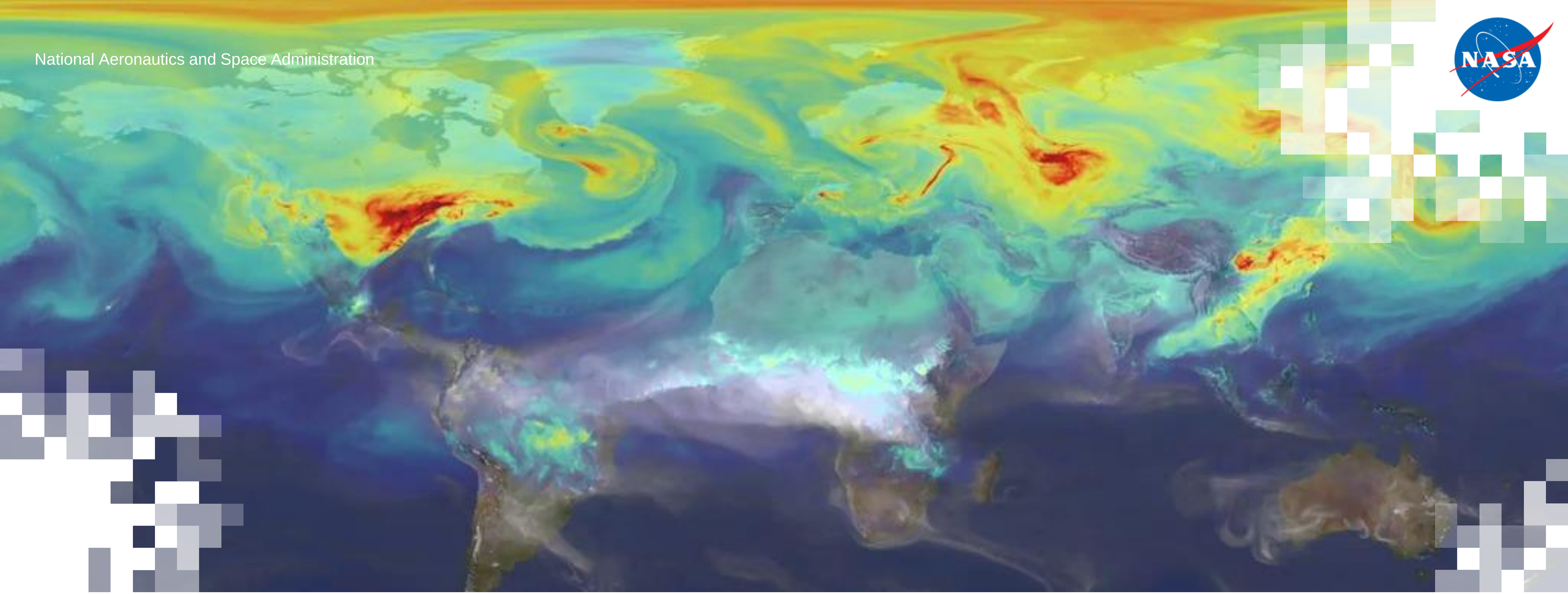


Atmospheric CO_2 and CH_4 Budgets to Support the Global Stocktake

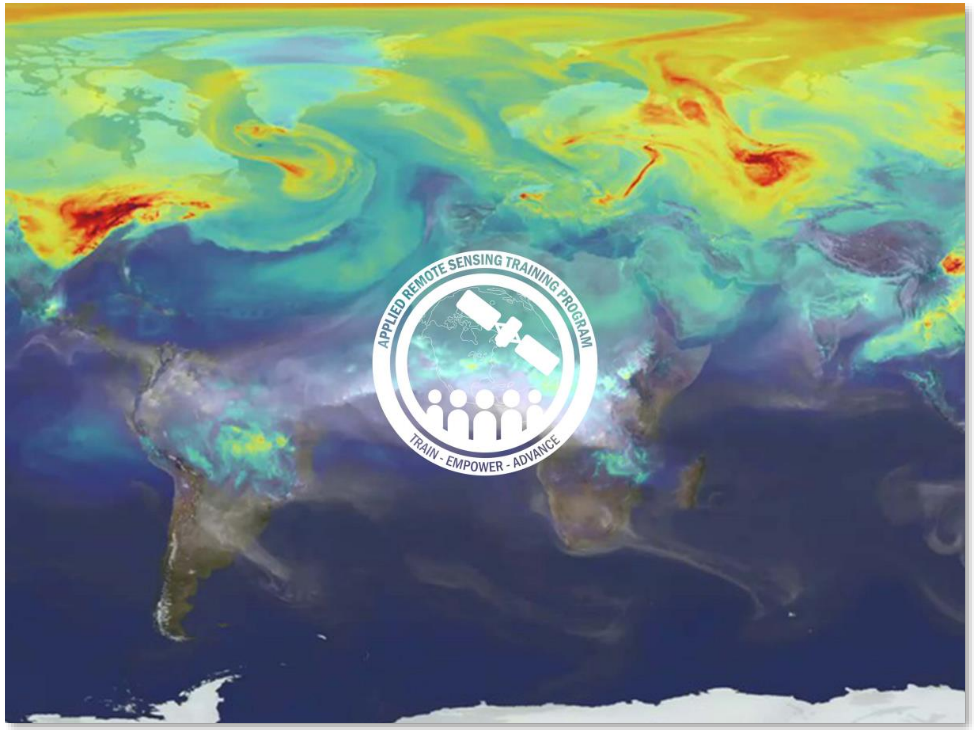
Part 2: Creating Top-Down Atmospheric Budgets of CO_2 and CH_4 on Policy-Relevant Scales

Brendan Bryne, Dan Cusworth, Sean McCartney

May 18, 2022

Course Materials and Q&A

- Webinar recordings, PowerPoint presentations, and the homework assignment can be found after each session at:
  - https://appliedsciences.nasa.gov/join-mission/training/english/arset-atmospheric-co2-and-ch4-budgets-support-global-stocktake
- Q&A: Following each lecture and/or by email:
  - sean.mccartney@nasa.gov



Homework and Certificate

- Homework Assignment:
  - One homework assignment submitted via Google Form
  - Due Date: **Wednesday, June 8**
- A certificate of completion will be awarded to those who:
  - Attend all live webinars
  - Complete the homework assignment by the deadline (access from website)
  - You will receive a certificate approximately two months after the completion of the course from: marines.martins@ssaihq.com

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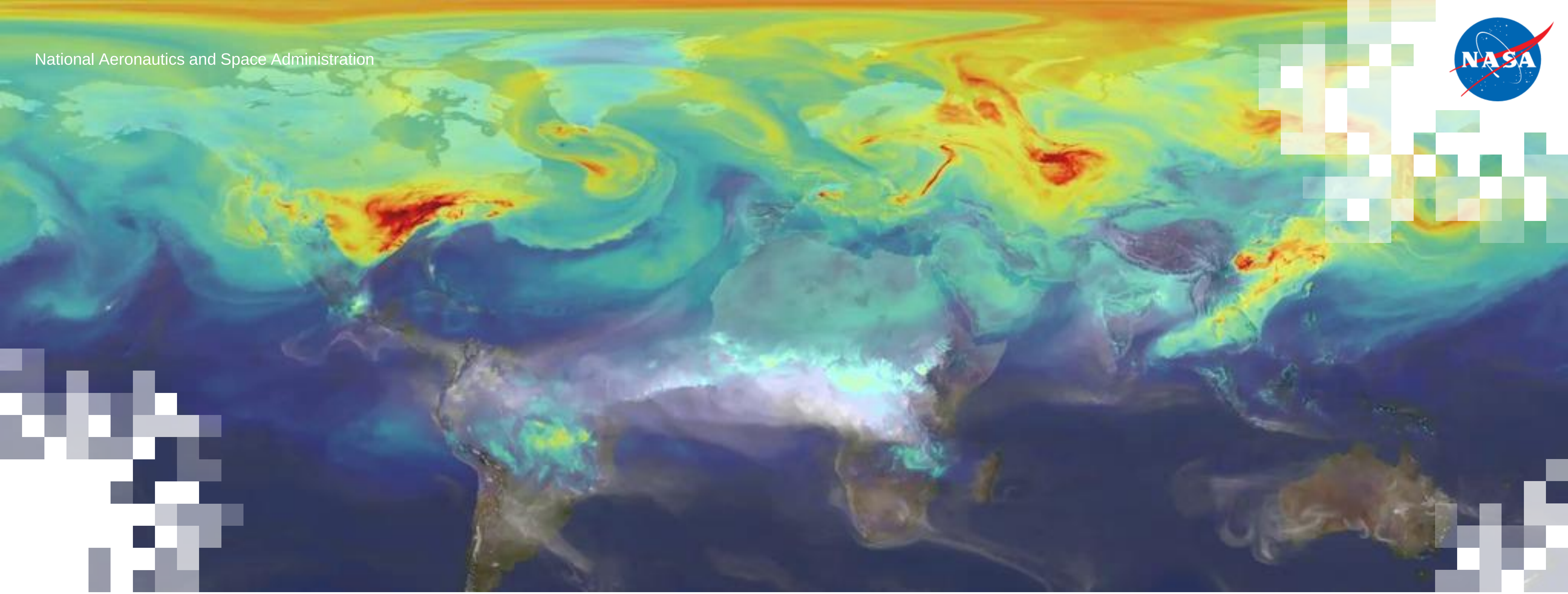


Part 2: Creating Top-Down Atmospheric Budgets of CO_2 and CH_4 on Policy-Relevant Scales

Brendan Bryne (NASA JPL)

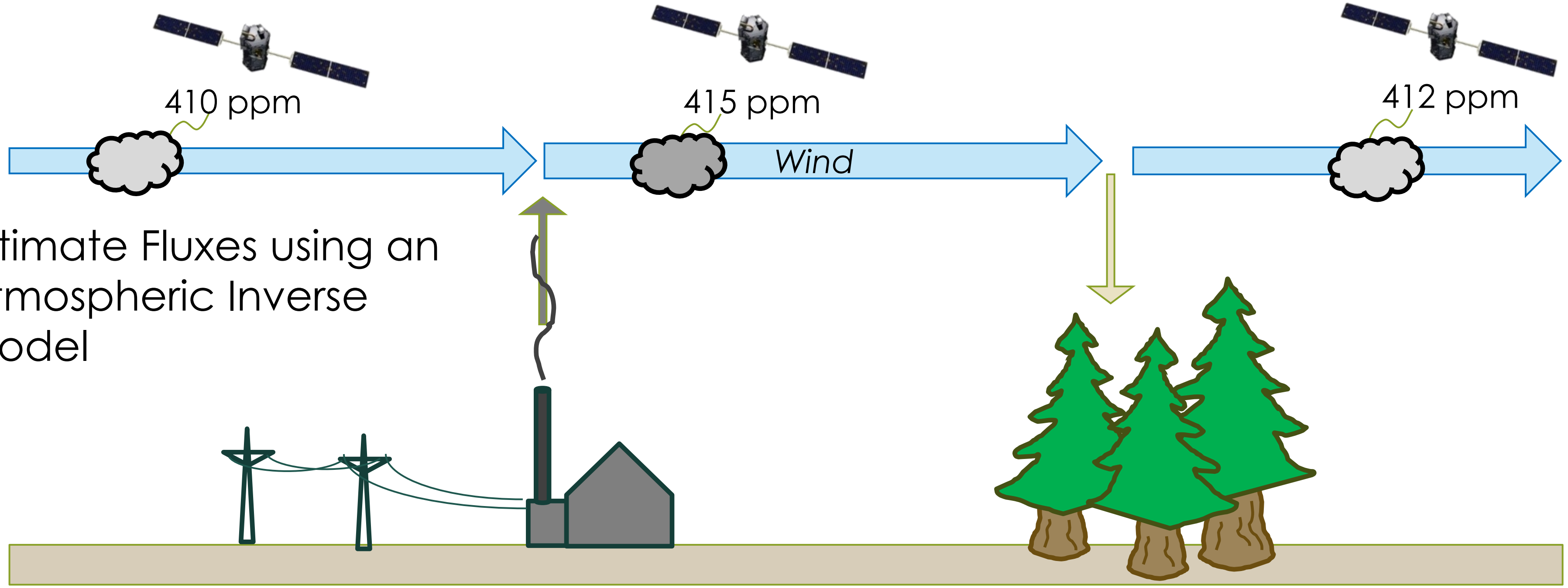
Objectives

After participating in this session, attendees should be able to:

- Describe the processes that add/remove CO_2 and CH_4 to/from the atmosphere
- Explain space-based, airborne, and ground-based measurements of CO_2 and CH_4
- Understand how CO_2 and CH_4 emissions and removals (fluxes) are estimated globally using inverse modeling
- Understand how top-down CO_2 stock loss estimates can be compared to inventories
- Recognize methods for quantifying CO_2 and CH_4 emissions from localized sources

Review from Part 1: *Bottom-Up* Inventories and *Top-Down* Atmospheric Budgets

Top-Down Atmospheric Budgets



Estimate Fluxes using an Atmospheric Inverse model

Bottom-Up National Inventories[1]

PetaJoules/yr × tCO_2/PJ + Hectares Field-Forest × tCO_2/hectare + …

tCO_2/yr = Activity × Emission Factor Activity × Emission Factor

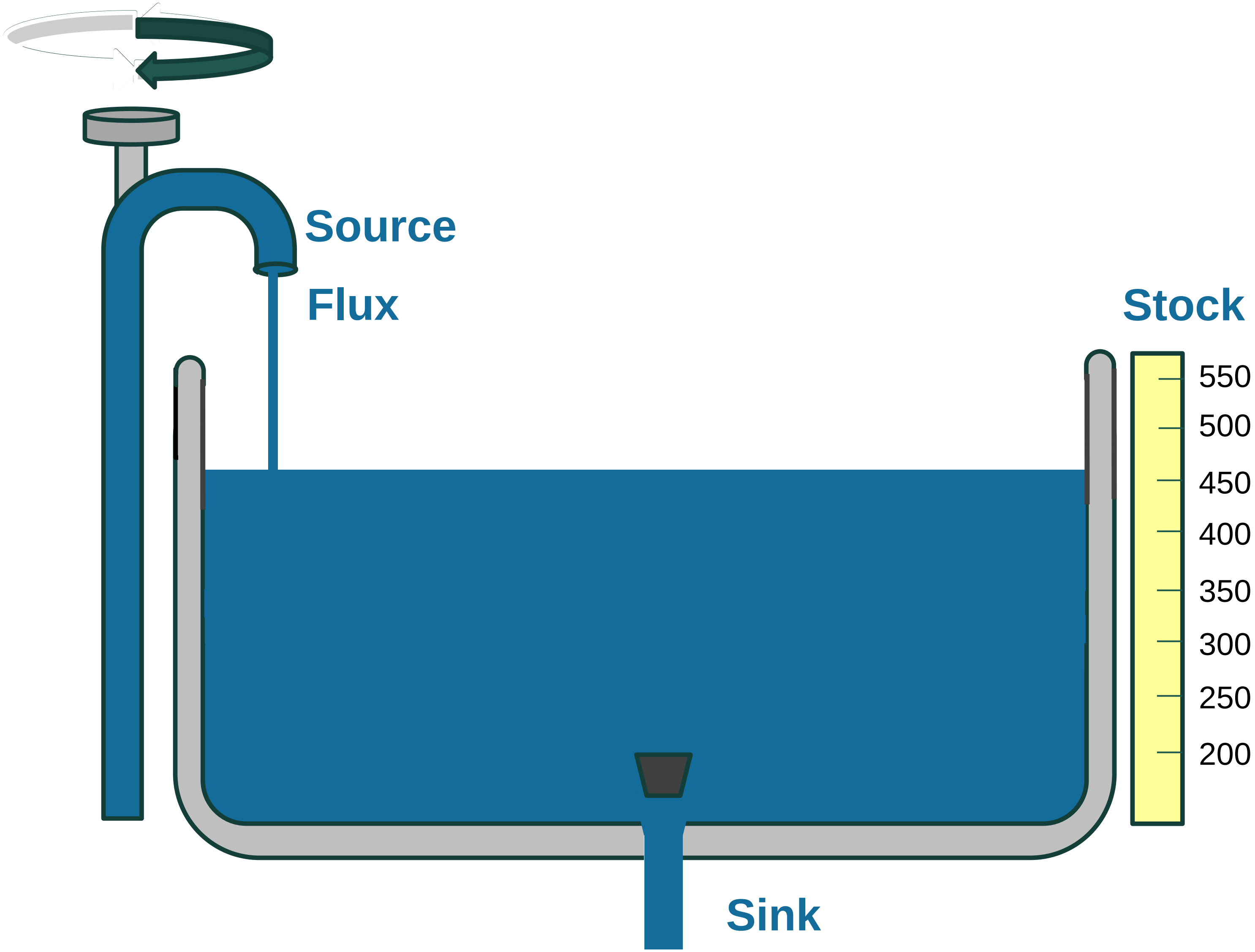
---

[1] Prepared in accordance with the Intergovernmental Panel on Climate Change (**IPCC**) Guidelines for GHG inventories, as adopted by the Conference of Parties (**COP**).

Review from Part 1:
A Few Definitions: Stocks, Fluxes, Sources, and Sinks

Consider a basin with faucet and a plug at its bottom.

- The amount of water in the basin is a measure of its **stock**.
- A processes that adds water to the basin is called a **source**.
- A processes that removes water from the basin is called a **sink**.
- If the faucet is turned on, water accumulates in the basin, increasing the stock.
- The ***rate*** of increase of the stock in the basin is called the **flux.**
  - **Sources** yield ***positive*** fluxes.
  - **Sinks** yield ***negative*** fluxes.



Similarities and Differences Between Top-Down CO_2 and CH_4 Methods

Top-down methods are used for quantifying CO_2 an CH_4 budgets. The approaches for these two gases have many similarities but also important differences:

Similarities:

- Atmospheric CO_2 and CH_4 can be measured using similar remote sensing methods.
- Surface-atmosphere fluxes can be estimated from atmospheric measurements with inverse methods

Differences:

- Different natural processes and human activities emit and remove CO_2 and CH_4
- Often different applications, such as land carbon stock change (CO_2) vs natural gas leaks (CH_4), that have different precision, accuracy, and spatial resolution requirements.

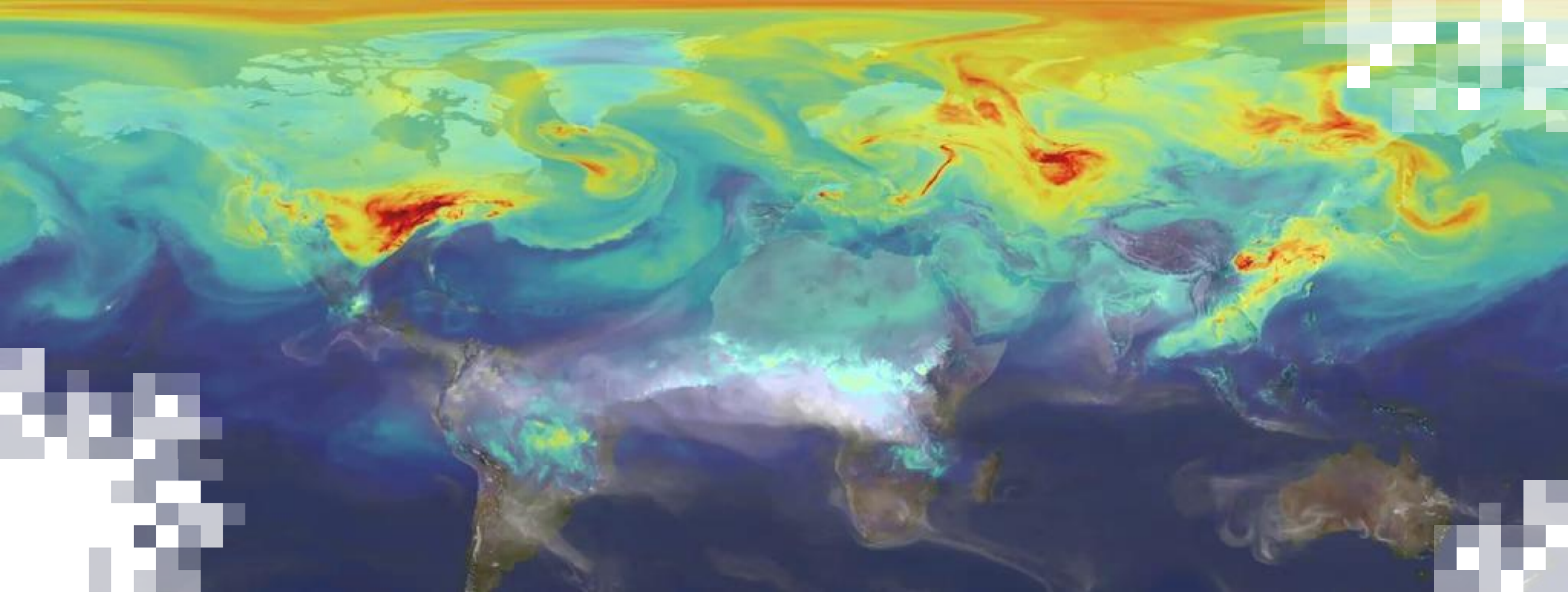
Outline

Part 2.1: Carbon Dioxide (CO_2)

- 2.1.1 Processes that emit and remove atmospheric CO_2
- 2.1.2 Space-based, airborne, and ground-based measurements of CO_2
- 2.1.3 Inverse modeling for estimating CO_2 emissions on regional/national scales
- 2.1.4 Estimating carbon stock loss for comparison with national inventories

Part 2.2: Methane (CH_4)

- 2.2.1 Processes that emit and remove atmospheric CH_4
- 2.2.2 Estimating CH_4 emissions on regional/national scales
- 2.2.3 Estimating CH_4 emissions from intense, localized sources



Carbon Dioxide (CO_2)

2.1.1 Emission and Removal of CO_2

- Plants pull carbon out of the atmosphere as they grow and release carbon as they rot.

Spring – trees start to grow, and take CO_2 from atmosphere

Summer – strong growth, strong removal of CO_2 from atmosphere

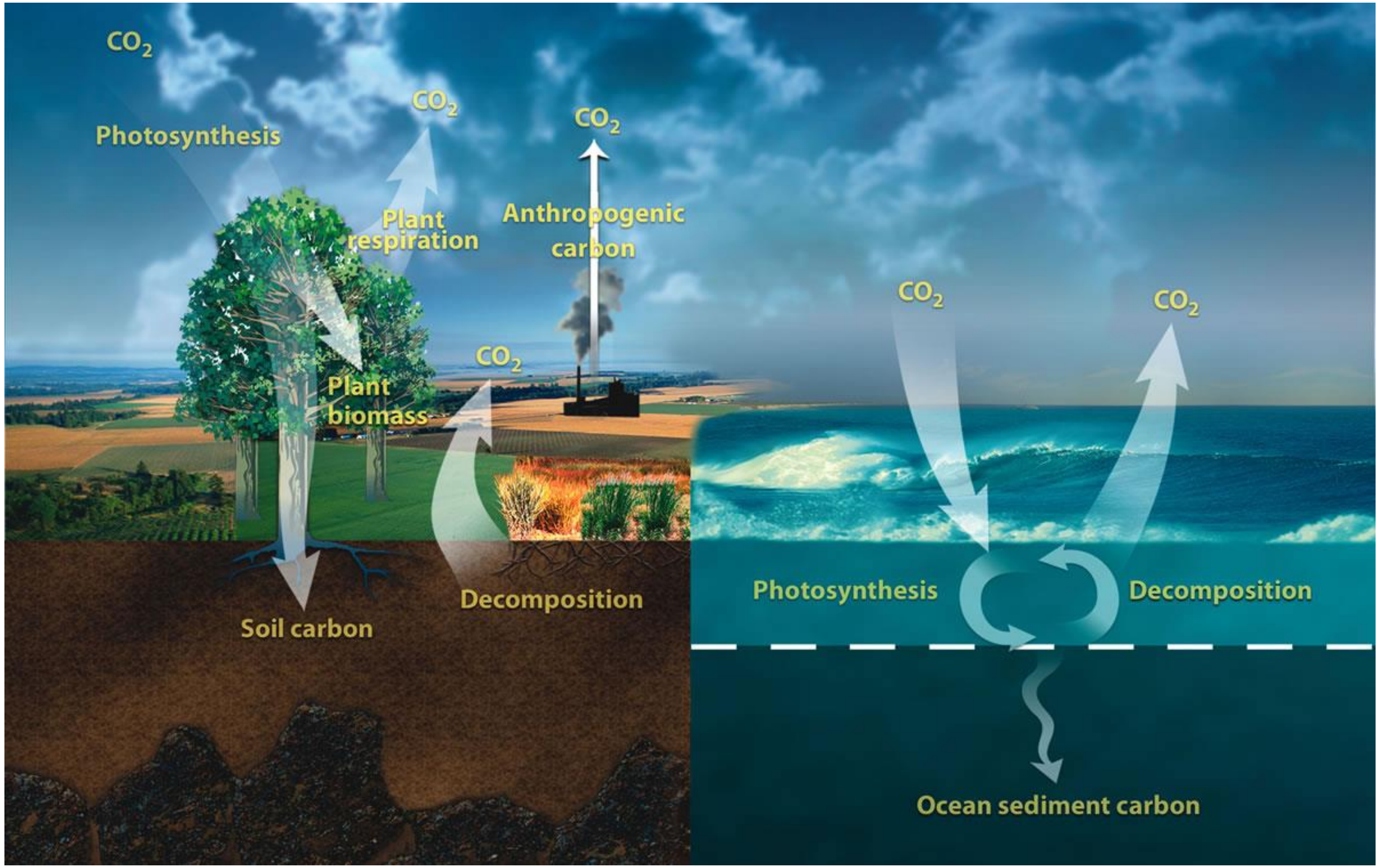
Fall– trees not growing, leaves start to die. When they decompose CO_2 goes back to atmosphere

Winter – decay finishes, then plants are dormant

https://www.freepik.com/free-vector/tree-each-season-design_1041974.htm

2.1.1 Emission and Removal of CO_2

- The biosphere continuously exchanges large amounts of CO_2 with the atmosphere
- Oceans also absorb and release a lot of CO_2 each year
- Fossil fuel use, land use change, and other human activities add CO_2 to the atmosphere



Gross CO_2 Fluxes:

Land Biosphere

- Emissions ~550 Pg CO_2 yr^{-1}
- Removals ~560 Pg CO_2 yr^{-1}

Ocean

- Emissions ~330 Pg CO_2 yr^{-1}
- Removals ~340 Pg CO_2 yr^{-1}

Human Activities

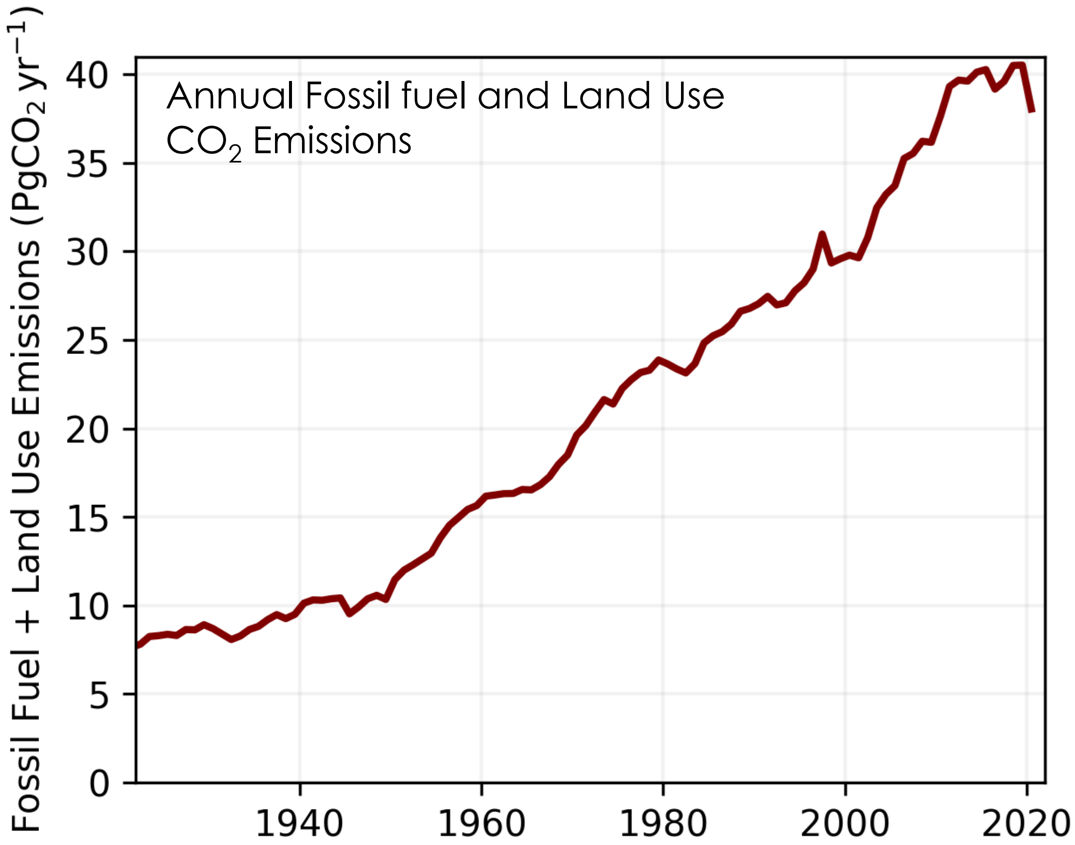
- Emissions ~39 Pg CO_2 yr^{-1}
- Removals ~0 Pg CO_2 yr^{-1}

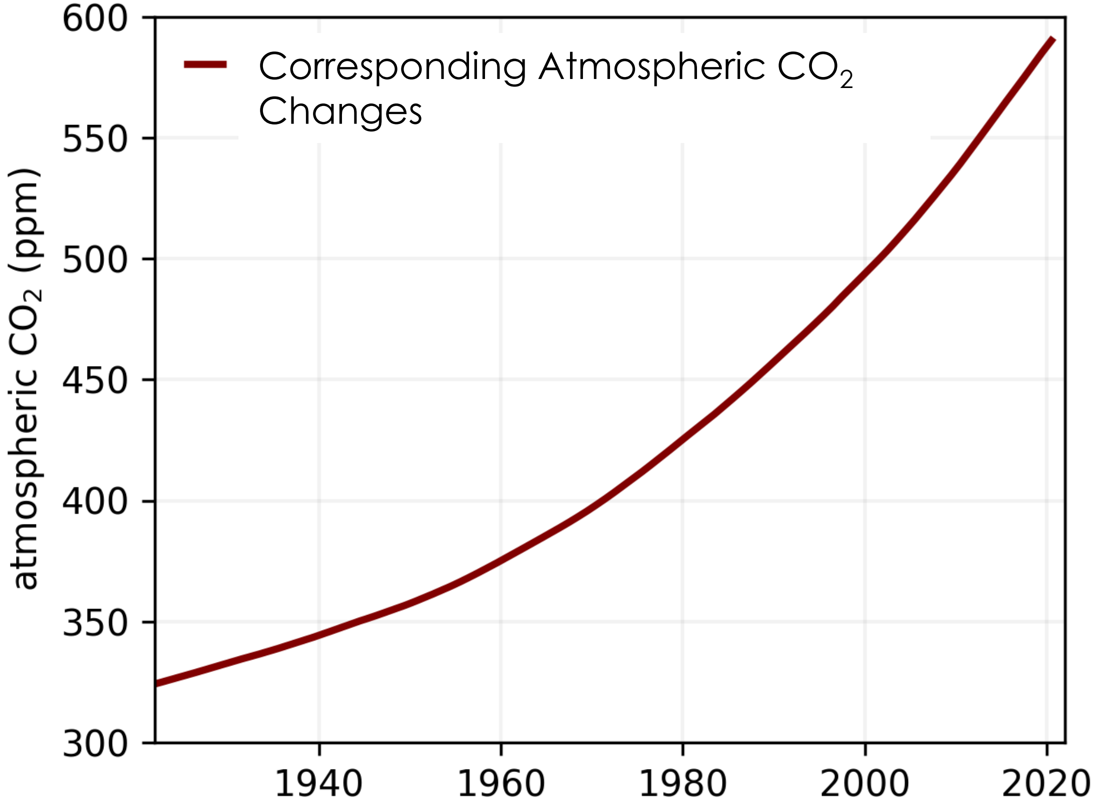
(1 Pg = 1 petagram = 1 billion metric tonnes = 10^{15} grams)

https://public.ornl.gov/site/gallery/originals/CCycle_cover_image.jpg

2.1.1 Emission and Removal of CO_2

- **Fossil Fuel (FF)** consumption and **Land Use Emissions (LUE)** have been releasing CO_2 from the geological and biosphere reservoirs to the atmosphere.

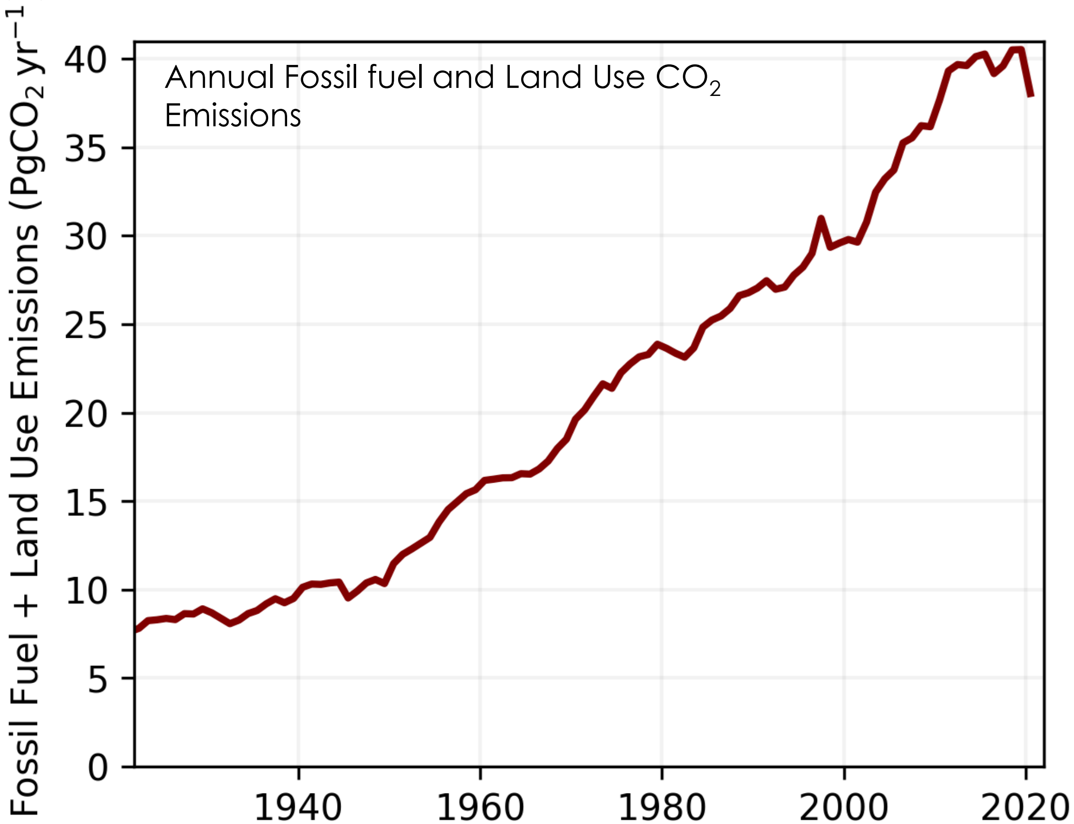




FF and LUE data from Friedlingstein et al. Global Carbon Budget 2021, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2021-386, in review, 2021.

2.1.1 Emission and Removal of CO_2

- **Fossil Fuel (FF)** consumption and **Land Use Emissions (LUE)** have been releasing CO_2 from the geological and biosphere reservoirs to the atmosphere.
- However, measurements of atmospheric CO_2 show only about half of this CO_2 stays in the atmosphere.



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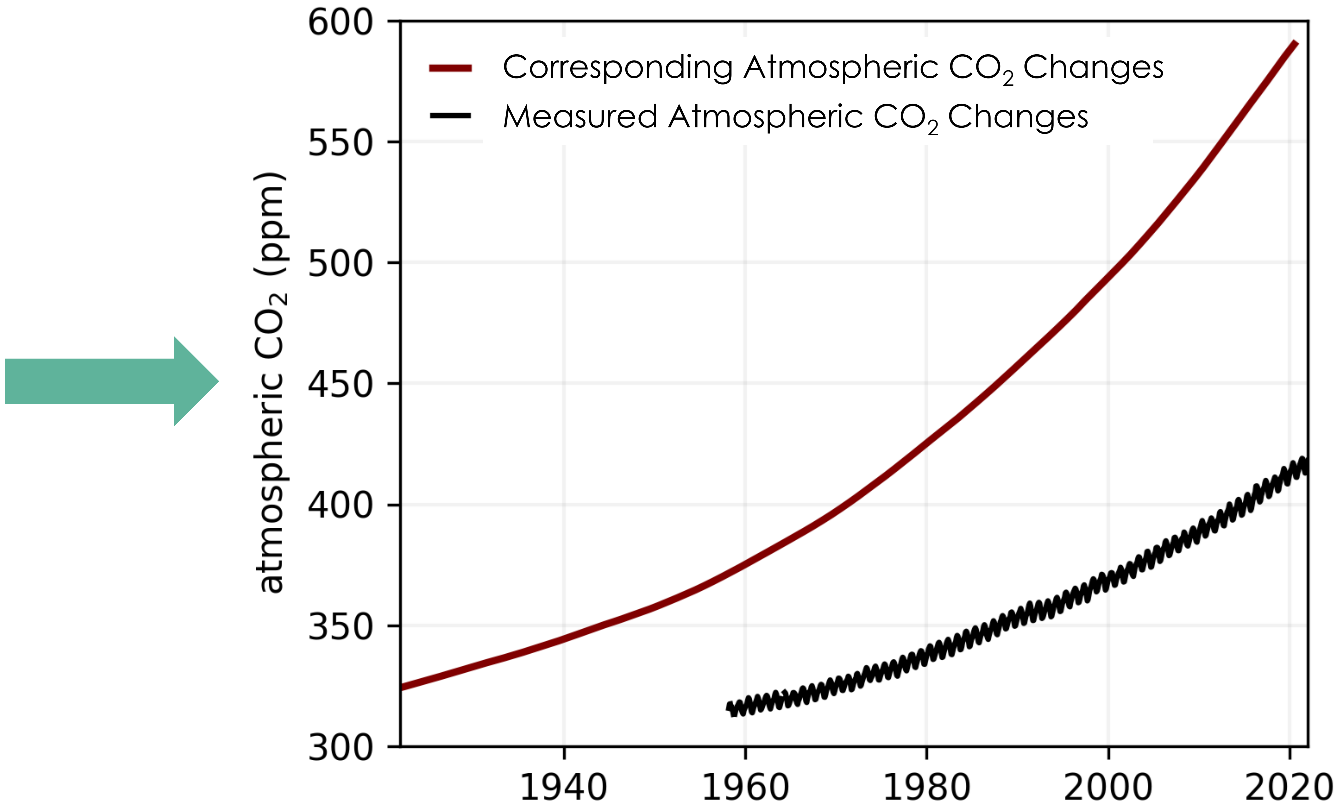
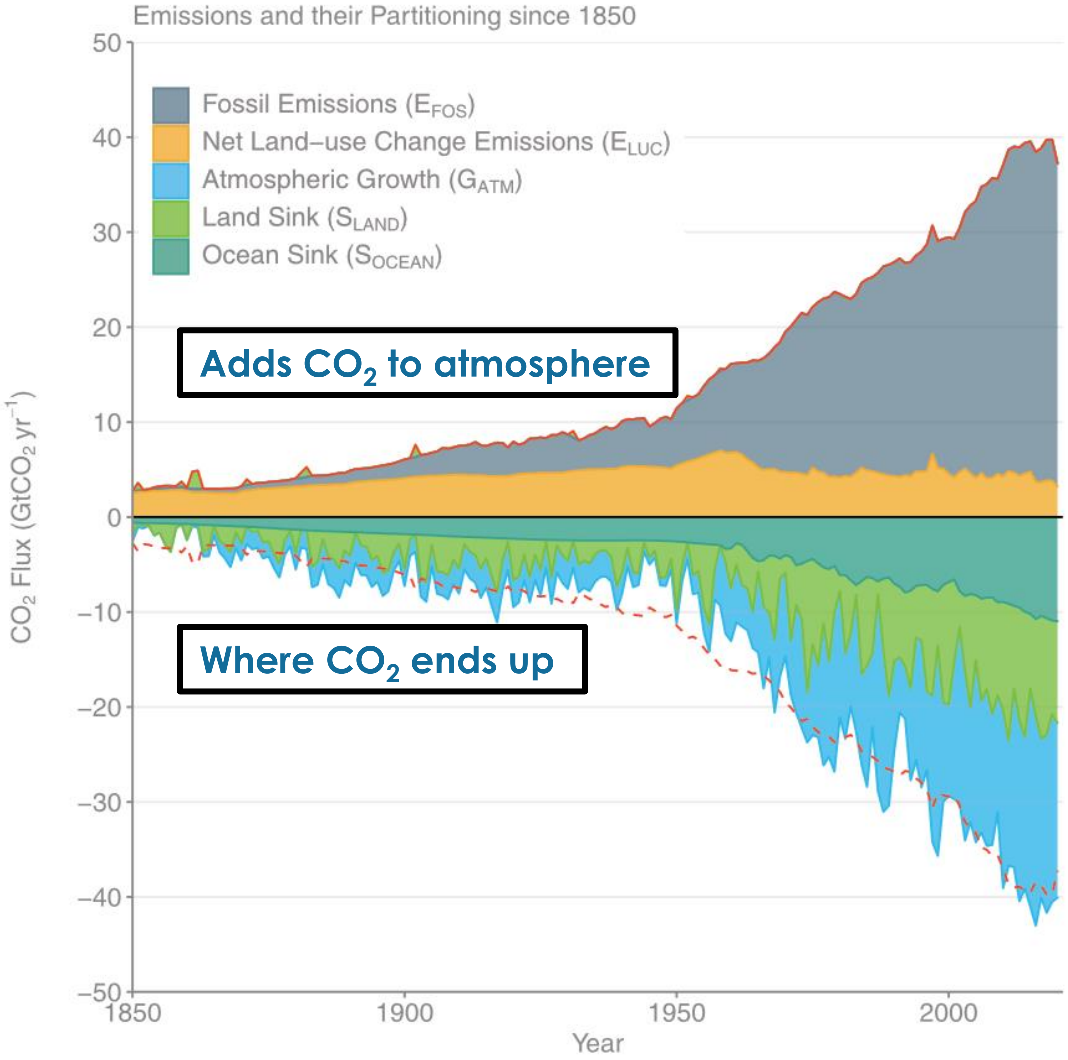


CO2 data downloaded from http://scrippsco2.ucsd.edu/data/atmospheric_co2/primary_mlo_co2_record. Keeling et al. Exchanges of atmospheric CO2 and 13CO2 with the terrestrial biosphere and oceans from 1978 to 2000. I. Global aspects, SIO Reference Series, No. 01-06, Scripps Institution of Oceanography, San Diego, 88 pages, 2001.

2.1.1 Emission and Removal of CO_2



Source: Friedlingstein et al 2021; Global Carbon Project 2021

- **41%** of anthropogenic CO_2 emissions remain in the atmosphere [Friedlingstein et al., 2021].

Natural **sinks** that remove CO_2 from the atmosphere:

- Oceans have absorbed **26%** of anthropogenic CO_2 emissions [Friedlingstein et al., 2021].
    - largely driven by the atmosphere-ocean partial pressure difference (due to increasing atmospheric CO_2).
- Terrestrial ecosystems have absorbed **30%** of anthropogenic CO_2 emissions [Friedlingstein et al., 2021].
    - Anthropogenic activities (deforestation, reforestation) impact the land sink, but other processes (CO_2 fertilization, climate change) also contribute.
    - Main drivers of carbon uptake by terrestrial ecosystems are not well understood, and likely vary by region.

Friedlingstein et al.: Global Carbon Budget 2021, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2021-386, in review, 2021.

2.1.1 Emission and Removal of CO_2

Goals of Top-Down Global Stocktake (GST) CO_2 Datasets:

Driving Questions:

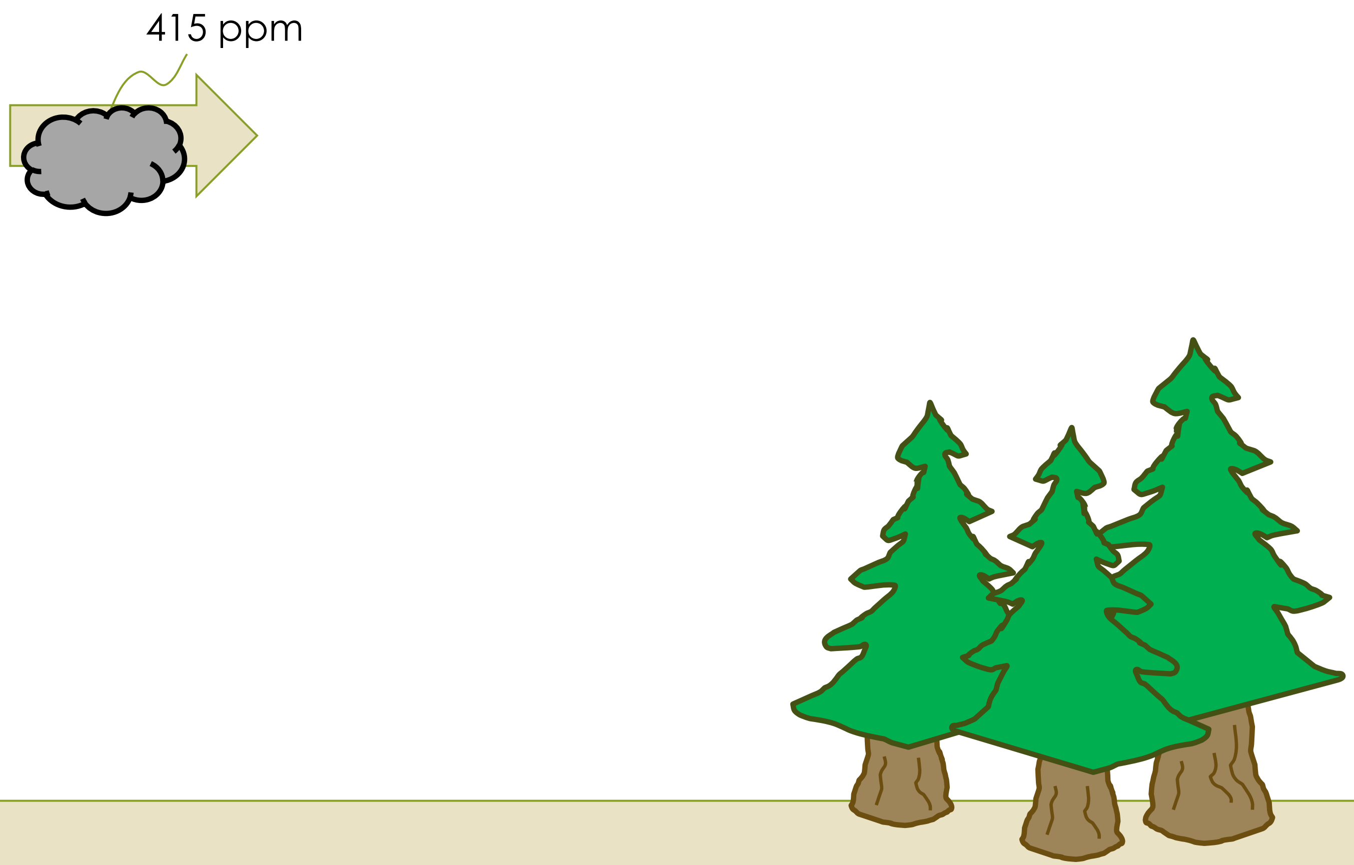
1) What are the net CO_2 emissions and removals for countries?
2) What is the change in terrestrial carbon stocks for countries?

Method:

1) Measure atmospheric CO_2 at high spatial and temporal resolution over the globe.
2) Perform flux inversion to estimate the surface-atmosphere flux from variability in atmospheric CO_2.
3) Calculate loss of land carbon stock loss using ancillary datasets.

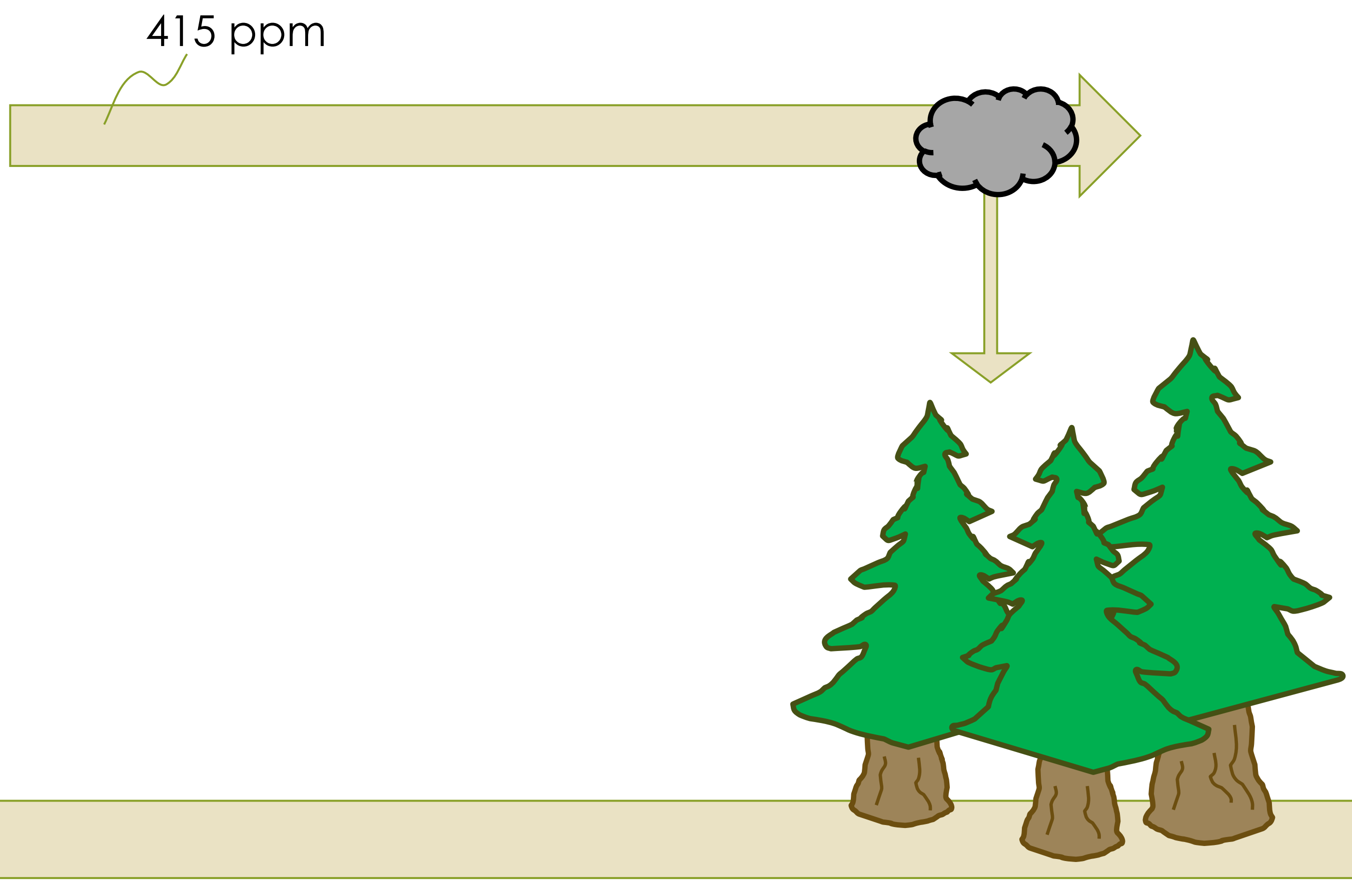
2.1.1 Emission and Removal of CO_2

Concept behind a CO_2 flux inversion:



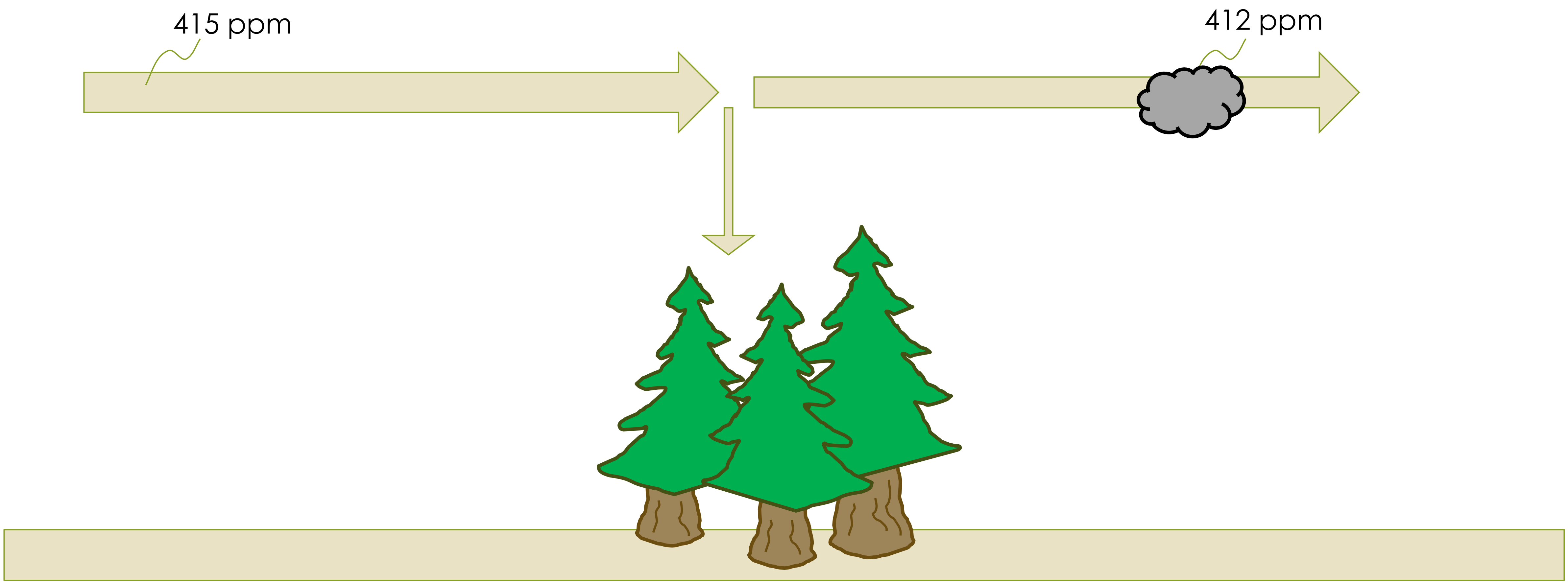
2.1.1 Emission and Removal of CO_2

Concept behind a CO_2 flux inversion:



2.1.1 Emission and Removal of CO_2

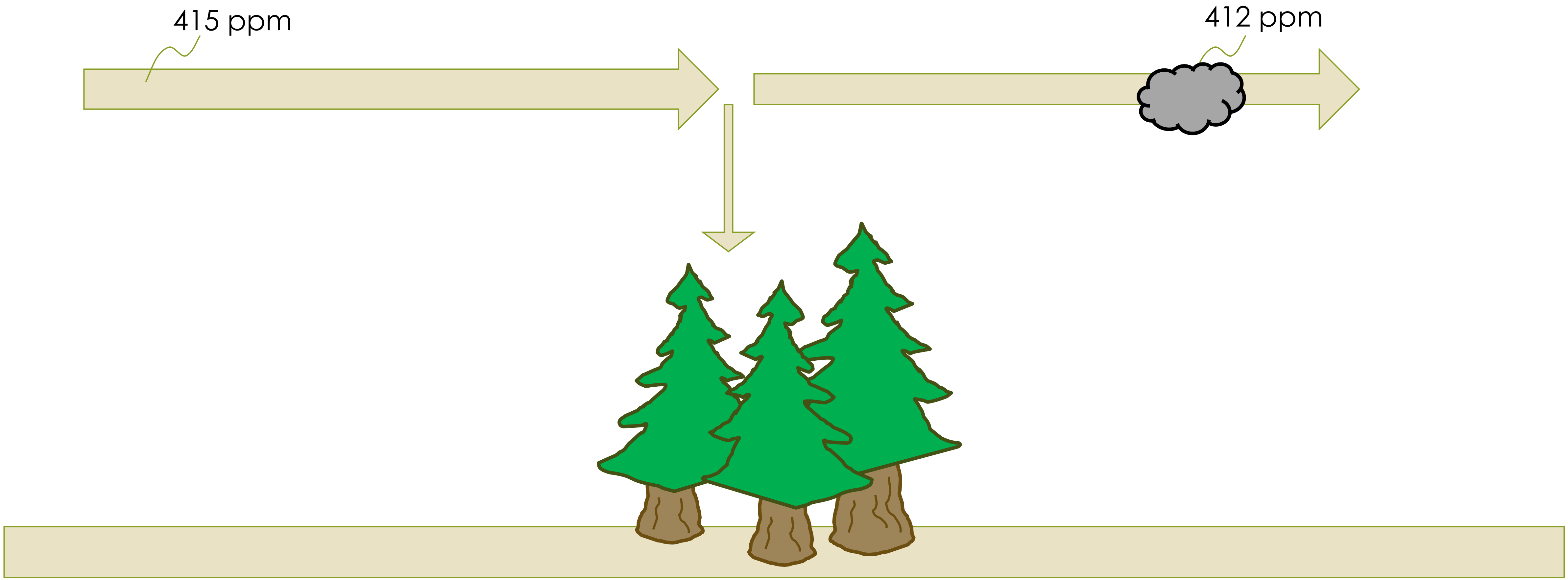
Concept behind a CO_2 flux inversion:



2.1.1 Emission and Removal of CO_2

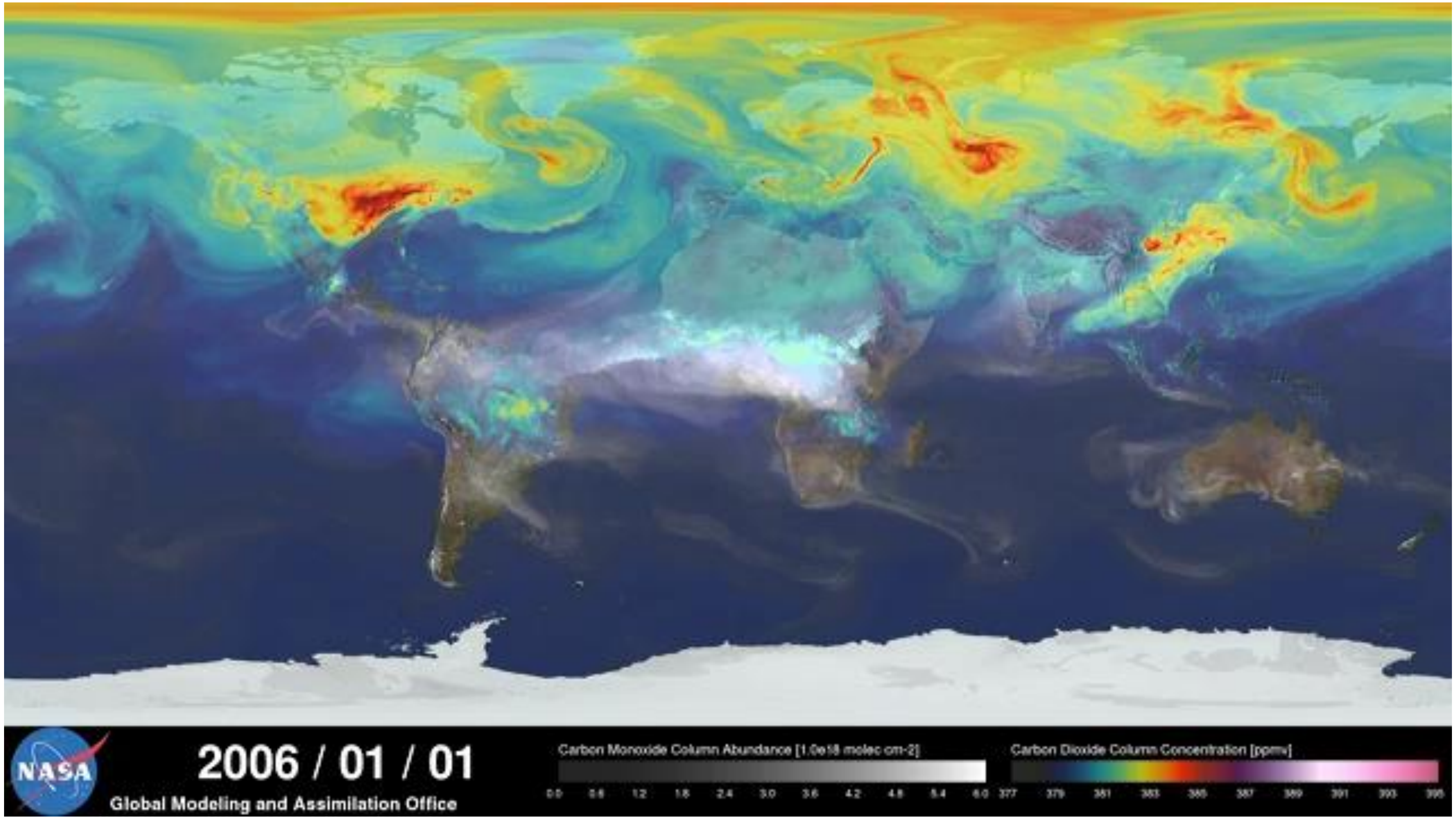
Concept behind a CO_2 flux inversion:

415 ppm - 412 ppm = 3 ppm of CO_2 absorbed by the forest



2.1.1 Emission and Removal of CO_2

- Variations in atmospheric CO_2 are caused by a combination of emissions/removals and transport by winds.
- To estimate emissions/removals, we need dense measurements of CO_2 and knowledge of winds.



Goddard Global Modeling and Assimilation Office

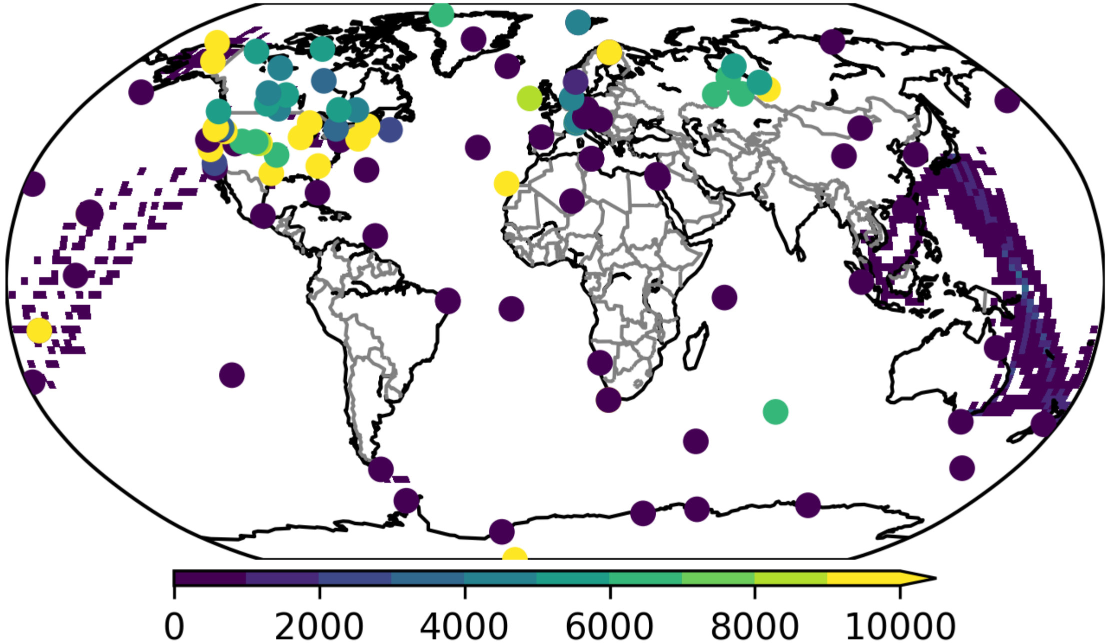
2.1.2 Space-Based, Airborne, and Ground-Based Measurements of CO_2

Datasets of Atmospheric CO_2:

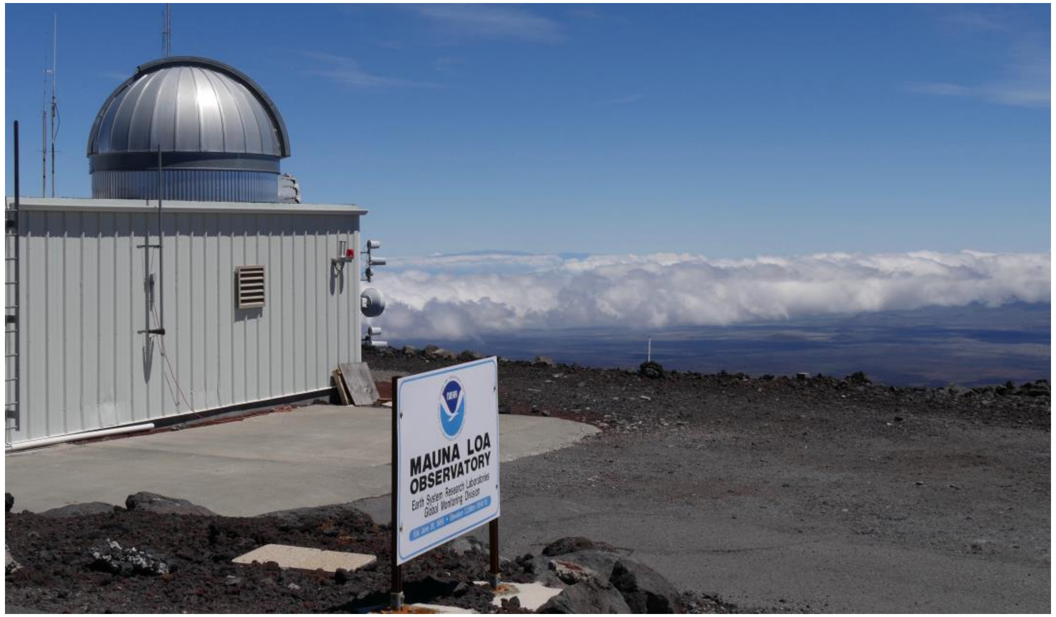
1) In Situ Measurements

- ➔ Advantages: Measurements are precise and accurate, and records extend over 60 years.
- ➔ Disadvantages: Coverage is sparse outside of North America and Europe.

Distribution of in situ CO_2 measurements



Number of in situ CO_2 measurements over 2015–2020

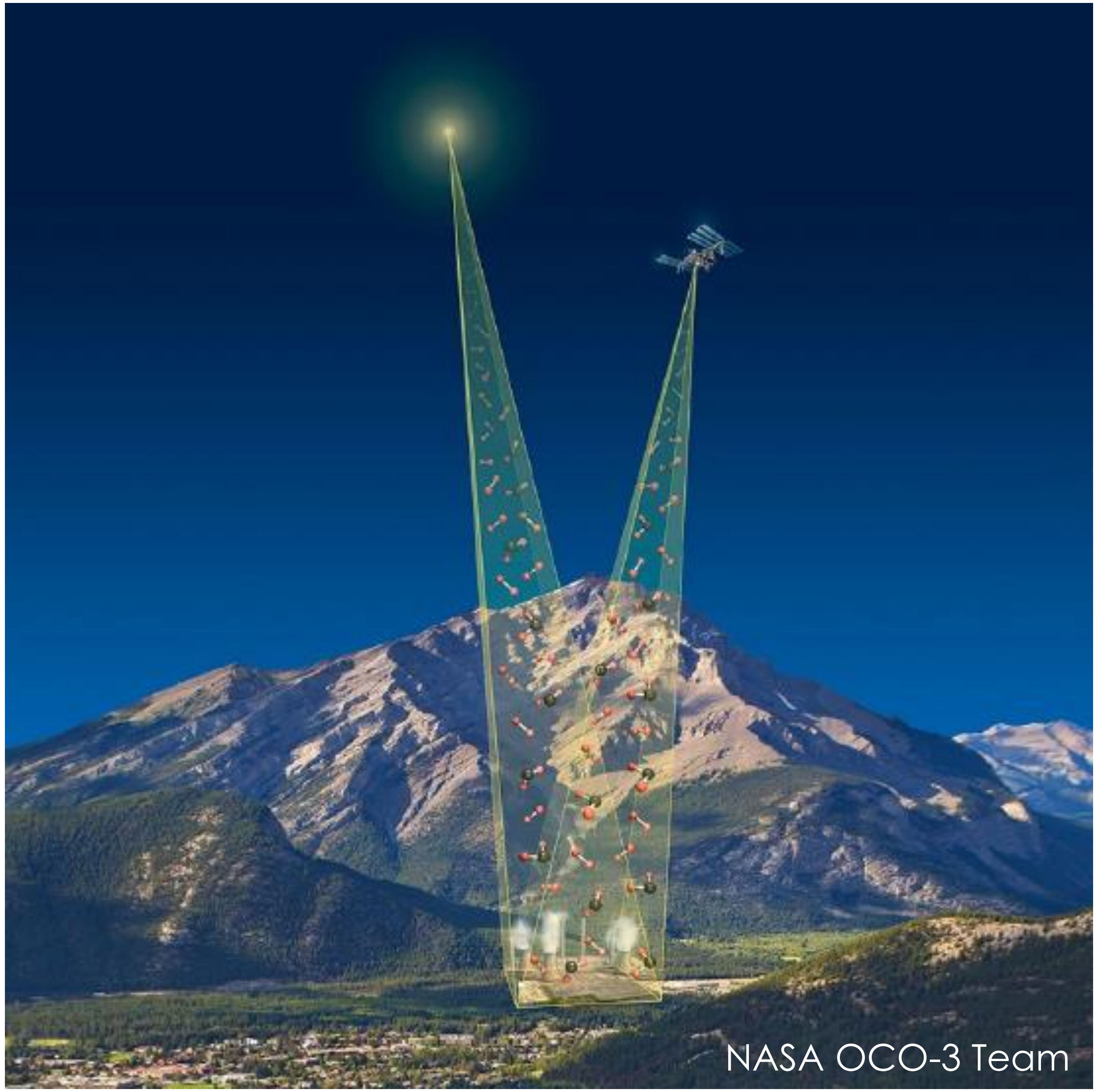


NOAA's Mauna Loa Atmospheric Baseline Observatory is perched high atop Hawaii's largest mountain in order to sample well-mixed background air free of local pollution.
Credit: Susan Cobb, NOAA Global Monitoring Laboratory.
Downloaded from https://research.noaa.gov

2.1.2 Space-Based, Airborne, and Ground-Based Measurements of CO_2

Datasets of Atmospheric CO_2:
2) Satellite Measurements

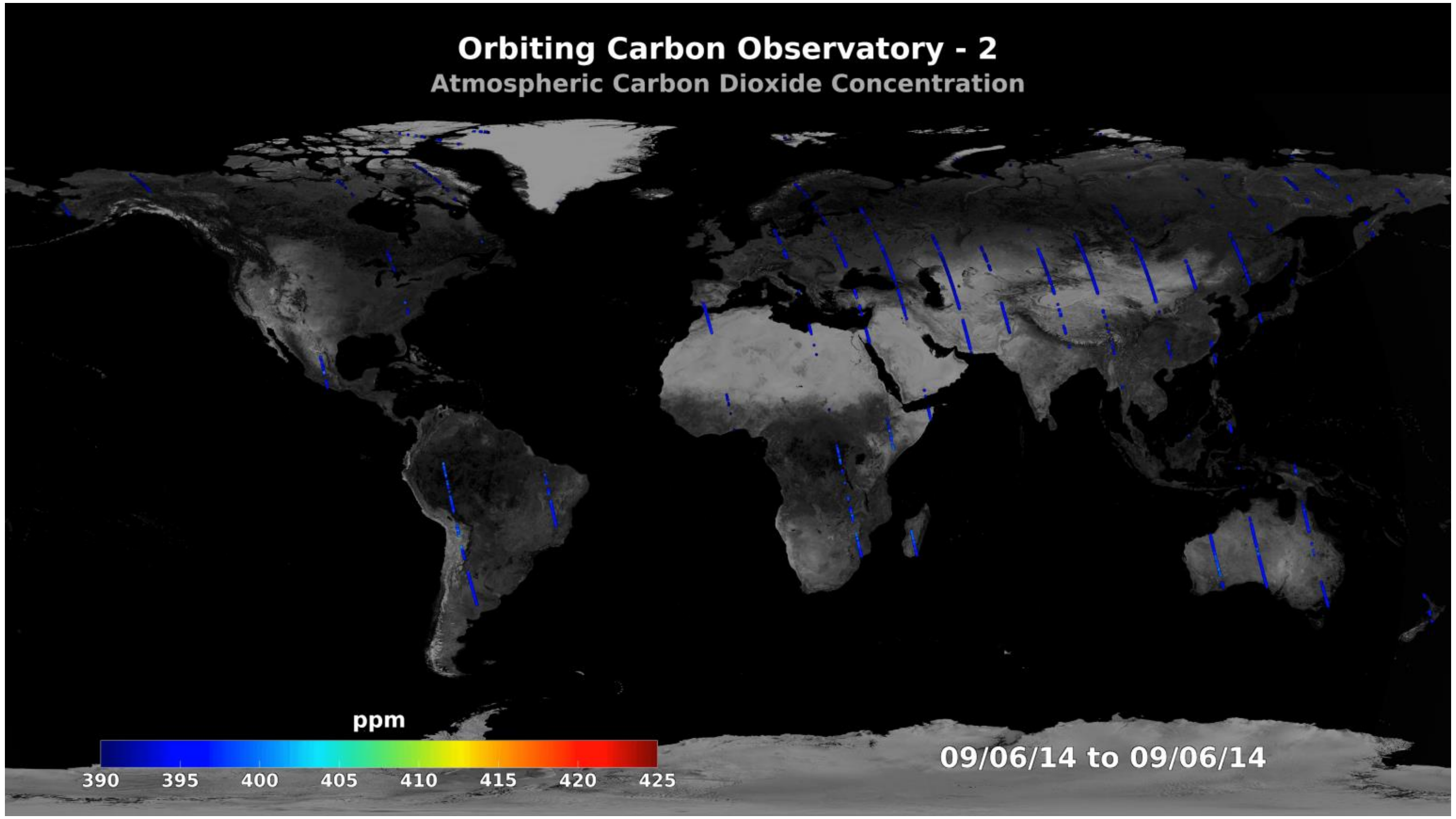
- Satellites measure sunlight reflected off the Earth's surface.
- Some wavelengths of light are absorbed by gases in the atmosphere (e.g., CO_2). From the amount of absorption, the total amount of CO_2 in the atmosphere is estimated.
- Retrieve "X_{CO2}", which is the average concentration of CO_2 throughout the atmosphere (often referred to as the column-average dry air mole-fraction of CO_2).


NASA OCO-3 Team

2.1.2 Space-Based, Airborne, and Ground-Based Measurements of CO_2

The Orbiting Carbon Observatory 2 (OCO-2):

- Polar orbiting satellite, traveling from south-to-north crossing the equator at 13:30 hours Mean Local Time (MLT).
- Continuously collects observations of reflected sunlight over a narrow band (~10 km) near orbit ground track.
- X_{CO2} can be estimated from measurements collected in clear-sky conditions (e.g., not blocked by clouds).
- High latitude measurements can also be limited due to low-light conditions during winter.



NASA OCO-2 Team

2.1.2 Space-Based, Airborne, and Ground-Based Measurements of CO_2

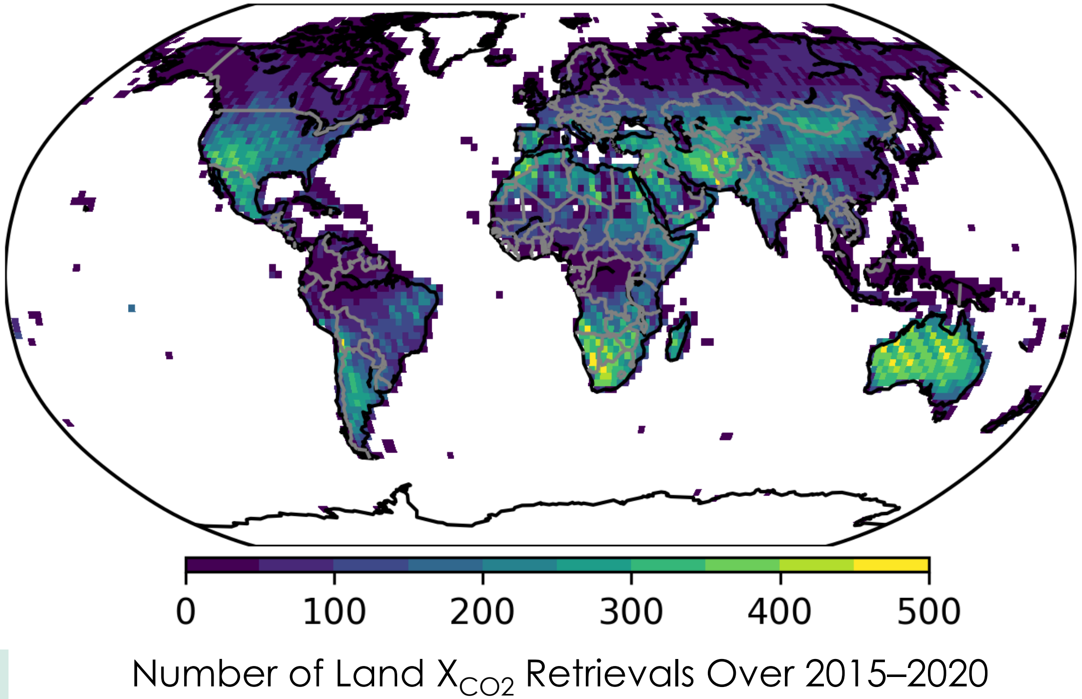
OCO-2 Land X_{CO2} Retrievals – Land Nadir and Land Glint (LNLG)

- ➔ Advantages: *Spatially extensive (cover many remote areas with no in situ measurements)*
- ➔ Disadvantages: *Subject to biases in retrieval algorithm (moderate concern)*

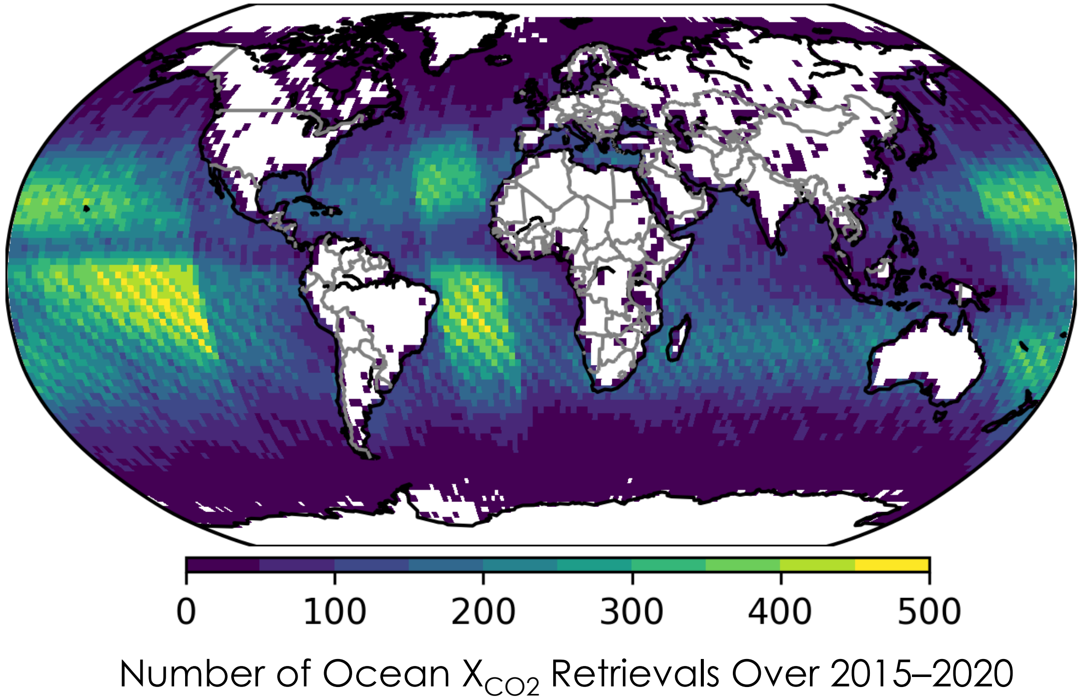
OCO-2 Ocean X_{CO2} Retrievals – Ocean Glint (OG)

- ➔ Advantages: *Spatially extensive, more precise than land measurements*
- ➔ Disadvantages: *Subject to biases in retrieval algorithm (major concern)*

Distribution of OCO-2 Land Retrievals



Distribution of OCO-2 Ocean Retrievals



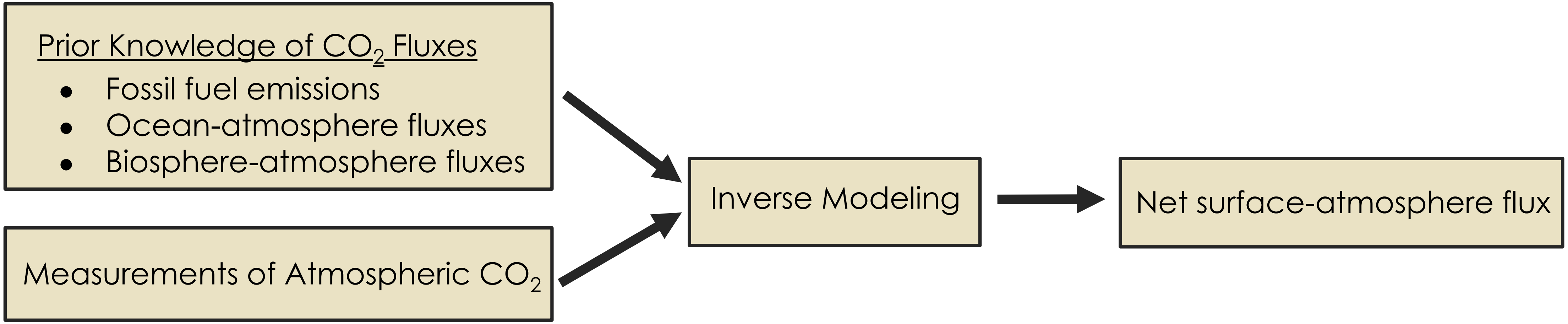
2.1.3 Inverse Modeling

Inverse Modeling:

- Inverse modeling allows us to estimate the surface-atmosphere flux that matches atmospheric CO_2 obs.

Approach:

- Simulate atmospheric CO_2 using prior estimate of surface-atmosphere fluxes and realistic winds.
- Compare "measurement" of model atmosphere with real measurements.
- Correct flux estimates to make model atmosphere agree with real measurements, within uncertainties.



Prior Knowledge of CO_2 Fluxes

- Fossil fuel emissions
- Ocean-atmosphere fluxes
- Biosphere-atmosphere fluxes

Measurements of Atmospheric CO_2

Inverse Modeling

Net surface-atmosphere flux

2.1.3 Inverse Modeling

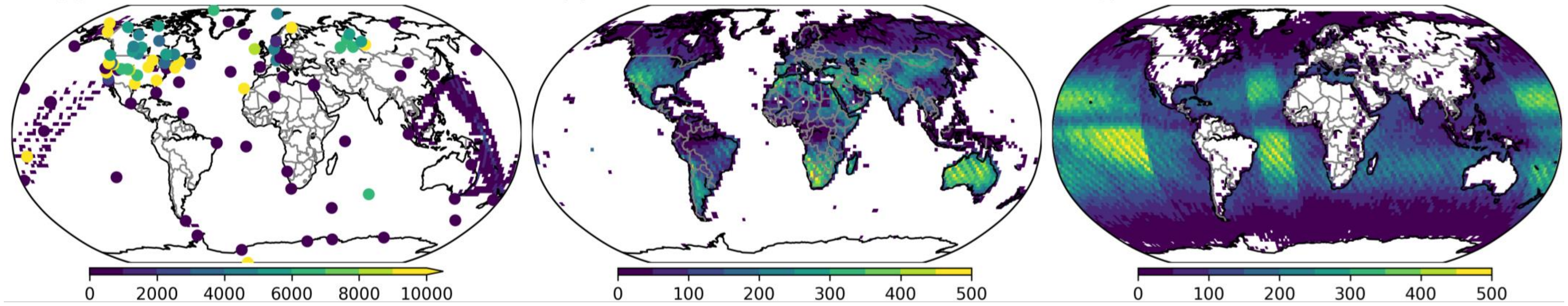
OCO-2 Model Intercomparison Project (MIP)

- No model is perfect (and no flux inversion is perfect).
  - Using ~12 models helps quantify systematic errors
- Estimate CO_2 fluxes for six years (2015–2020).

Includes four MIP experiments that use different datasets:

- **In situ (IS)**: *uses in situ CO_2 measurements.*
- **Land nadir + land glint (LNLG)**: *uses OCO-2 land X_{CO2} retrievals.*
- **Land nadir + land glint + in situ (LNLGIS)**: *uses OCO-2 land X_{CO2} retrievals and in situ CO_2 measurements.*
- **Land nadir + land glint + ocean glint + in situ (LNLGOGIS)**: *uses OCO-2 land and ocean X_{CO2} retrievals and in situ CO_2 measurements.*

Each experiment has advantages and disadvantages that impact flux estimates.



2.1.3 Inverse Modeling

IS:

- In situ data undergoes direct validation and has high accuracy and precision.
- Observations are sparse over much of globe (outside North America and Europe).

LNLG:

- OCO-2 land data is less precise and accurate than IS data but is generally high quality (remaining regional biases may be present).
- Global land coverage (particularly during the summer), but seasonal data gaps.

LNLGIS:

- Combined information of in situ and OCO-2 land data, which betters fills observational gaps.
- Main concern is intercalibration errors between IS and LNLG datasets.

LNLGOGIS:

- Combines all data providing very dense observation constraints.
- Still significant concerns about OCO-2 ocean data which means great caution is needed.

2.1.3 Inverse Modeling

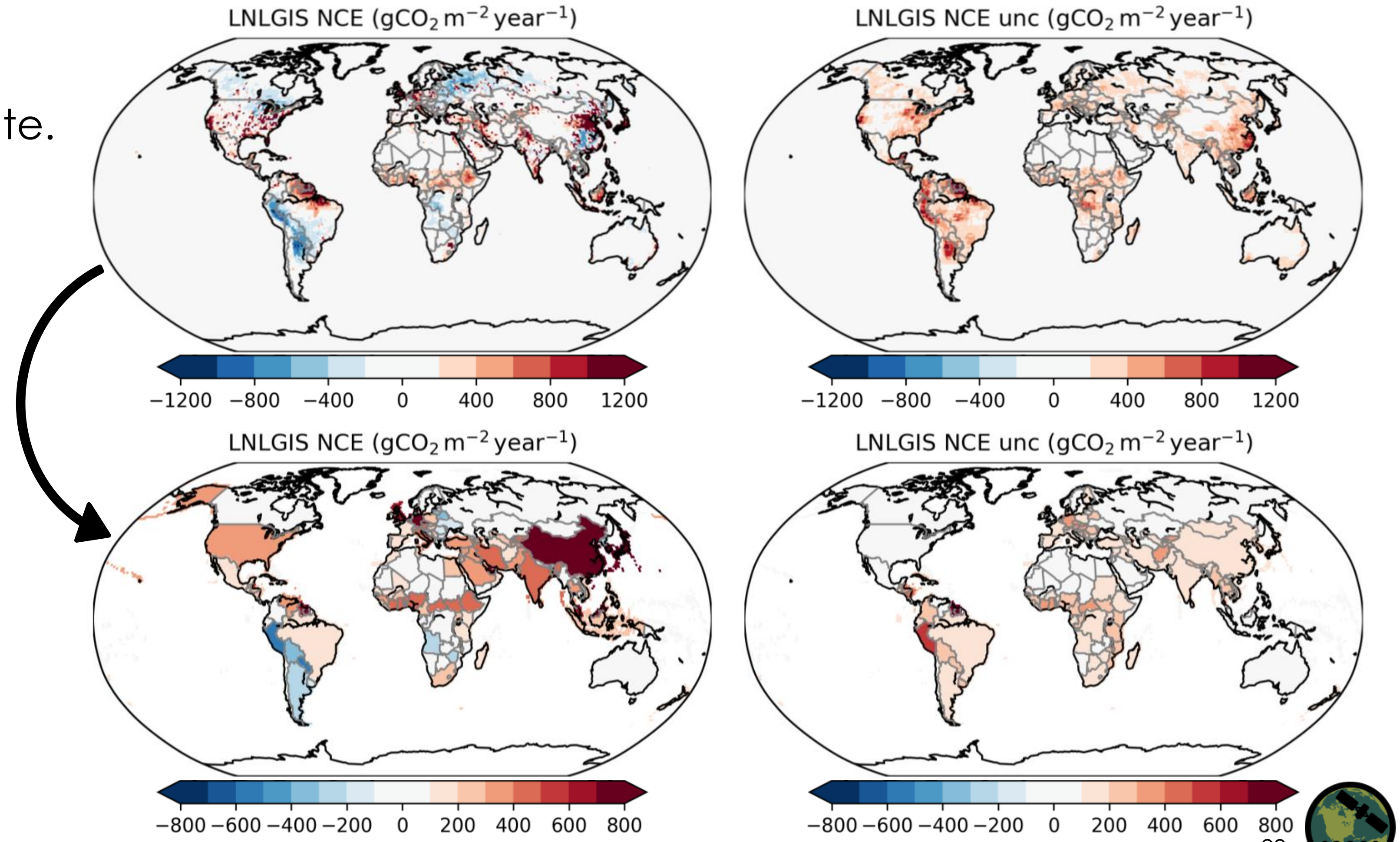
Each modeling group estimates the **Net Carbon Exchange (NCE) = Fossil Fuel + Net Biosphere Exchange**

- Estimates provided on a 1° x 1° grid.
- We aggregate to country totals.
- Take model median as best estimate.
- Uncertainty is estimated as the standard deviation across model estimates.

Net Carbon Exchange (NCE) for 2015–2020

Median

Uncertainty



NCE fluxes Aggregated to Country Totals

2.1.4 Carbon Stock Loss

Enabling Comparisons with Inventories

- The global stocktake examines changes in land carbon stocks (for AFOLU sector).
- **Land carbon stock loss (ΔC_{loss})** estimated by combining top-down NCE with other carbon flux datasets.
- Calculate:

$$\Delta \mathrm{C}_{\mathrm{loss}} = \mathrm{NCE} - \mathrm{FF} - \mathrm{Fcrop}_{\mathrm{trade}} - \mathrm{Fwood}_{\mathrm{trade}} - \mathrm{Frive}_{\mathrm{rs\ export}}$$

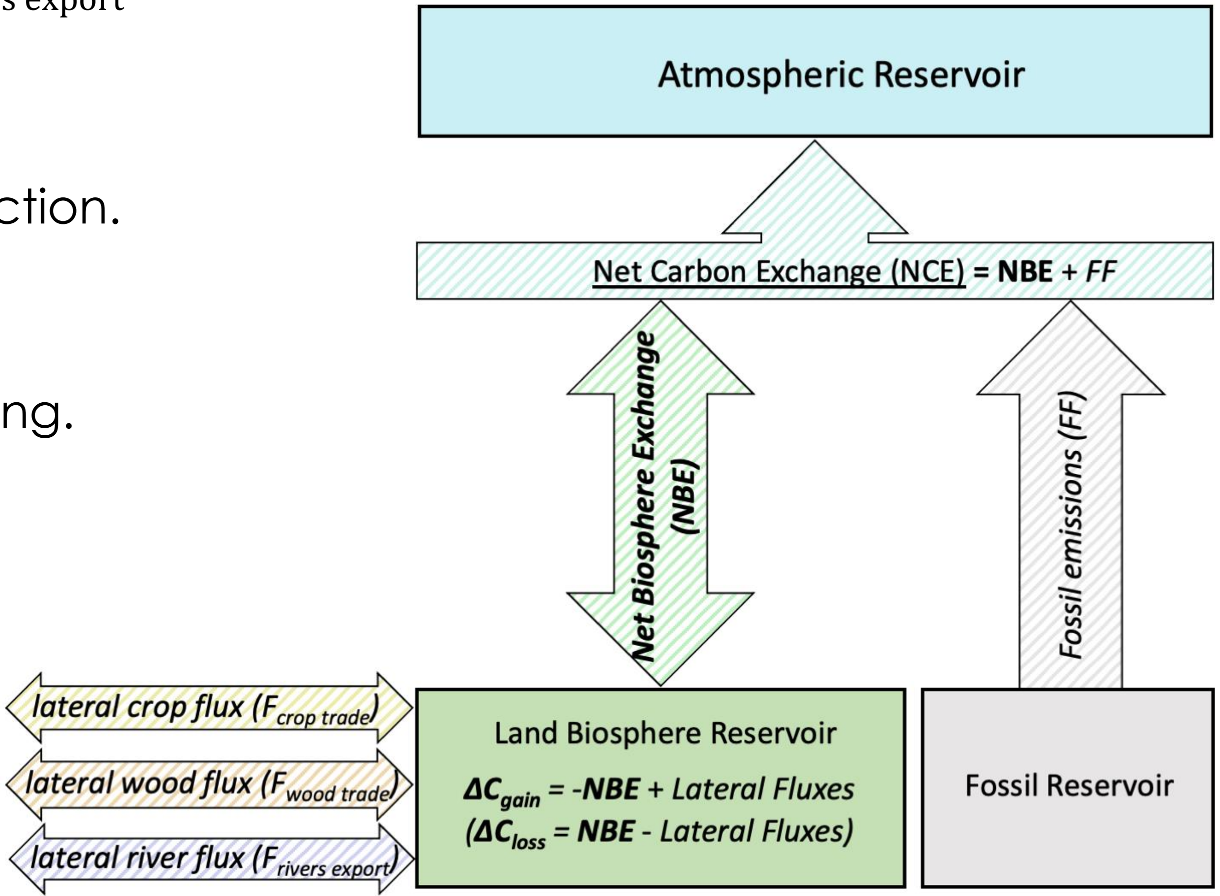
FF: CO_2 emissions from fossil fuels and cement production.

$F_{crop\ trade}$: lateral flux of carbon due to farming.

$F_{wood\ trade}$: lateral flux of carbon due to wood harvesting.

$F_{rivers\ export}$: lateral flux of carbon due to rivers.

Carbon fluxes for a given land region

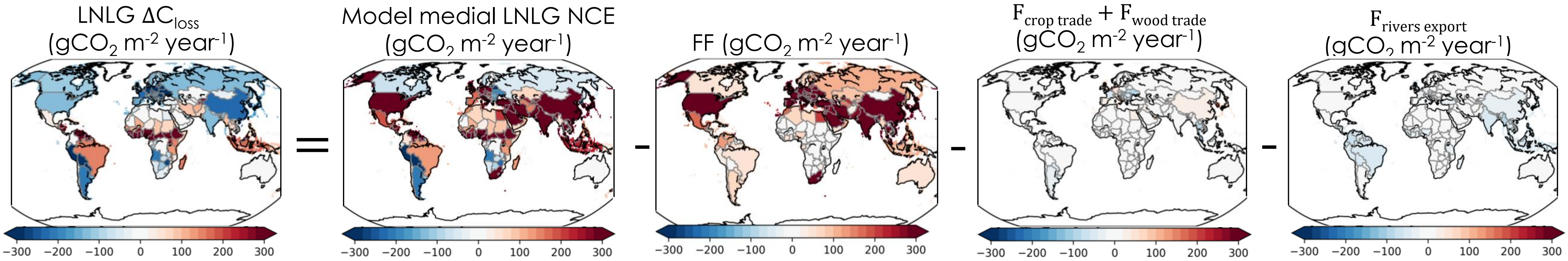


2.1.4 Carbon Stock Loss

Calculation of Land Carbon Stock Loss (ΔC) and Uncertainties

$$\Delta C_{\mathrm{loss}} = \mathrm{NCE} - \mathrm{FF} - \mathrm{Fcrop}_{\mathrm{trade}} - \mathrm{Fwood}_{\mathrm{trade}} - \mathrm{Frivers}_{\mathrm{export}}$$

Best Estimate of ΔC_{loss} for LNLG Experiment



LNLG ΔC_{loss} (gCO_2 m^{-2} $year^{-1}$)

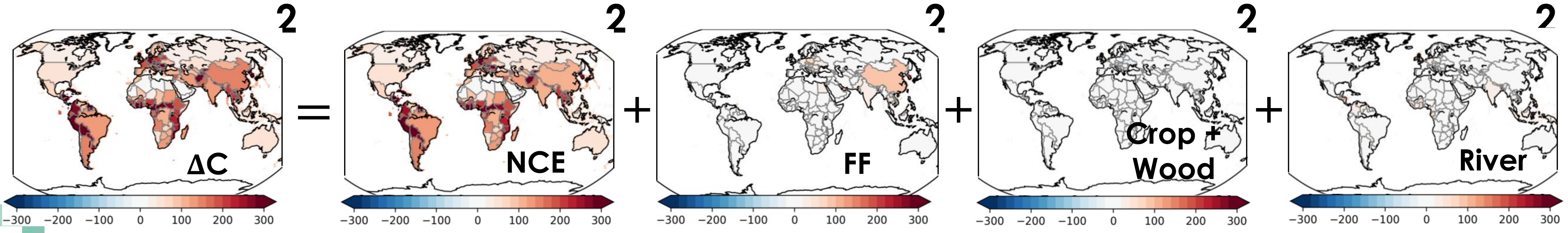
Model medial LNLG NCE (gCO_2 m^{-2} $year^{-1}$)

FF (gCO_2 m^{-2} $year^{-1}$)

$F_{crop\ trade} + F_{wood\ trade}$ (gCO_2 m^{-2} $year^{-1}$)

$F_{rivers\ export}$ (gCO_2 m^{-2} $year^{-1}$)

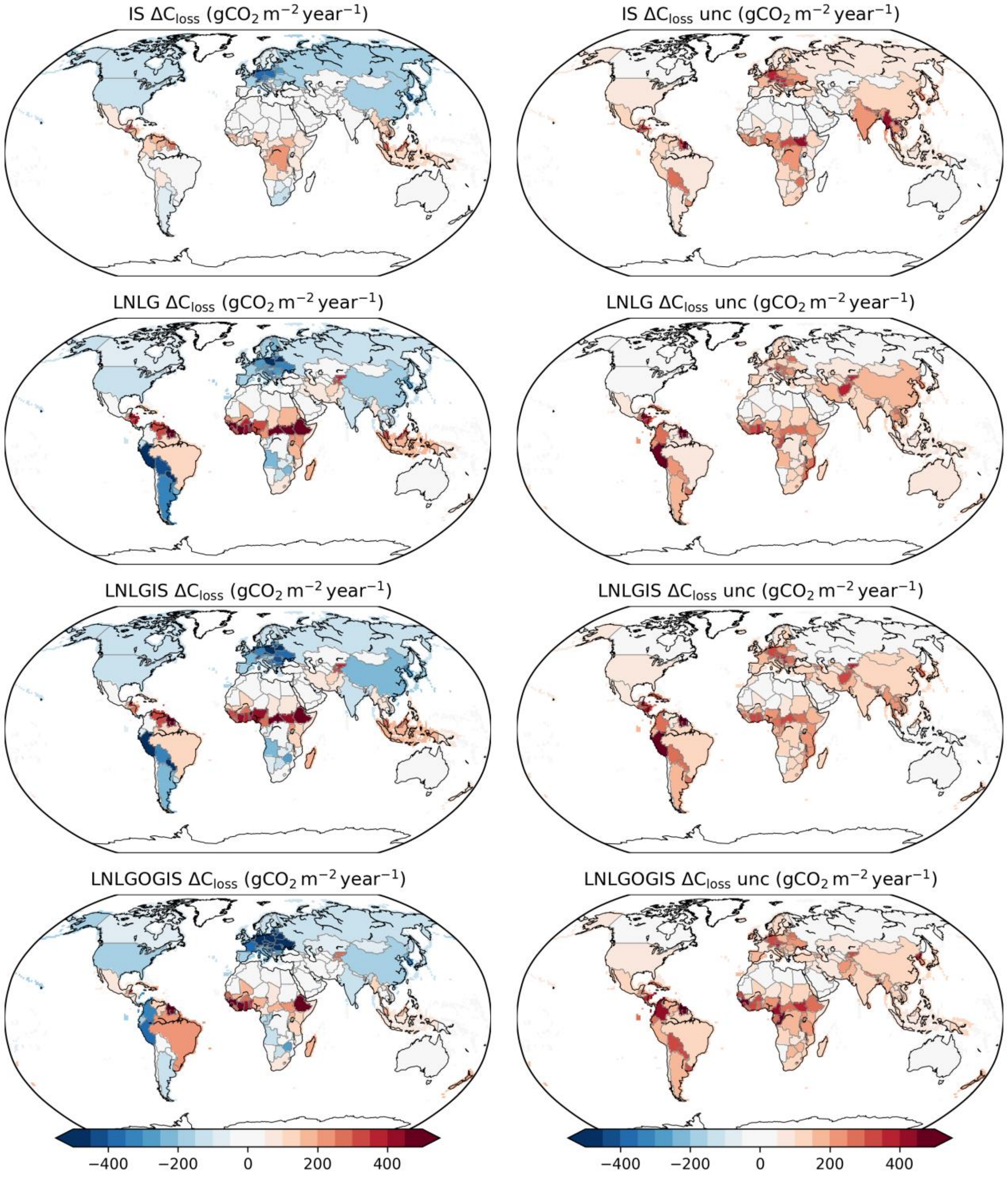
Uncertainty in ΔC_{loss} for LNLG Experiment



2.1.4 Carbon Stock Loss

2015 – 2020 ΔC for Each MIP Experiment

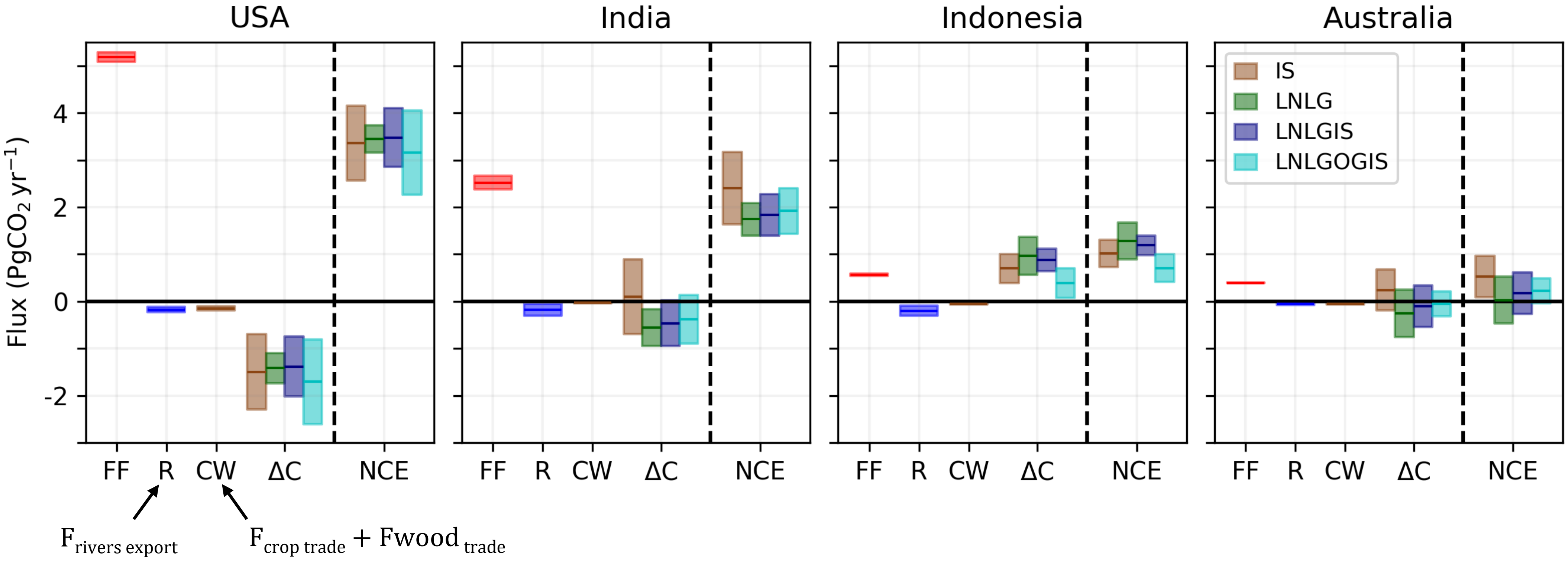
- ΔC_{loss} shows many consistent signals across the experiments.
    - Negative (land carbon gain) across northern high latitudes
    - Positive (land carbon loss) across tropics.
- However, some important differences appear
    - OCO-2 vs IS differences in tropics
    - Factors driving differences:
        - Lack of in situ data
        - Retrieval biases in OCO-2 XCO_2 retrievals
- We have the highest confidence in ΔC_{loss} estimates when they are consistent across all experiments (excluding LNLGOGIS).



2.1.4 Carbon Stock Loss

Example 2015–2020 Carbon Budgets for Four Countries

- Recall: $\mathrm{FF} + \mathrm{Fcrop}_{\mathrm{trade}} + \mathrm{Fwood}_{\mathrm{trade}} + \mathrm{Frivers}_{\mathrm{export}} + \Delta \mathrm{C}_{\mathrm{loss}} = \mathrm{NCE}$
- Figure below shows how each component contributes to the NCE for a few specific countries, constrained by atmospheric CO_2 measurements.
- Increasing land carbon stocks decrease NCE relative to FF emissions for USA, but the opposite occurs for Indonesia.



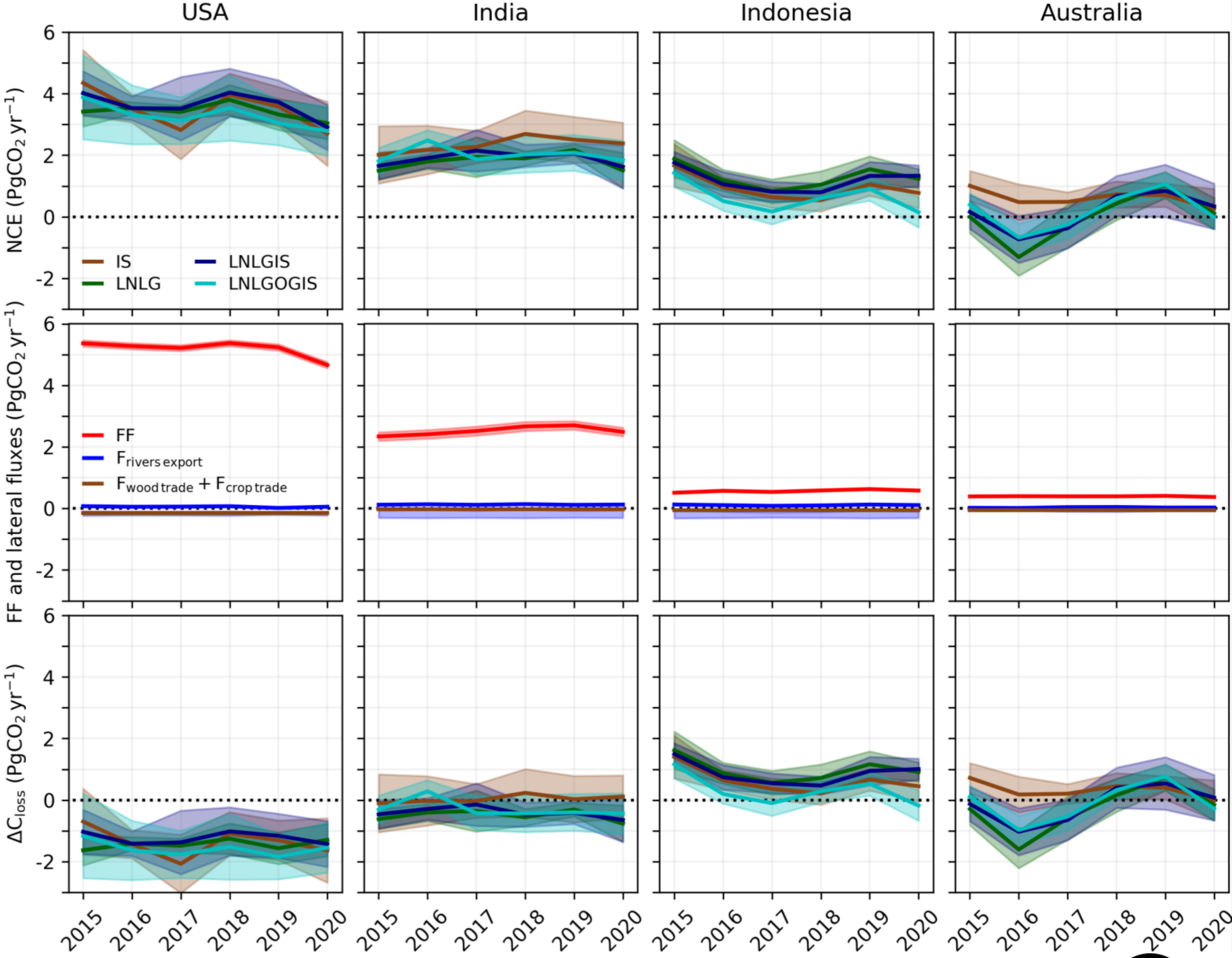
$\mathrm{F}_{\mathrm{rivers\ export}}$

$\mathrm{F}_{\mathrm{crop\ trade}} + \mathrm{Fwood}_{\mathrm{trade}}$

2.1.4 Carbon Stock Loss

Example Carbon Budget Time Series for Four Countries

- Provide annual net fluxes for six years covering 2015 through 2020.
- Interannual variations in NCE are driven primarily ΔC_{loss} due to climate variability and trends in FF.
- Droughts reduce carbon uptake by the ecosystem. Variability associated with El Niño in the tropics is a strong driver of variability in ΔC_{loss}.



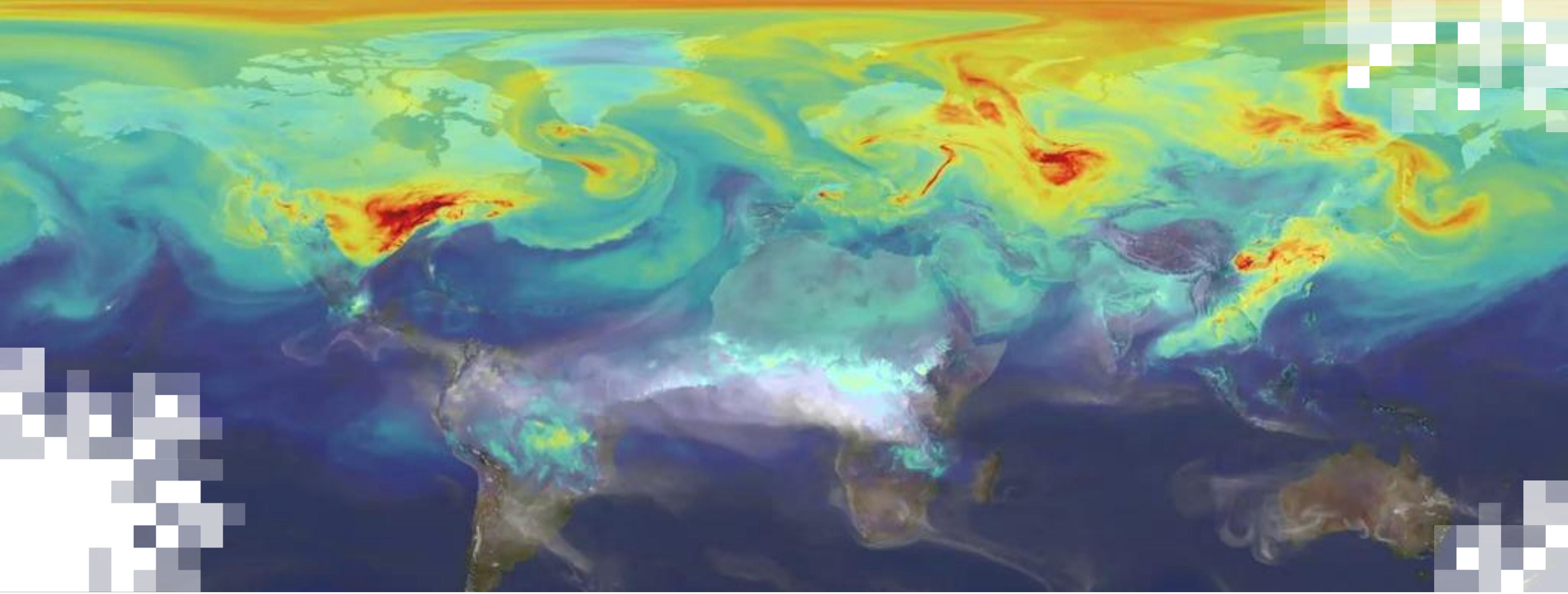
Dataset overview

- ✓ Annual net fluxes for six year (2015-2020)
- ✓ Provided for each country and regions (African Union, Association of Southeast Asian Nations, South Asian Association for Regional Cooperation, European Union)
- ✓ NCE, NBE, and ΔC_{loss} for four experiments (IS, LNLG, LNLGIS, LNLGOGIS)
- ✓ Bottom-up fluxes used to derive ΔC_{loss}: FF, $\mathrm{F}_{\text{crop trade}}$, $\mathrm{F}_{\text{wood trade}}$, and $\mathrm{F}_{\text{rivers export}}$
- ✓ Quantities for interpreting robustness of flux estimates: Z-statistic, Influence Assimilated Data (IAD) …. See Part 3 for details.

2.1 CO_2 – Takeaways

Key Takeaways: Top-Down CO_2 Estimates

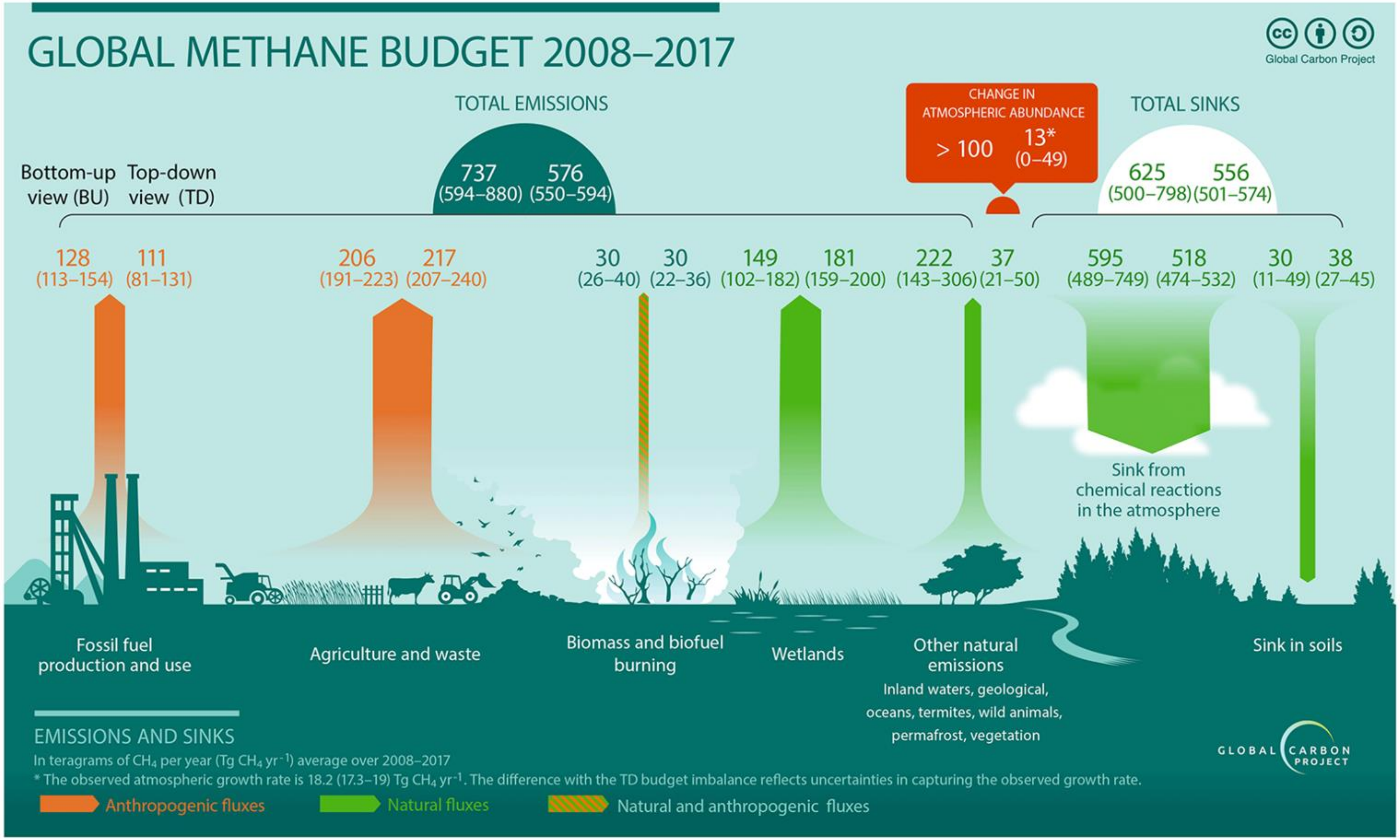
- ~50% of anthropogenic CO_2 emissions are absorbed by the land biosphere and oceans.
- Flux inversions provide regional emissions and removals of CO_2 from atmospheric CO_2 measurements using a transport model and data assimilation techniques.
- The OCO-2 MIP provides estimates of net carbon exchange (NCE) between the land and atmosphere for four experiments that assimilate different CO_2 datasets.
- We estimate the land carbon stock loss (ΔC_{loss}) by combining OCO-2 MIP NCE with inventories of fossil fuel emissions and lateral fluxes.
- Download the CO_2 dataset and try plotting some country totals in preparation for Part 3.
- Research paper accompanying this dataset coming in June.



Methane (CH_4)

Dan Cusworth (University of Arizona)

2.2.1 Processes that Emit and Remove Atmospheric CH_4



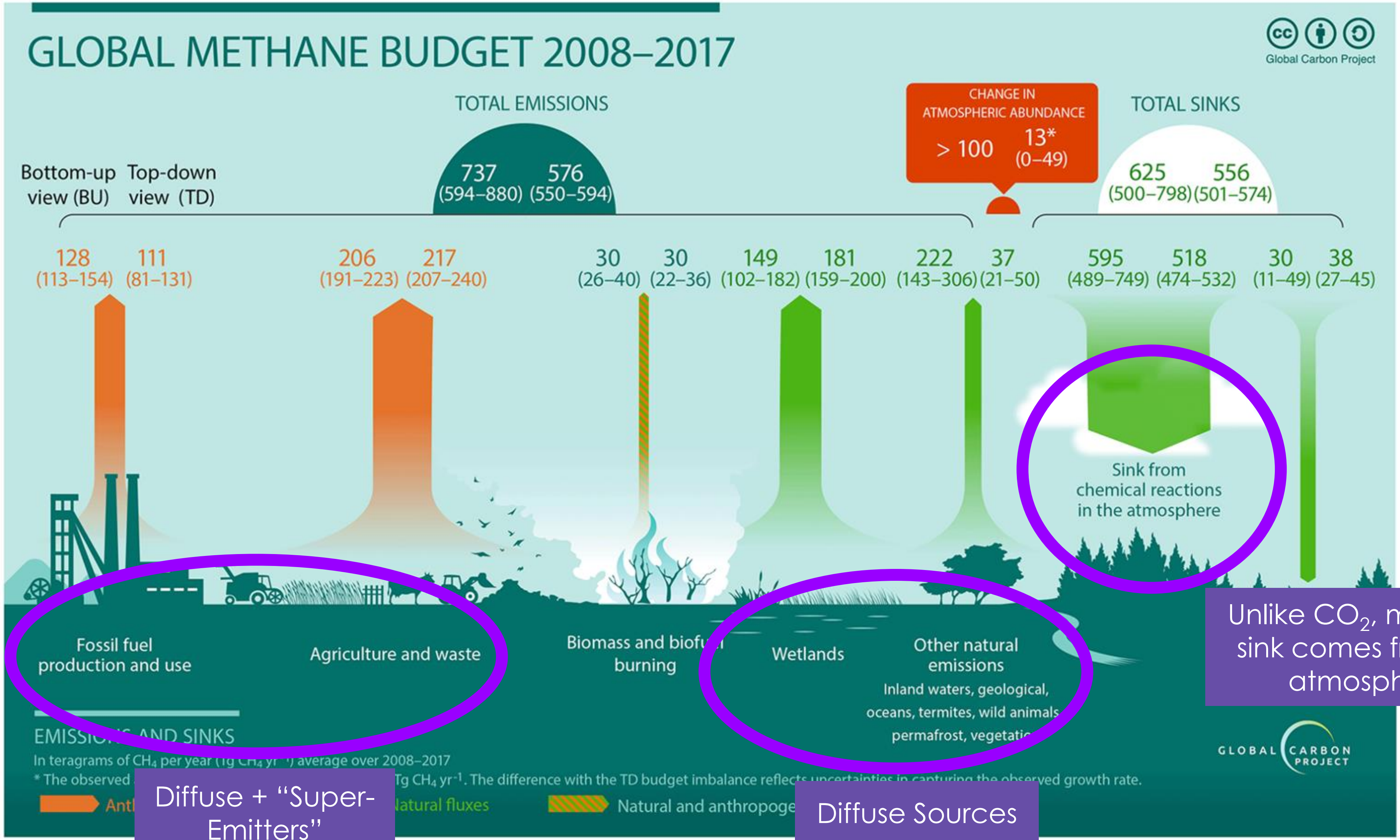
EMISSIONS AND SINKS

In teragrams of CH_4 per year (Tg CH_4 yr^{-1}) average over 2008–2017

* The observed atmospheric growth rate is 18.2 (17.3–19) Tg CH_4 yr^{-1}. The difference with the TD budget imbalance reflects uncertainties in capturing the observed growth rate.

Saunois et al. (2020)

2.2.1 Processes that Emit and Remove Atmospheric CH_4



Unlike CO_2, main CH_4 sink comes from the atmosphere

Diffuse + "Super-Emitters"

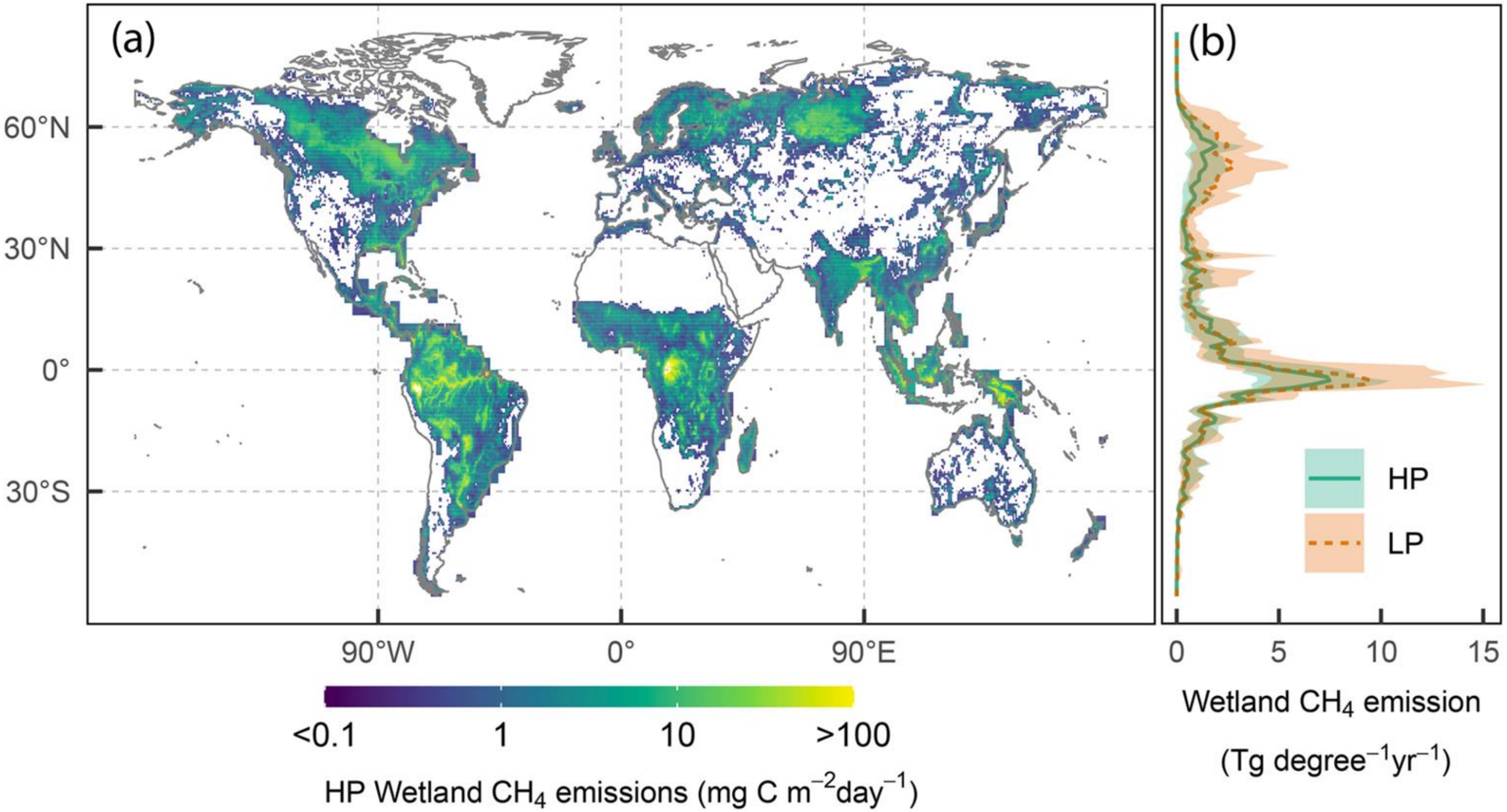
Diffuse Sources

Saunois et al. (2020)

2.2.1 Processes that Emit and Remove Atmospheric CH_4

Diffuse emission sources that occur over large spatial areas require precise measurements.

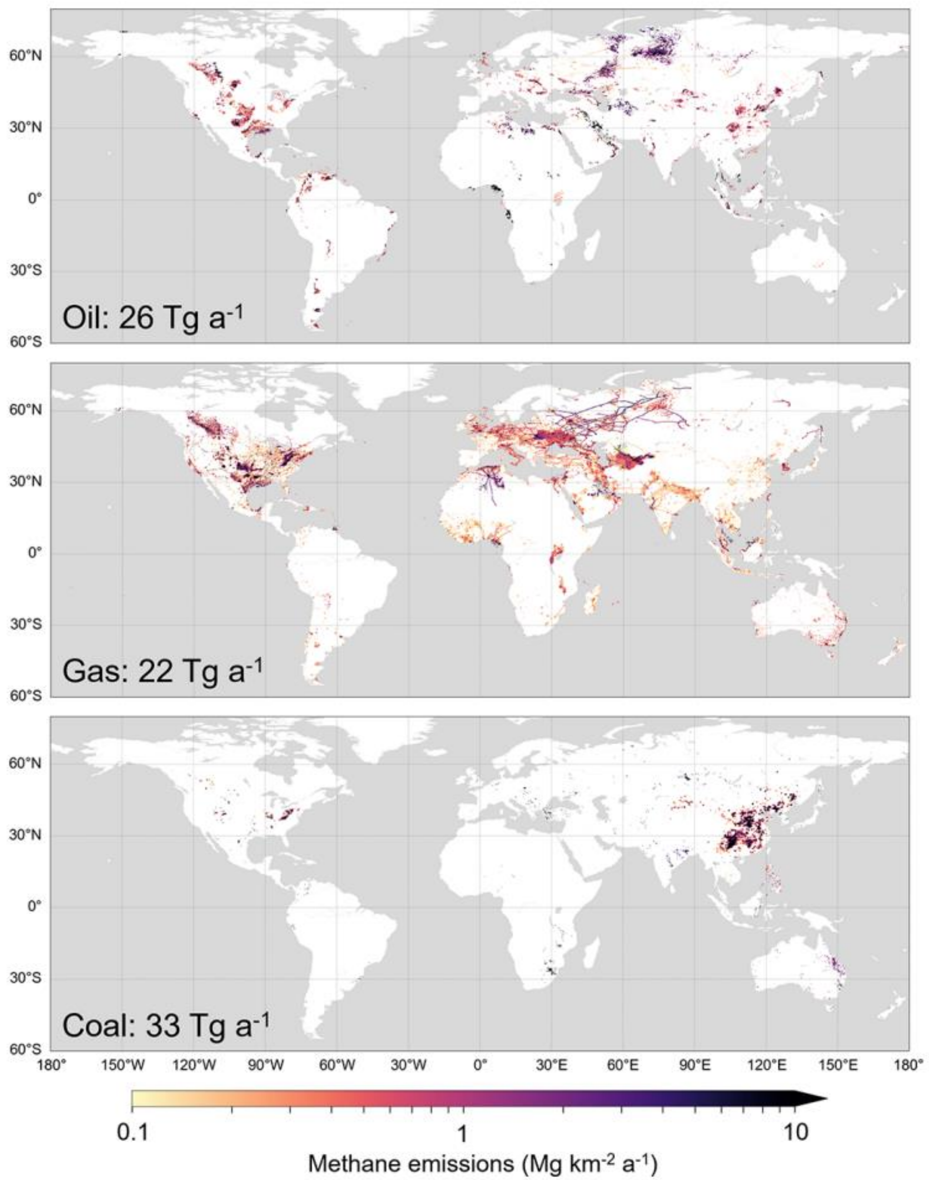
Model Estimate: Mean Wetland CH_4 Emissions During 2010–2012



Ma et al. (2022)

For wetlands, clouds in the tropics and low solar backscatter at high latitudes complicate measurements from space.

2.2.1 Processes that Emit and Remove Atmospheric CH_4



Some anthropogenic sectors consist of both diffuse "area sources" and strong localized "point sources".

Examples in Gas Sector:

Diffuse Source: Residential gas distribution system

Point Source: Leak in a gas storage tank at a production site

Scarpelli et al. (2022)

2.2.1 Processes that Emit and Remove Atmospheric CH_4

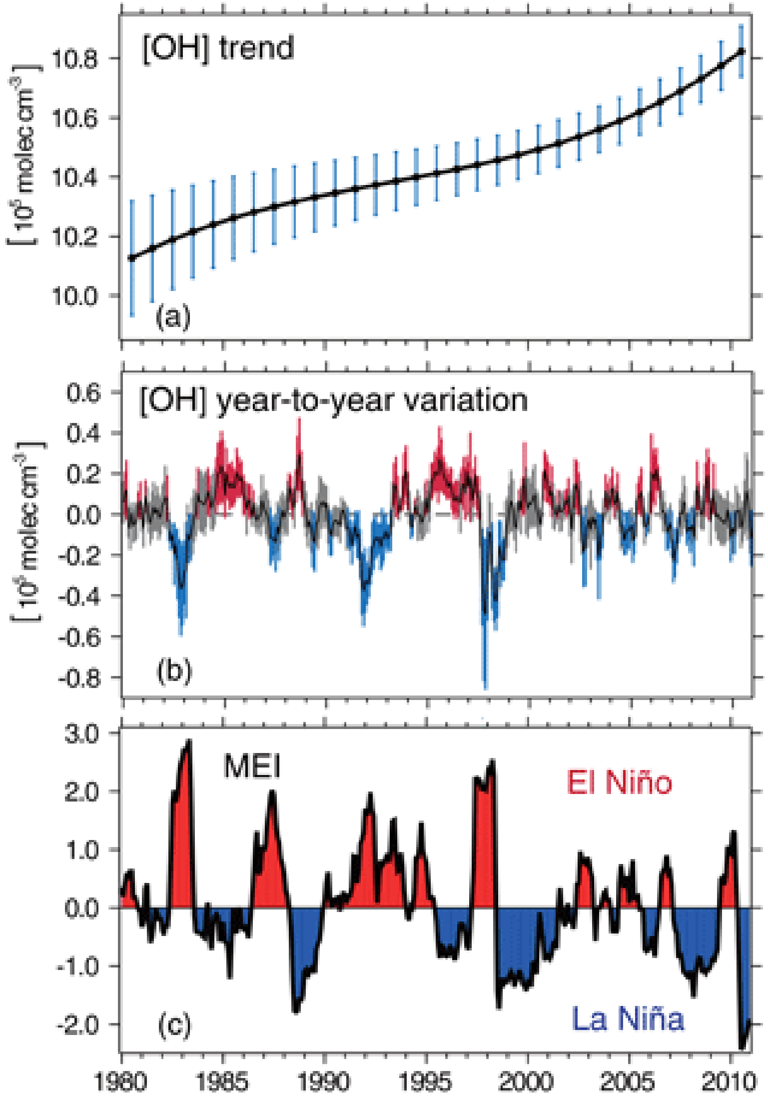
The main sink of CH_4 is a chemical reaction with atmospheric hydroxyl, **OH**. But our understanding of the global OH distribution and its trends remains uncertain.

Modeled OH Production and Loss Mechanisms

Chemical reaction	Mean ± SD	%
Production	209 ± 12	–
$O(^1D) + H_2O$	96 ± 2	46 %
$NO + HO_2$	63 ± 4	30 %
$O_3 + HO_2$	26 ± 3	13 %
Other	24 ± 7	12 %
Loss*	209 ± 12	–
$CO + OH$	82 ± 4	39 %
$CH_4 + OH$	32 ± 1	15 %
$CH_2O + OH$	12 ± 1	6 %
Isoprene + OH	13 ± 1	6 %
Other	70 ± 5	33 %

Zhao et al. (2020)

Teramoles Per Year



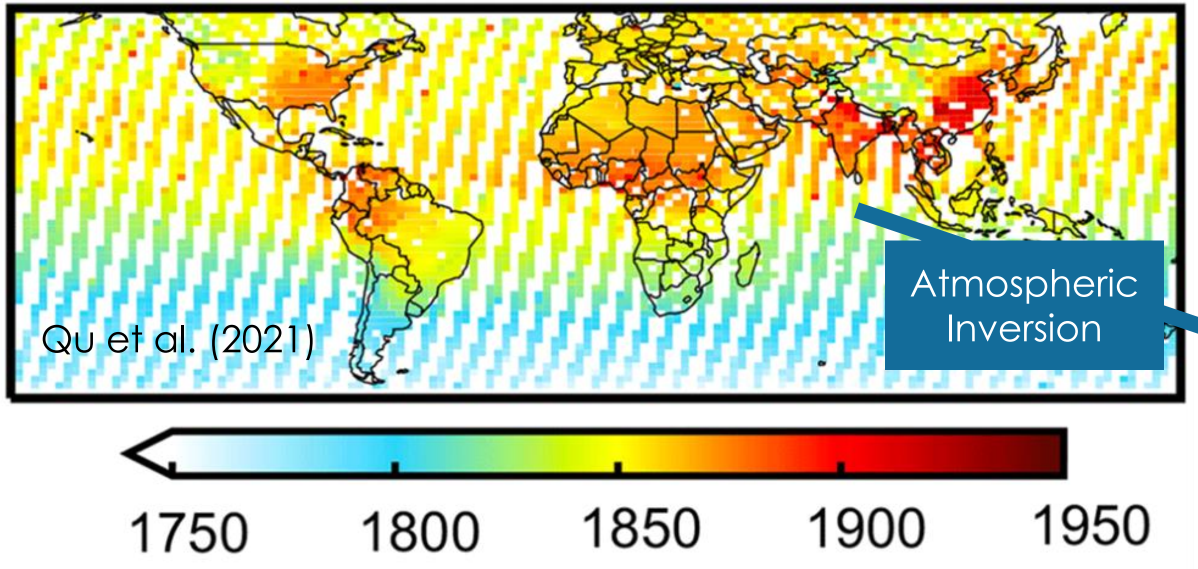
Long-term trends in OH still under debate (potentially due to increasing ozone, for example).

Inter-annual variability in OH may be due to ENSO -> variability in biomass burning, i.e., CO emissions.

2.2.2 Estimating CH_4 Emissions on Regional/National Scales

High precision global satellites (e.g., GOSAT) can estimate average annual emissions at country scales.

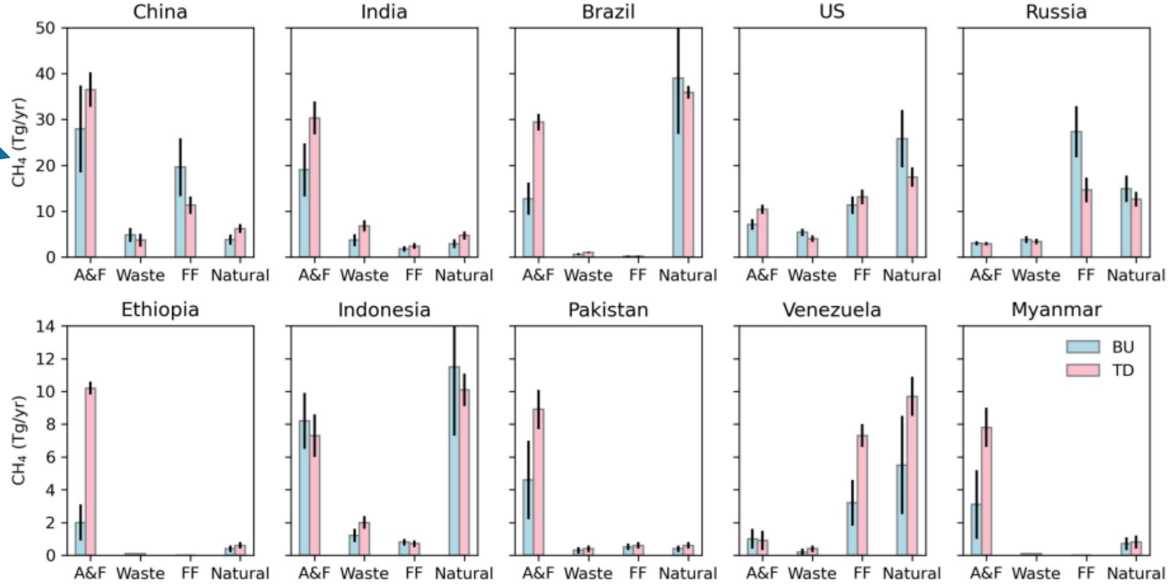
2019 GOSAT Mean XCH_4



Qu et al. (2021)

Atmospheric Inversion

Top-Down (Pink) vs. Bottom-Up (Blue) Emission Comparisons by Country



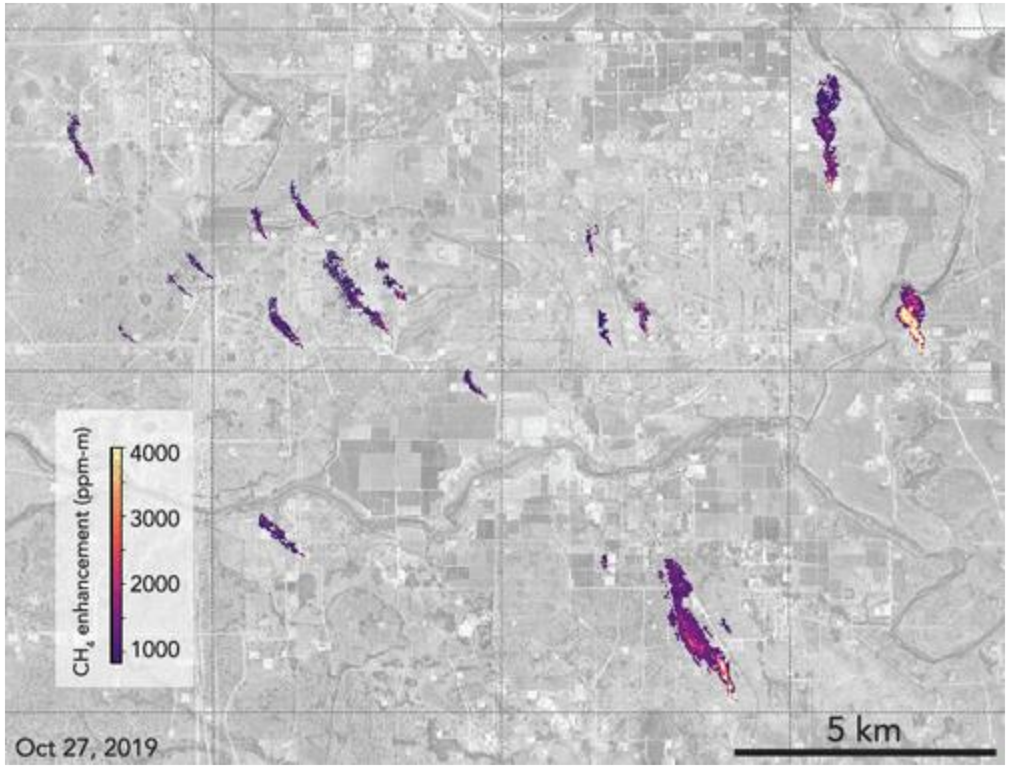
Worden et al. (2021)

A lack of major land sinks simplifies CH_4 inverse problems compared to CO_2, though strong uncertainties remain (e.g., global OH concentration, vertical transport in tropics).

2.2.3 Estimating CH_4 Emissions from Intense, Localized Sources

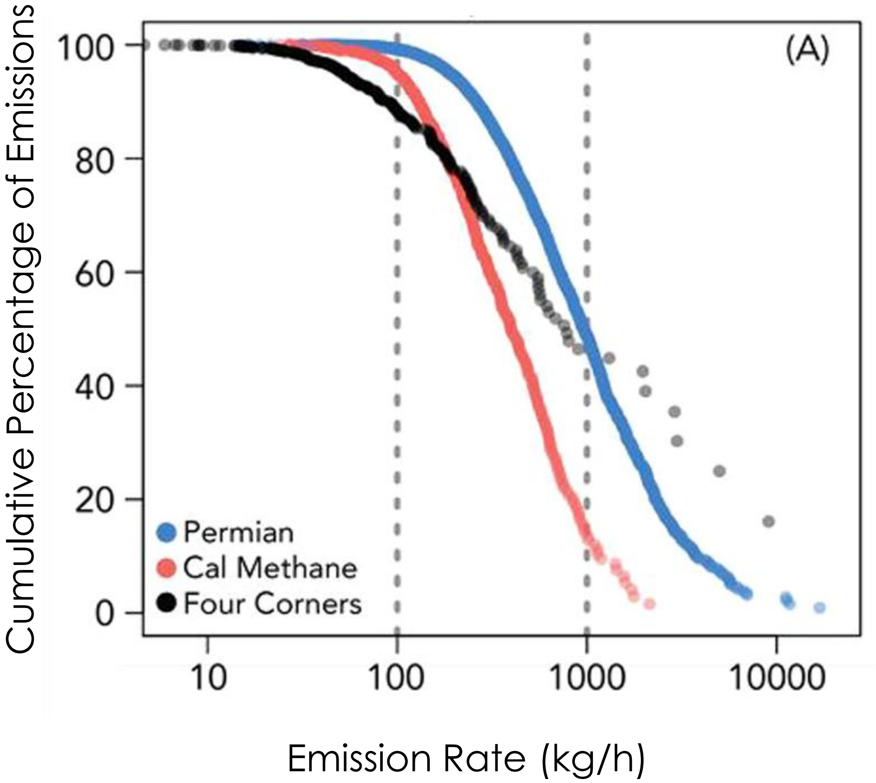
Airborne studies have shown the prevalence of "super-emitting" point sources in certain emission sectors.

O&G Super-Emitters Plumes in Permian Basin



Cusworth et al. (2021)

Power-Law Distribution of Super-Emitters



These point sources/super-emitters can be highly sporadic/intermittent in nature.

Generally, follow power-law distribution:
1% of infrastructure can make up ~50% of total basin's CH_4 emissions.

2.2.3 Estimating CH_4 Emissions from Intense, Localized Sources

Super-emitters are a global phenomenon.

Global "Ultra-Emitters" Detected by Sentinel-5p TROPOMI

Lauvaux et al. (2022)

TROPOMI instrument sensitive to ultra-emitting CH_4 sources (>10,000 kg CH_4 h^{-1})

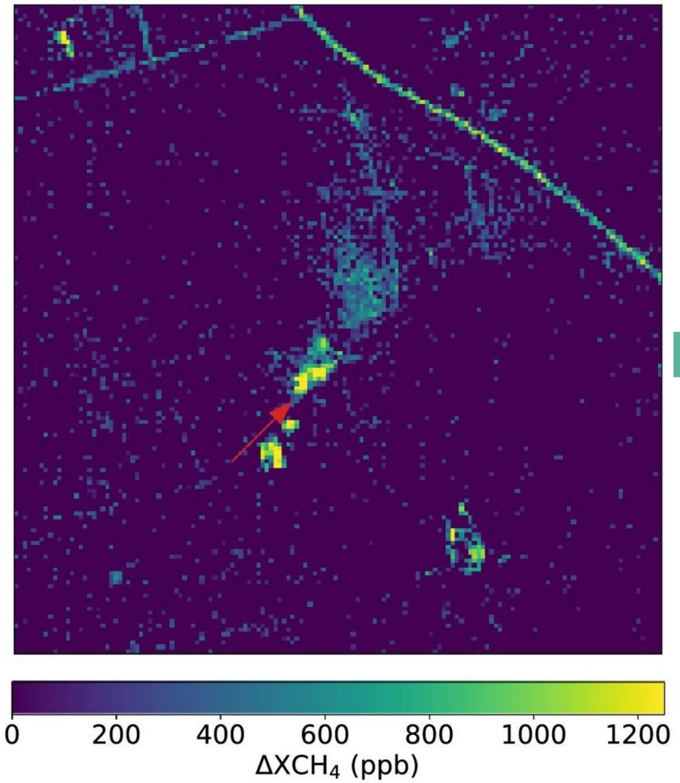
Geolocation accuracy limited to spatial resolution of measurement (~5 x 7 km pixels)

These ultra-emitters estimated to make up 12% of global O&G emissions

2.2.3 Estimating CH_4 Emissions from Intense, Localized Sources

Lower-precision, high-spatial resolution “plume mappers” quantify emissions from single facilities.

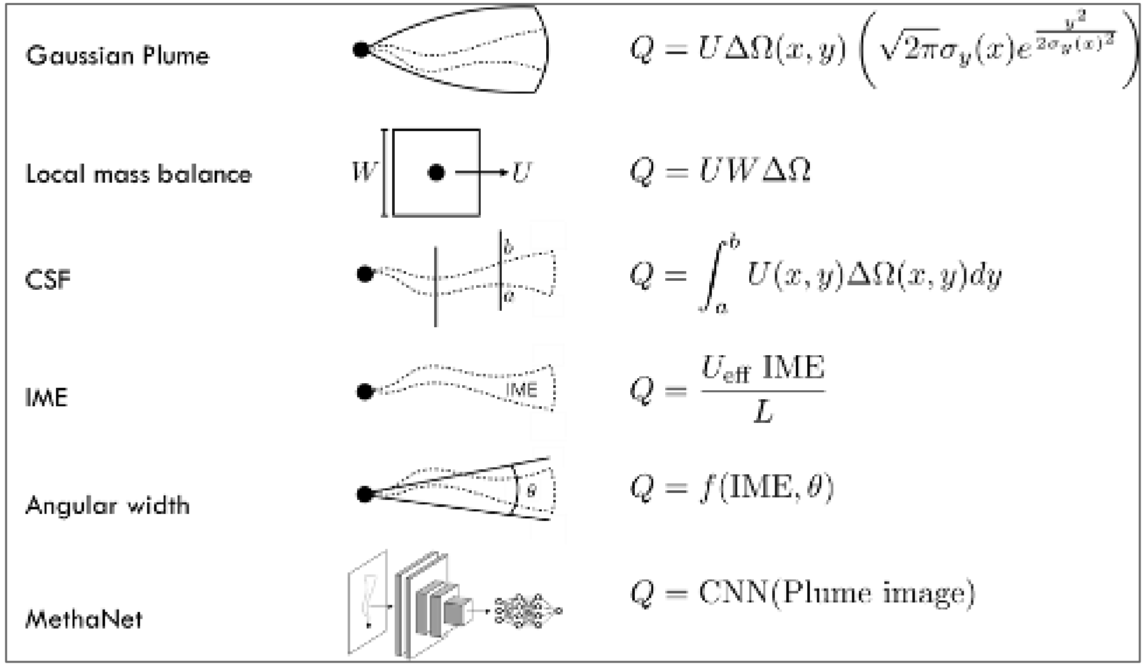
CH_4 Plume Detected in Shanxi, China by PRISMA Satellite



Guanter et al. (2021)

Multiple approaches to estimate an emission rate from plume imagery

Plume Emission Estimation Algorithms



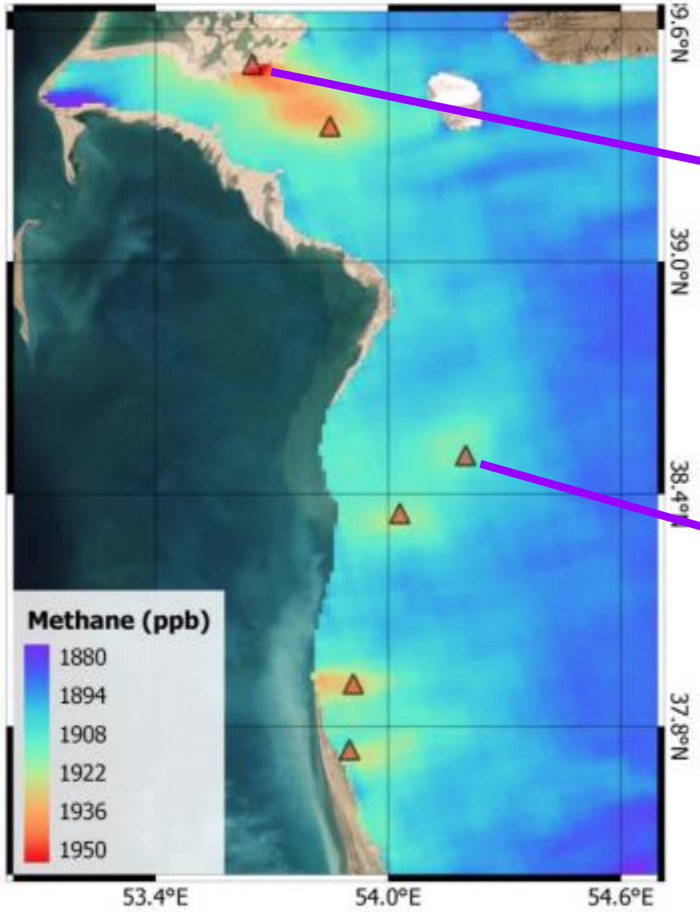
Jacob et al. (2022)

There is ongoing work to ground-validate these plume-scale emission estimation approaches.

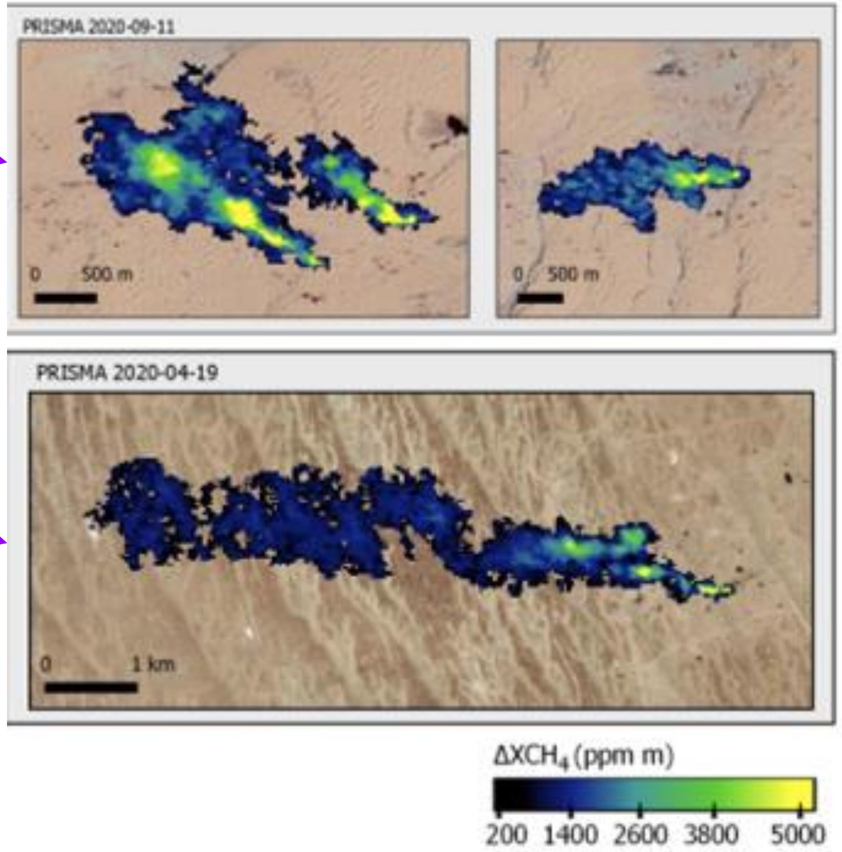
2.2.3 Estimating CH_4 Emissions from Intense, Localized Sources

Current high-resolution plume mappers have limited temporal/spatial capacities, but ***tip-and-cue*** with coarser-resolution instruments can be employed to understand facility-scale emissions.

Mean 2018–2020 XCH_4 from TROPOMI in Turkmenistan

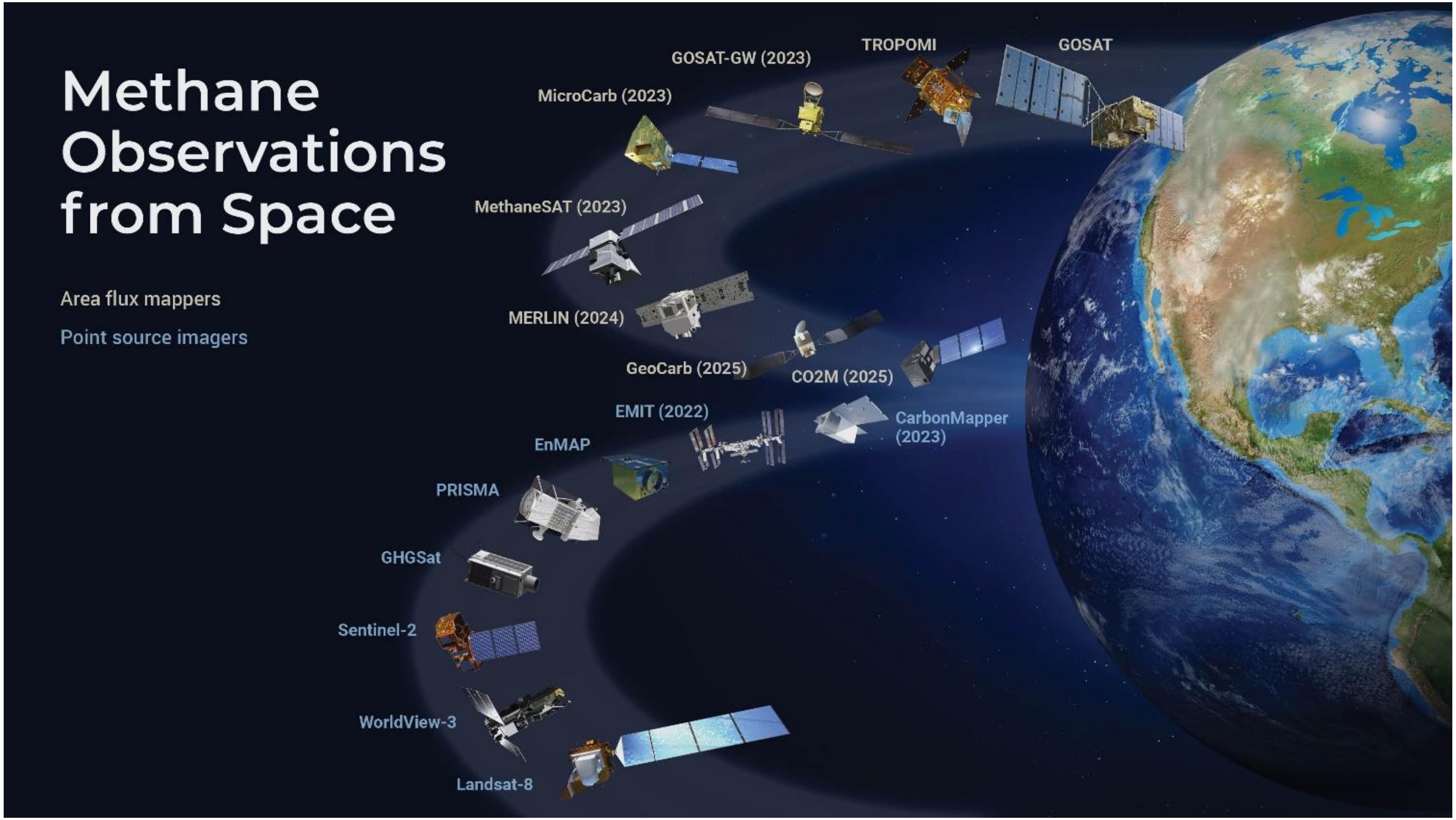


PRISMA Plume Detections Resulting from Tip-and-Cue



Irakulis-Loitxate et al. (2021)

When data are fused properly, current and future satellite missions can be used to jointly estimate global to regional budgets and identify large point sources.

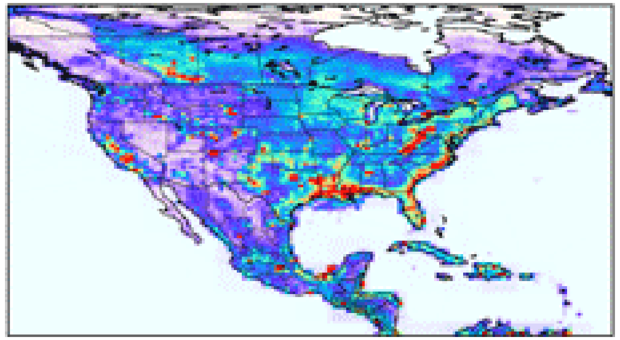


Jacob et al. (2022)

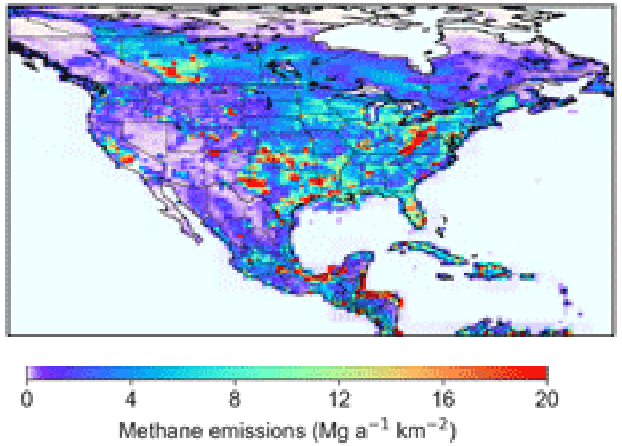
Examples of How CH_4 Information can be Used to Inform Inventories and Mitigation

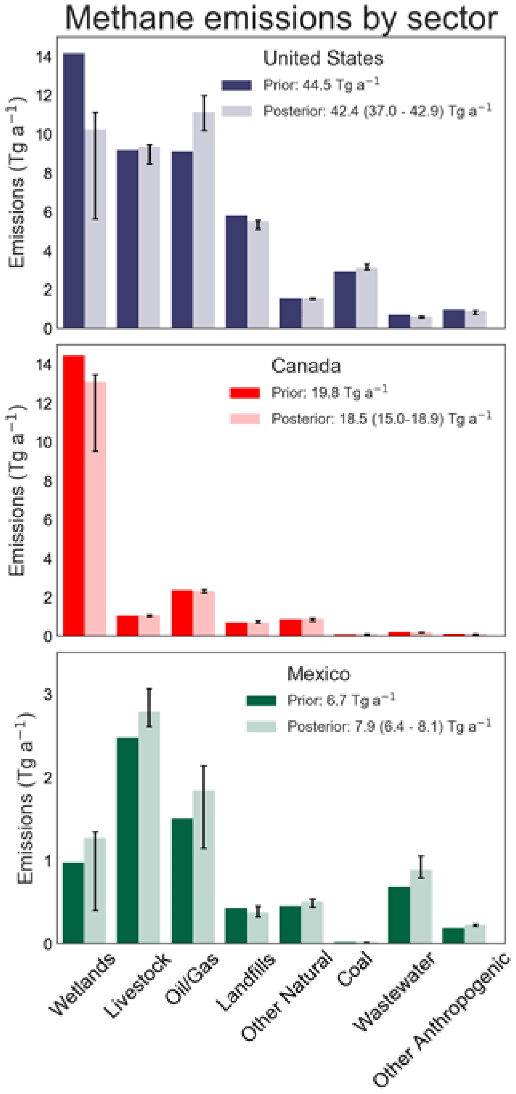
Like CO_2, inversions at global and regional scales can be used to compare against bottom-up inventories.

Bottom-Up Inventory (prior)



Top-Down Inventory (posterior)





Source (Tg a^{-1})	Prior estimate[a]	Posterior estimate[b]	Sensitivity[c]
Natural	15.7	11.8 (7.1–12.7)	0.63
Wetlands	14.2	10.2 (5.6–11.1)	0.71
Open fires	0.5	0.4 (0.4–0.5)	0.13
Termites	0.6	0.6 (0.6–0.6)	−0.02
Geological seeps	0.5	0.5 (0.5–0.5)	0.06
Anthropogenic	28.7	30.6 (29.4–31.3)	0.53
Livestock			
Enteric fermentation	6.7	6.9 (6.3–7.0)	0.16
Manure management	2.5	2.5 (2.1–2.5)	0.22
Oil and natural gas			
Gas production	4.4	5.4 (4.9–5.9)	0.28
Oil production	2.3	3.1 (2.7–3.6)	0.53
Gas transmission	1.1	1.1 (1.1–1.2)	0.03
Gas processing	0.9	1.1 (1.0–1.2)	0.41
Gas distribution	0.5	0.4 (0.4–0.4)	0.35
Landfills			
Municipal	5.2	5.0 (4.7–5.0)	0.26
Industrial	0.6	0.5 (0.5–0.5)	0.13
Coal mining			
Underground	2.2	2.4 (2.3–2.5)	0.22
Surface	0.5	0.5 (0.4–0.5)	0.30
Abandoned	0.2	0.3 (0.3–0.3)	0.10
Wastewater			
Municipal	0.5	0.4 (0.4–0.4)	0.09
Industrial	0.2	0.2 (0.1–0.2)	0.16
Rice cultivation	0.5	0.4 (0.3–0.5)	0.28
Other anthropogenic[d]	0.5	0.4 (0.4–0.5)	0.05
Total source	44.5	42.4 (37.0–42.9)	0.64

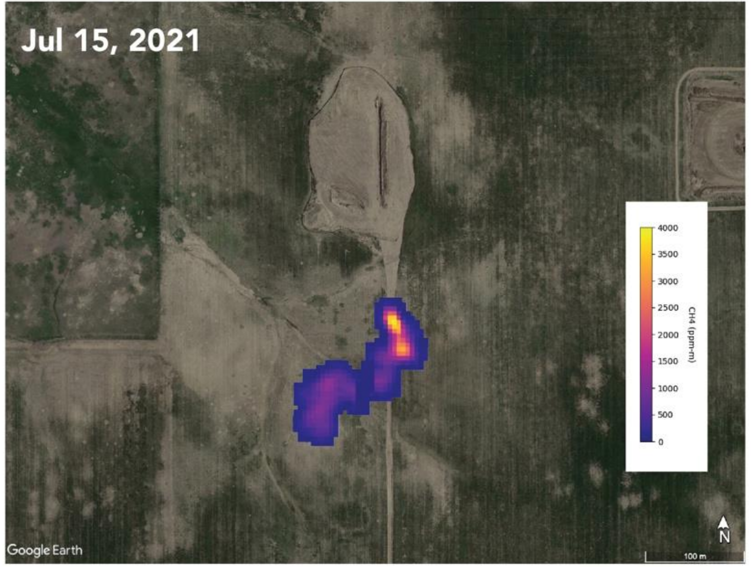
Maasakkers et al. (2021)

Examples of How CH_4 Information can be Used to Inform Inventories and Mitigation

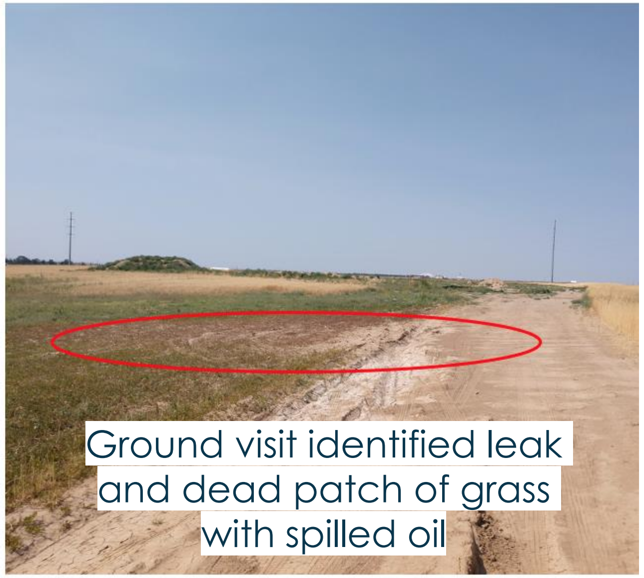
For localized plume sources, information can be used for inventories and/or for direct ground follow-up.

Example: Leaking Pipeline Discovered from Aircraft in Colorado

Pipeline leak: Denver-Julesberg

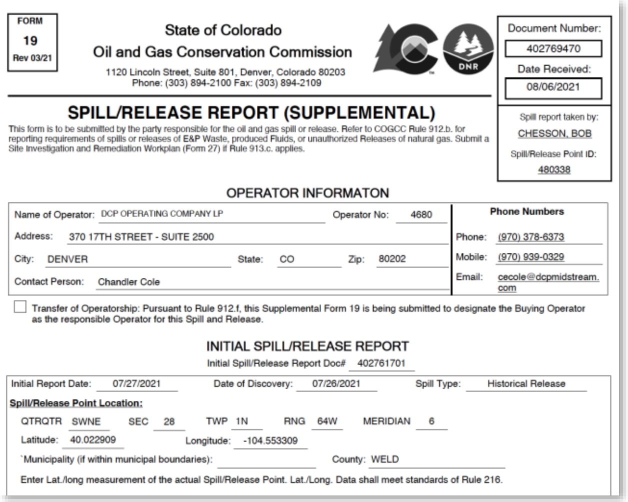


Information shared with State of Colorado



Ground visit identified leak and dead patch of grass with spilled oil

Leak fixed; report issued



FORM
19
Rev 03/21

State of Colorado
Oil and Gas Conservation Commission
1120 Lincoln Street, Suite 801, Denver, Colorado 80203
Phone: (303) 894-2100 Fax: (303) 894-2109

Document Number: 402769470
Date Received: 08/06/2021

SPILL/RELEASE REPORT (SUPPLEMENTAL)

This form is to be submitted by the party responsible for the oil and gas spill or release. Refer to COGCC Rule 912.b. for reporting requirements of spills or releases of E&P Waste, produced Fluids, or unauthorized Releases of natural gas. Submit a Site Investigation and Remediation Workplan (Form 27) if Rule 913.c. applies.

Spill report taken by: CHESSON, BOB
Spill/Release Point ID: 480338

OPERATOR INFORMATON

Name of Operator: DCP OPERATING COMPANY LP
Operator No: 4680
Address: 370 17TH STREET - SUITE 2500
City: DENVER
State: CO
Zip: 80202
Contact Person: Chandler Cole

Phone Numbers
Phone: (970) 378-6373
Mobile: (970) 939-0329
Email: cecole@dcpmidstream.com

☐ Transfer of Operatorship: Pursuant to Rule 912.f, this Supplemental Form 19 is being submitted to designate the Buying Operator as the responsible Operator for this Spill and Release.

INITIAL SPILL/RELEASE REPORT

Initial Spill/Release Report Doc# 402761701

Initial Report Date: 07/27/2021
Date of Discovery: 07/26/2021
Spill Type: Historical Release

Spill/Release Point Location:

QTRQTR SWNE
SEC 28
TWP 1N
RNG 64W
MERIDIAN 6
Latitude: 40.022909
Longitude: -104.553309
`Municipality (if within municipal boundaries):
County: WELD

Enter Lat./long measurement of the actual Spill/Release Point. Lat./Long. Data shall meet standards of Rule 216.

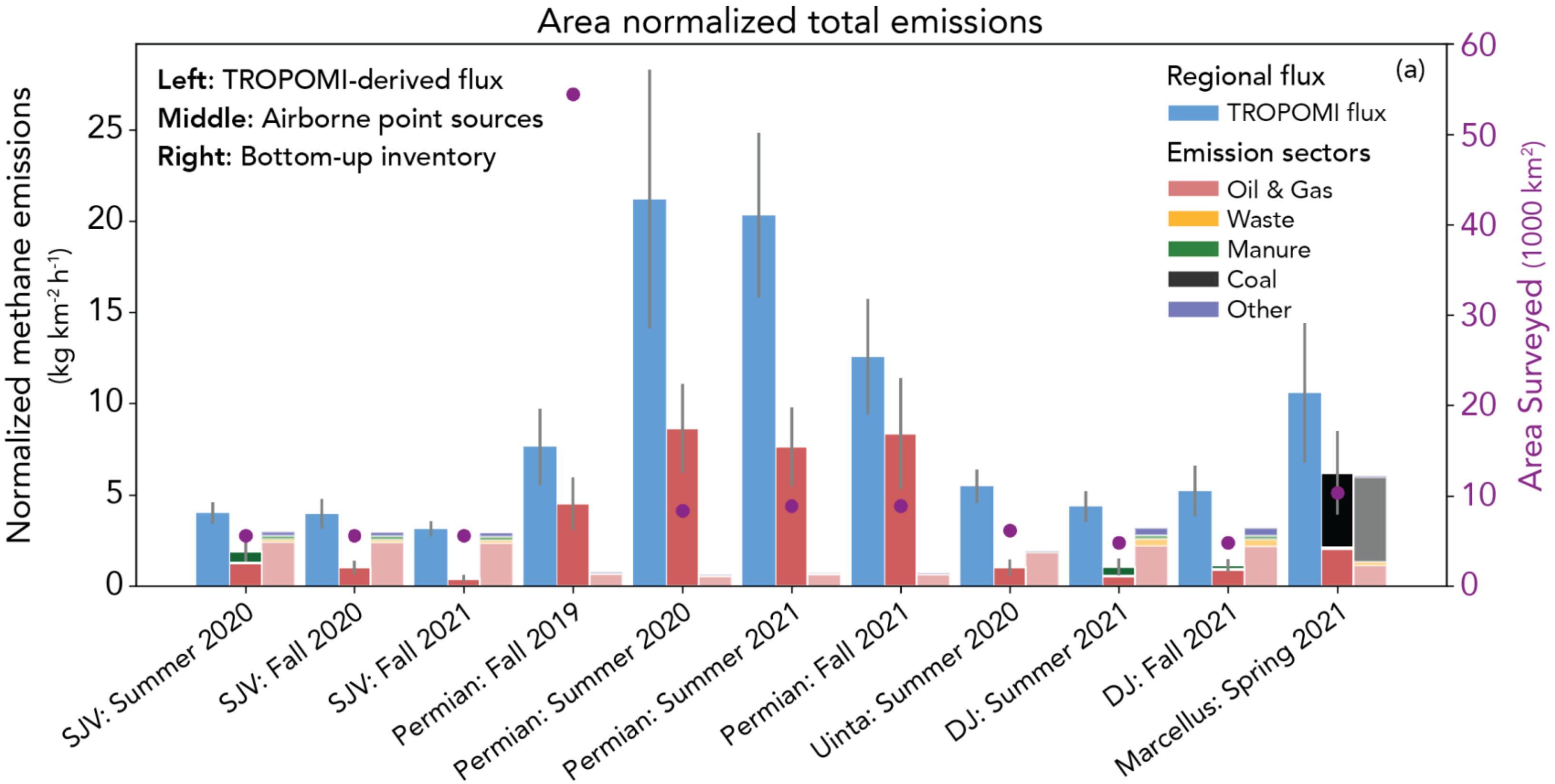
Cusworth et al. (2022)

"Hand-off" top-down information to agencies to prompt corrective action

Examples of How CH_4 Information can be Used to Inform Inventories and Mitigation

Localized point sources can be compared to regional inversions to contextualize impact of these few, but large emitters.

Summary of methane emissions for each surveyed basin



For example, in many U.S. basins, local point sources make up 20–60% of total CH_4 budget.

Cusworth et al. (2022)

What have we learned from CH_4?

- Like CO_2, global emission budgets can be derived from satellite observations.

- The main sink of CH_4 is atmospheric OH.

- CH_4 emitters tend to be either diffuse (e.g., wetlands) or localized point sources (e.g., gas leak).
  - High-precision/coarse-resolution satellites are best suited for global/regional inversion estimation.
  - Low-precision/fine-resolution satellites are best suited for detecting, geolocating, and quantifying localized point sources.

- Information from CH_4-sensing satellites can be used to compare against bottom-up inventories and can be used to motivate action for localized point sources that are unexpected (e.g., leaks).

Contacts

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  - Daniel Cusworth: dcusworth@arizona.edu
  - Sean McCartney: sean.mccartney@nasa.gov
- Training Webpage:
  - https://appliedsciences.nasa.gov/join-mission/training/english/arset-atmospheric-co2-and-ch4-budgets-support-global-stocktake
- ARSET Website:
  - https://appliedsciences.nasa.gov/arset
- Twitter: @NASAARSET

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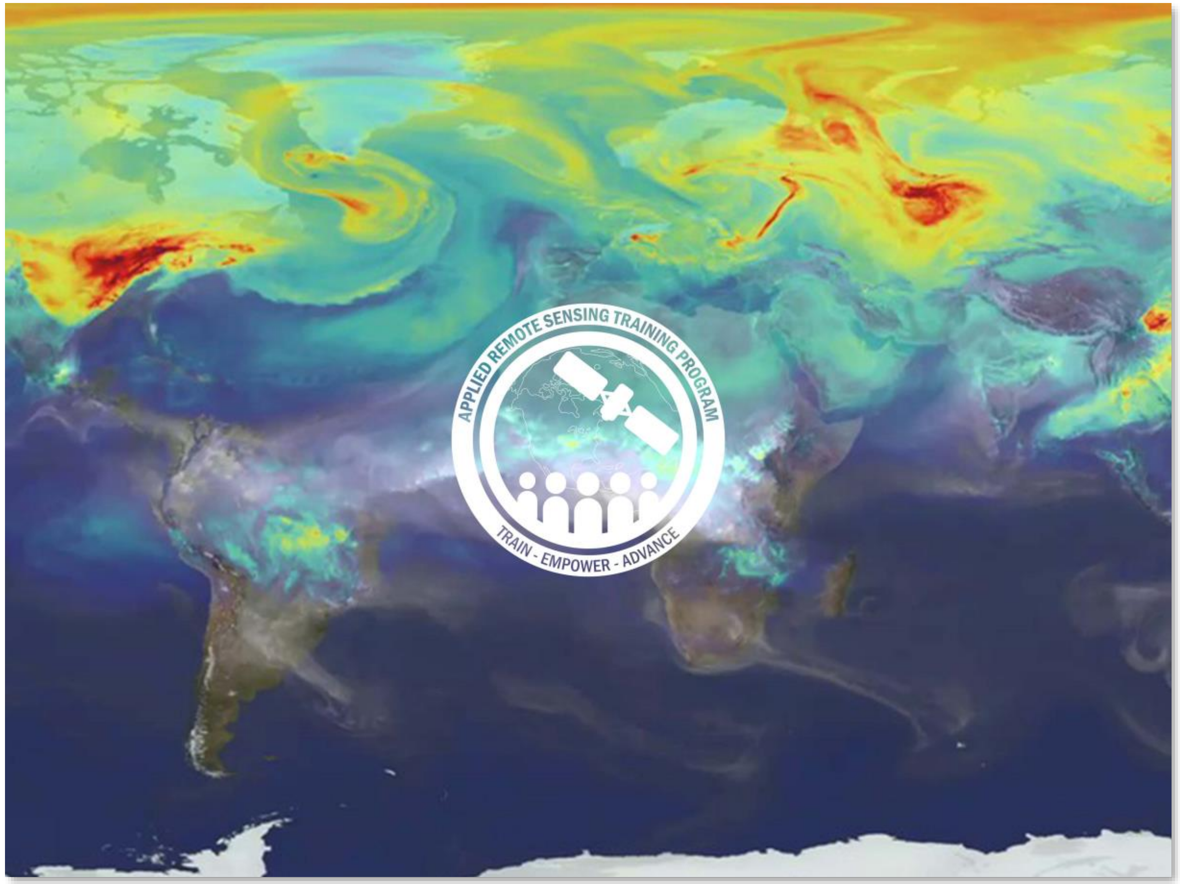
Questions?

- Please enter your questions in the Q&A box. We will answer them in the order they were received.
- We will post the Q&A to the training website following the conclusion of the webinar.




APPLIED REMOTE SENSING TRAINING PROGRAM
TRAIN - EMPOWER - ADVANCE

Thank You!