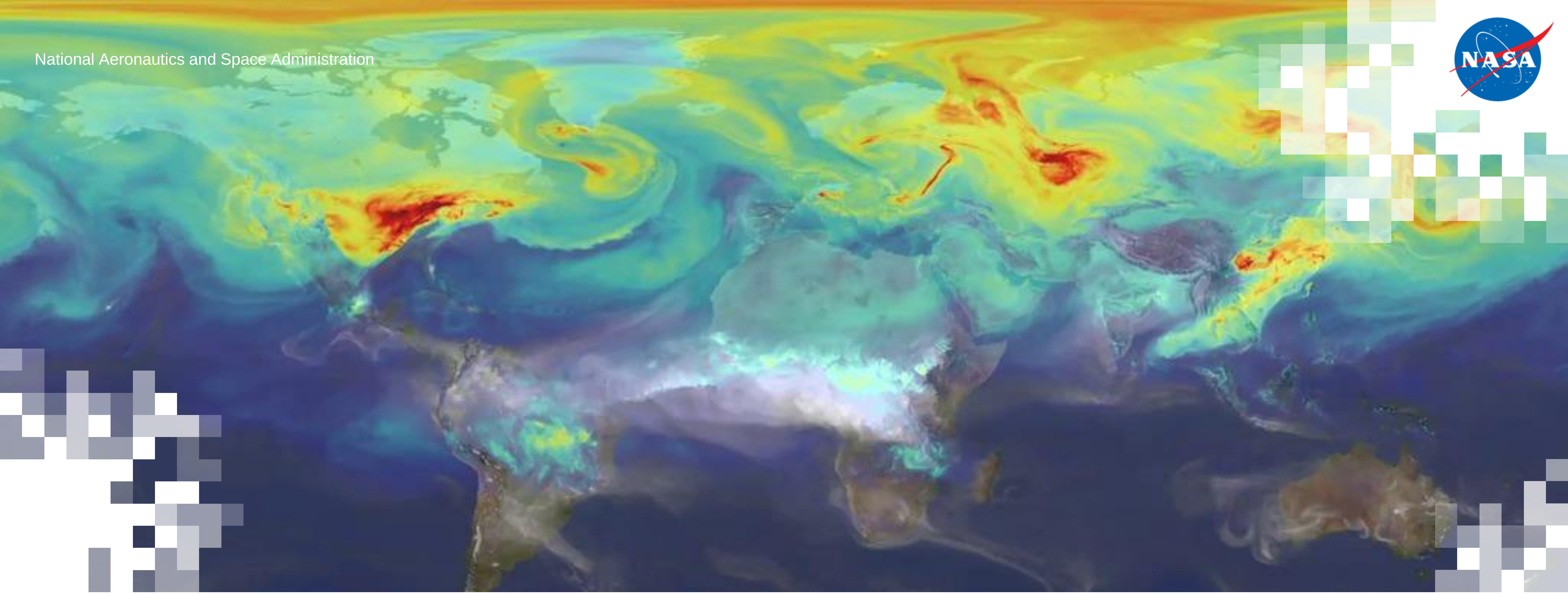
National Aeronautics and Space Administration



Atmospheric CO_2 and CH_4 Budgets to Support the Global Stocktake

Part 3: Top-Down and Bottom-Up Inventories to Support the Global Stocktake

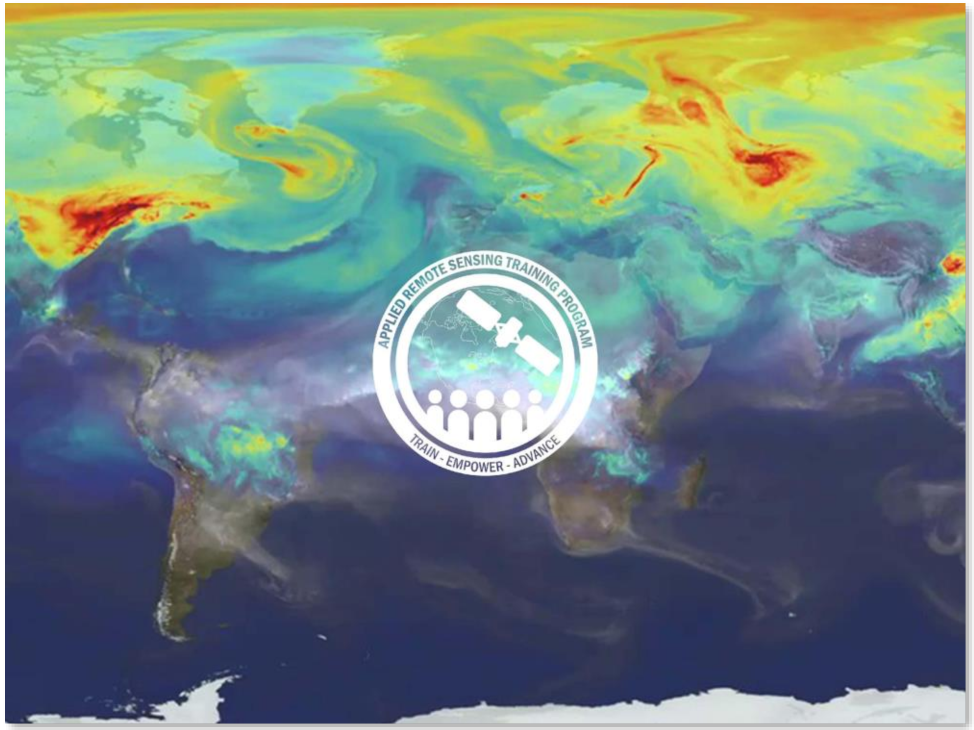
Brendan Bryne, Dan Cusworth, David Crisp, Sean McCartney

May 25, 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 Certificates

- **Homework:**
  - One homework assignment for the intermediate sessions submitted via Google Forms
    - Available on training website
- **Certificate of Completion**
  - Attend all three live introductory webinars
  - Complete the homework assignment by **Wednesday, June 8**
  - You will receive certificates approximately two months after completion of the course from: marines.martins@ssaihq.com

Webinar Agenda

Part 1. Wednesday, May 11, 2022

Tracking Greenhouse Gas Emissions and Removals – The Paris Agreement

- Tracking greenhouse gas emissions and removals to meet the Mitigation objectives of the Paris Agreement
- The need for transparent methods for tracking greenhouse gas emissions and removals at national scales
- National inventories and top-down atmospheric budgets for tracking greenhouse gases

Part 2. Wednesday, May 18, 2022

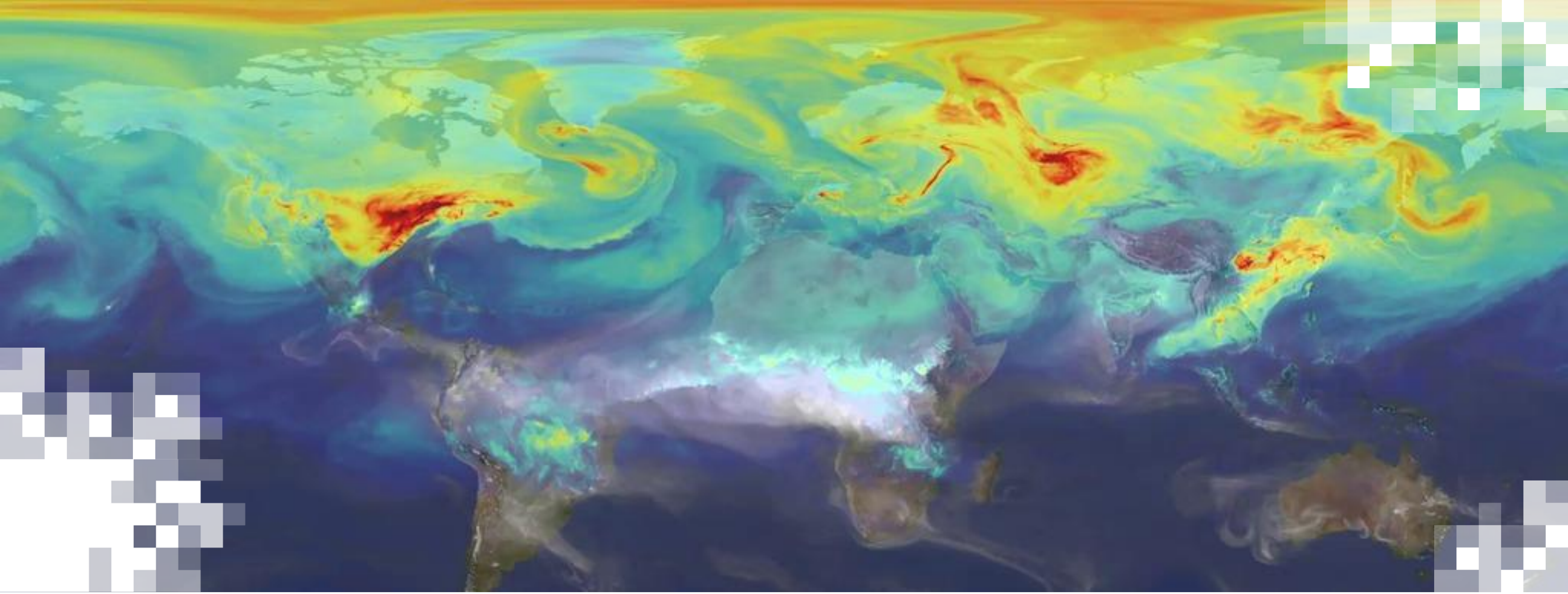
How do we create atmospheric budgets of carbon dioxide (CO_2) and methane (CH_4) on policy-relevant national to sub-national scales?

- What human activities and natural processes control emissions and removals of CO_2 and CH_4?
- How well can we measure CO_2 and CH_4 with existing ground-based, airborne, and space-based sensors?
- How are these data used to estimate emissions and removals of these gases on national scales?

Part 3. Wednesday, May 25, 2022

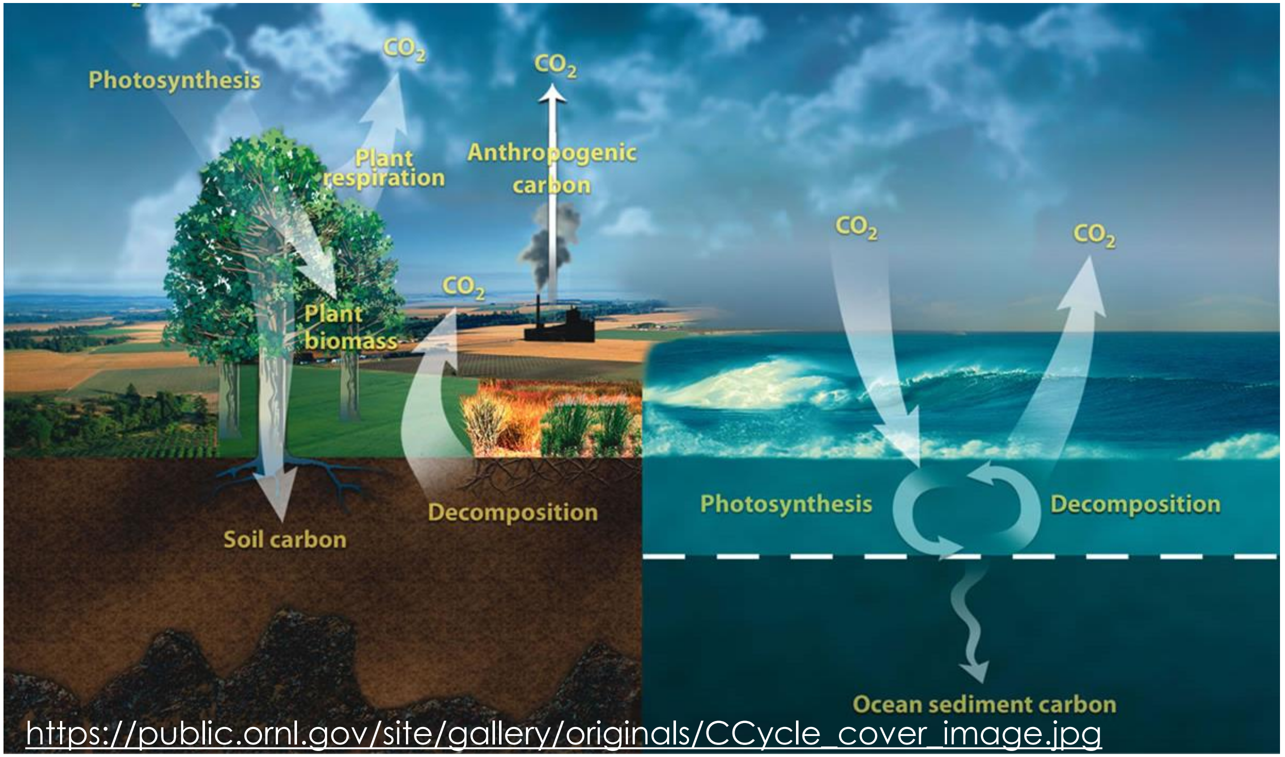
How can atmospheric CO_2 and CH_4 budgets be combined with inventories to support a more complete, accurate, and transparent global stocktake?

- Define best available products and best practices for combining these methods to develop national inventories and to assess the collective progress of those efforts towards the goals of the Paris Agreement
- Exploring "Use Cases" that illustrate the application of these methods



Review of Path Traveled So Far

Human Activities Contributing to CO_2 and CH_4 Emissions



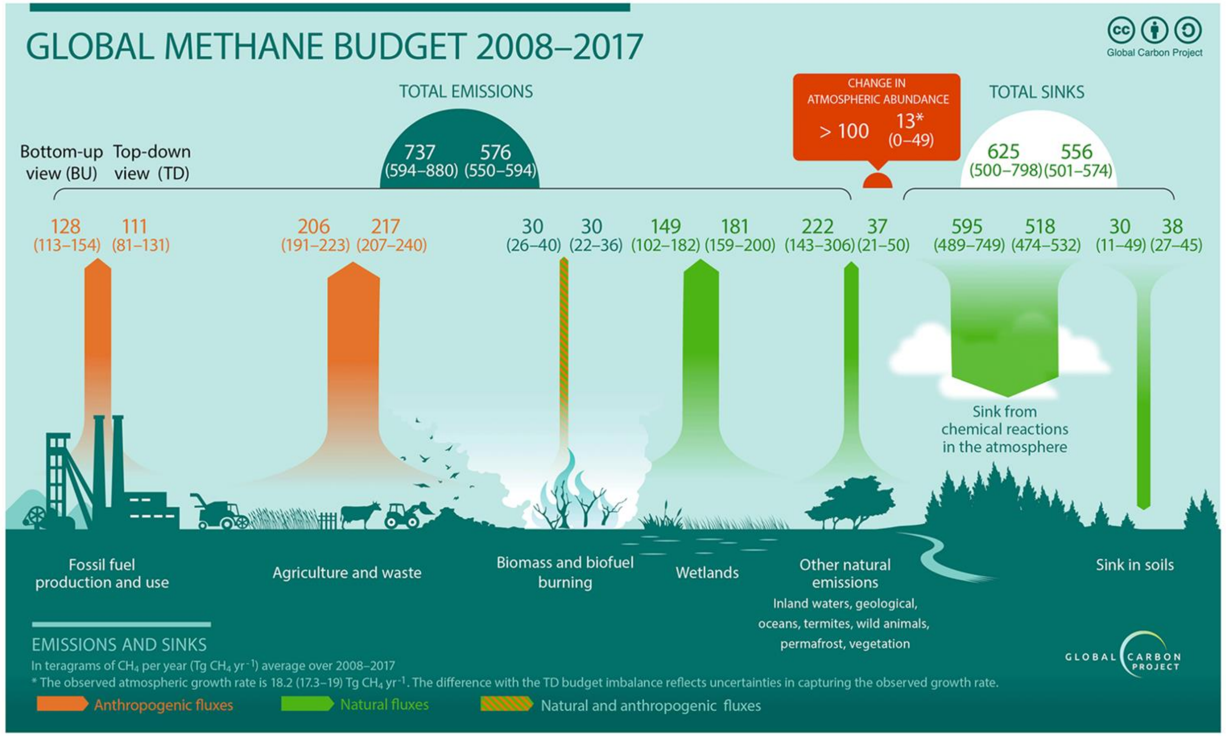
https://public.ornl.gov/site/gallery/originals/CCycle_cover_image.jpg

Human activities are adding **~40 billion tons** of carbon dioxide (CO_2) to the atmosphere each year primarily by:

- Fossil Fuel Use in the Energy Sector
- Land Use, Land Use Change, and Forestry (LULUCF)

Human activities contribute **~60% of the 0.6 billion tons** of methane (CH_4) emitted to the atmosphere each year.

- The rest is emitted primarily by natural wetlands and wildfires.

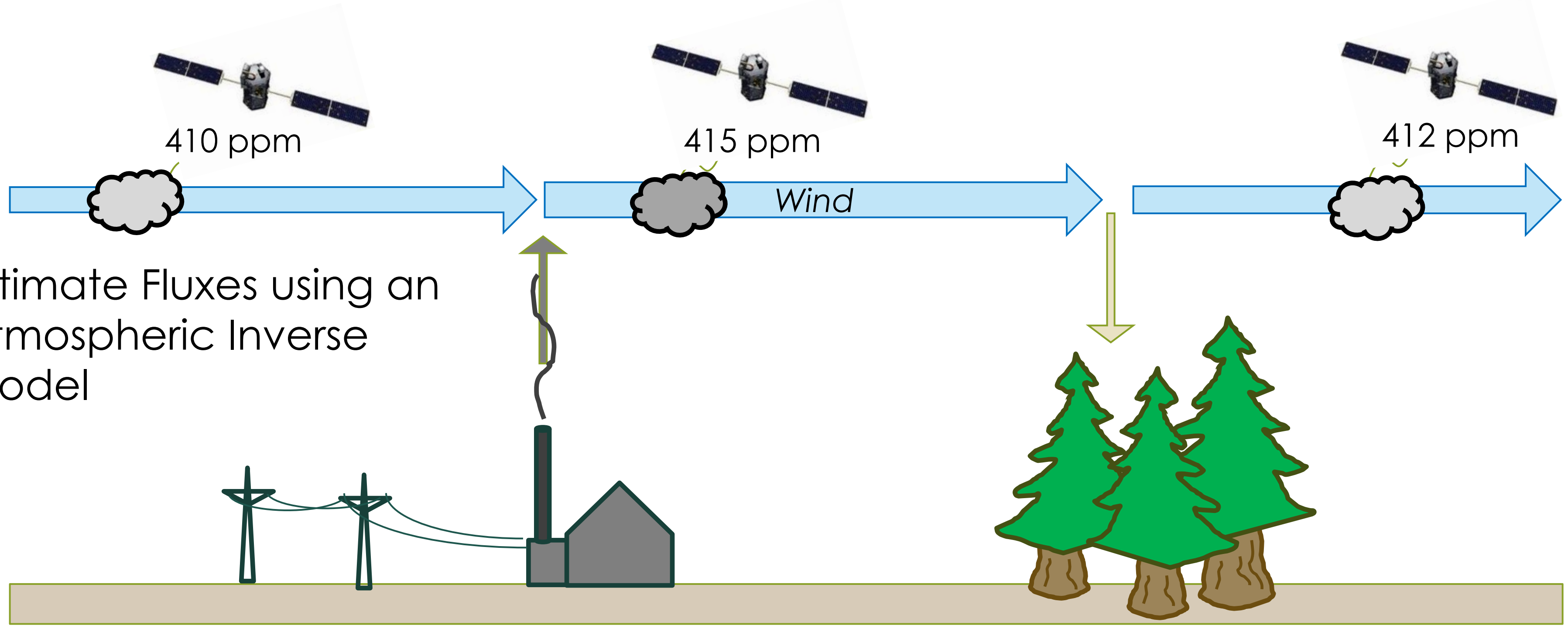


Saunois et al. (2020), https://doi.org/10.5194/essd-12-1561-2020

Natural processes are removing over half of the CO_2 produced by these human activities.
This may change as the natural carbon cycle responds to human activities and climate change.

Tracking GHG Emissions: *Bottom-Up* Inventories and *Top-Down* Atmospheric Budgets

Top-Down Atmospheric Budgets



Bottom-Up National Inventories[1]

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

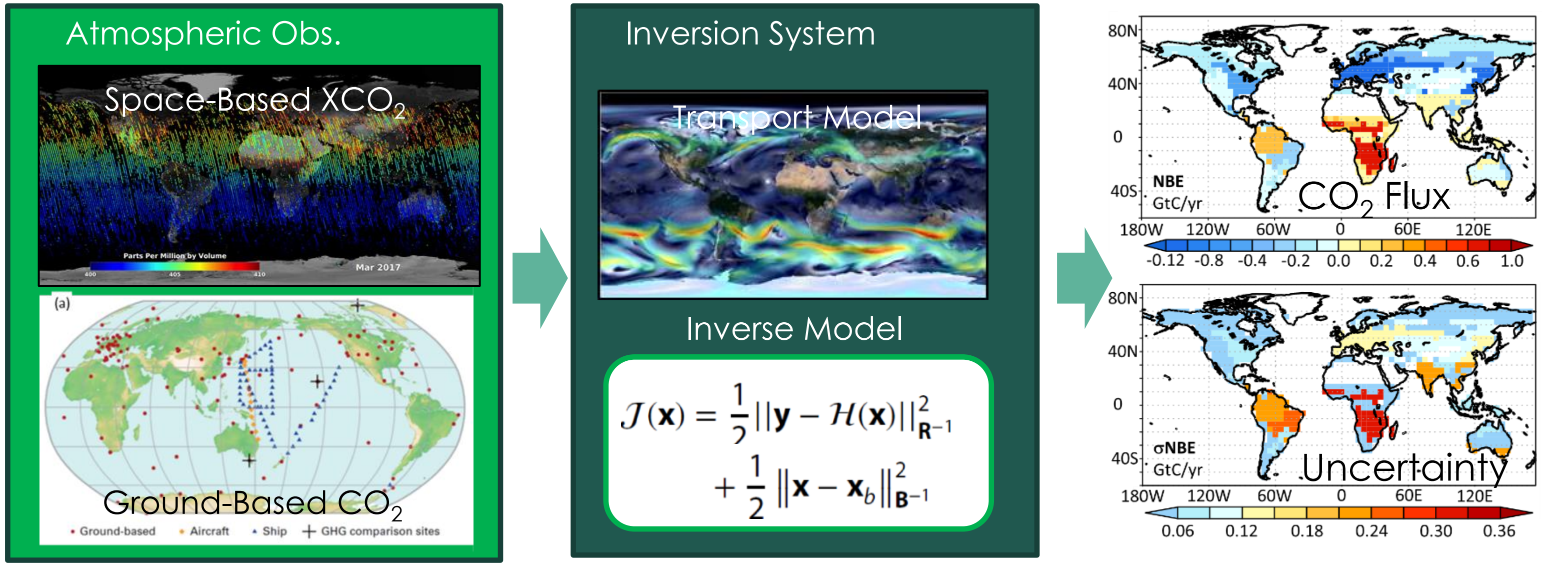
Activity × Emission Factor + Activity × Emission Factor

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

Key Assets of Bottom-Up and Top-Down Methods

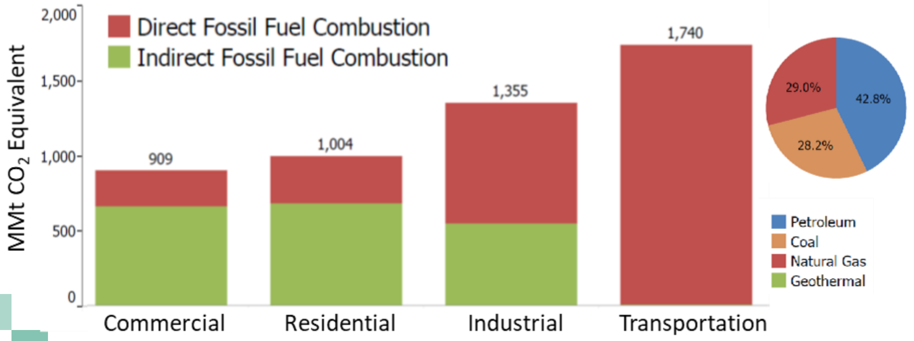
- **Bottom-Up Inventories of Greenhouse Gas Emissions and Removals**
  - Provide the best method for tracking emissions and removals by **known sources** with well-characterized ***activity data*** and ***emission factors***
  - Can yield direct insight into the **effectiveness of emissions reduction policies** for specific categories of specific sectors included in the inventory
  - Provide ***prior*** information needed for top-down atmospheric inversions
- **Top-Down Estimates of Net Greenhouse Gas Emissions and Removals**
  - Exploit the ***best available science*** for assessing **collective progress** toward the greenhouse gas emissions reduction targets
  - Offer a ***partially*** independent approach for assessing completeness of standard inventory methods based on activity data and emission factors
  - Can track emissions changes on **unmanaged lands** and **oceans** associated with human activities or climate change, which are ***not included in inventories***
  - Improve traceability of emissions **policies**, to greenhouse gas **abundances** to **climate**

Combining Bottom-Up and Top-Down Inventories to Support the Global Stocktakes



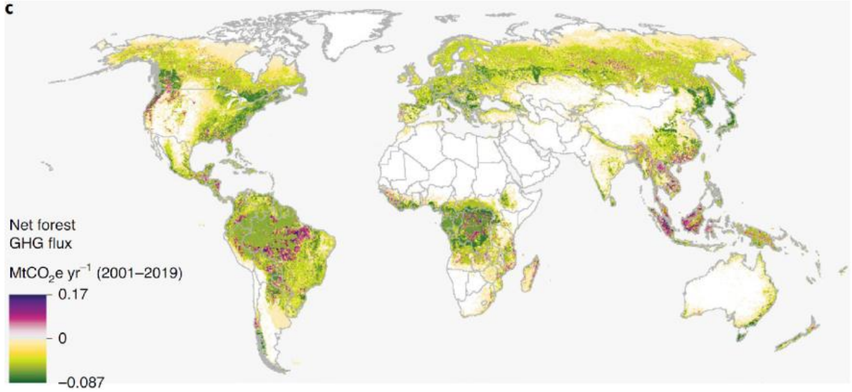
Top-Down Budgets

- Provide an integrated constraint on emissions and removals
- Can track emission changes from the natural carbon cycle caused by human activities and climate change

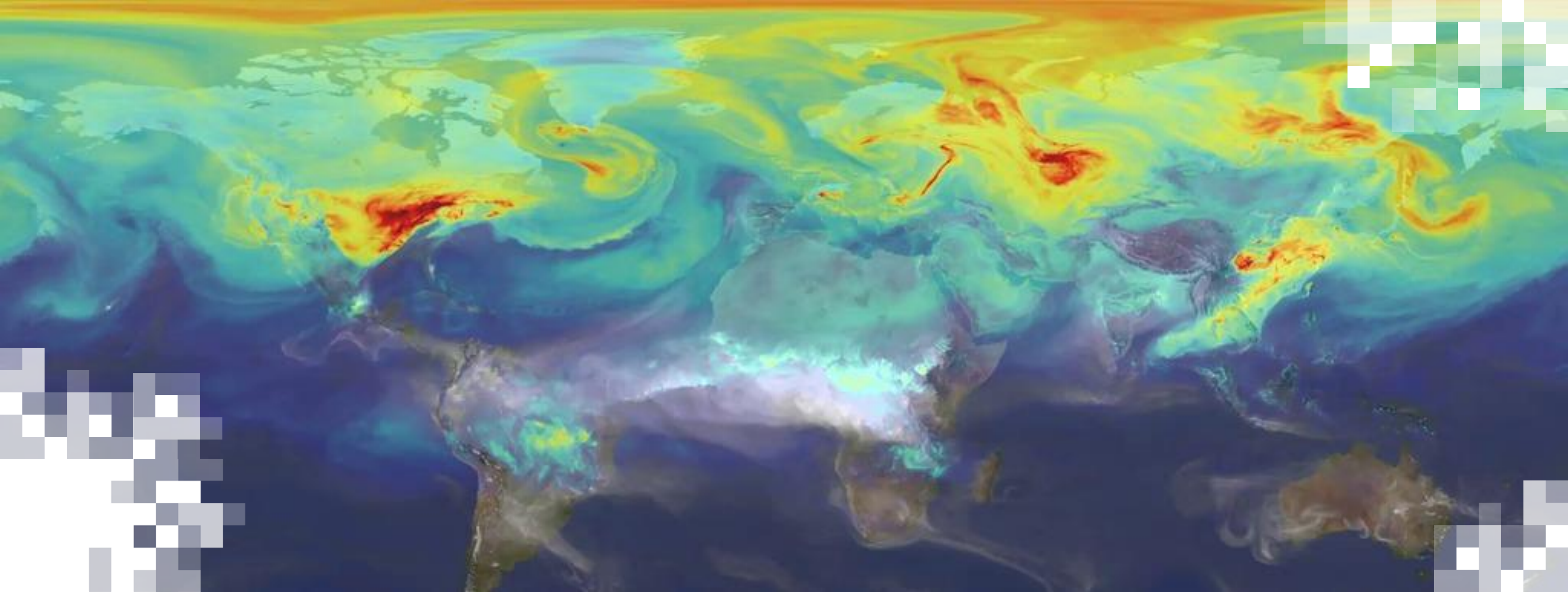


Bottom-Up Inventories

- Source-specific estimates of emissions and removals by known processes with well-characterized activity and emission factors



Harris et al. Nature Climate Change, 2021



Comparing and Combining Top-Down Budgets with Bottom-Up Inventories

Combining Bottom-up and Top-down Methods

- **In principle, bottom-up inventories and top-down flux budgets can be:**
  - **Combined** to produce a more complete and transparent inventory of emissions and removals of greenhouse gases
  - **Compared** to assess collective progress toward the goals of the UNFCCC and Paris Agreement and to track the effects of human activities and climate change on the efficiency of land, ocean, and atmospheric sinks of GHGs

- **In practice, this process is complicated because bottom-up inventories and top-down flux budgets:**
  - Do not measure the same **quantities** over the same **areas** and **time periods**
  - Have different sources of **uncertainties**

- **Here we review assets and challenges and identify gaps needing attention.**

Comparing Top-Down Budgets with Bottom-Up Inventories

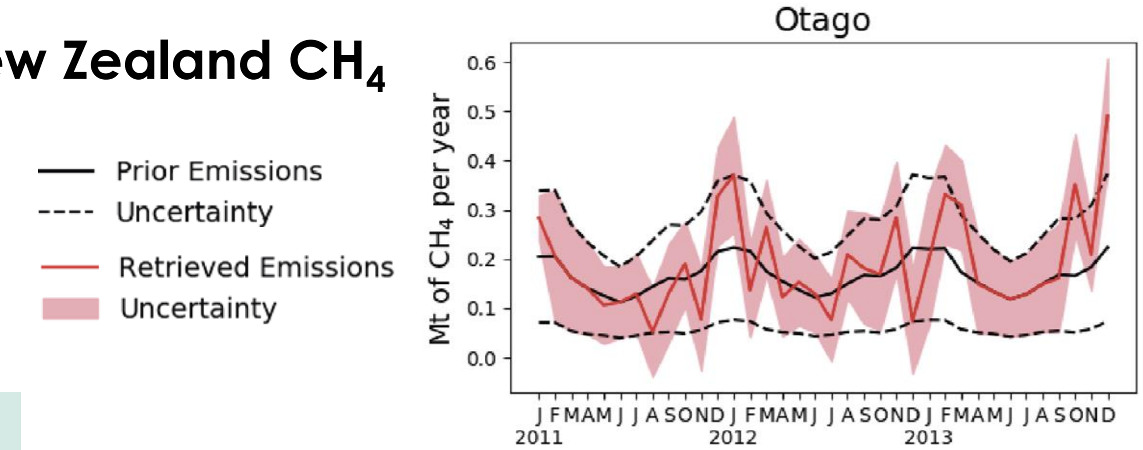
- The Intergovernmental Panel on Climate Change (**IPCC**) Taskforce on Inventories provided some guidance in their ***2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories***.
  - **Recognized** that atmospheric measurements and inverse models had **made notable advances** since the 2006 guidelines were adopted, and examined their utility in quality assessment (**QA**) and quality control (**QC**) (Vol. 1, Ch. 6)
  - **Concluded** that these methods are improving rapidly, but **were not widely established as a standard tool for verification of conventional inventories** because:
    - Limitations in existing measurement capabilities, transport errors, and other uncertainties in models can introduce uncertainties in national-scales estimates.
    - They do not clearly separate **anthropogenic emissions** from **natural sources & sinks**.

- Parties to the Paris Agreement have not yet acknowledged this refinement to the IPCC guidelines, but **some have started implementing its recommendations**.

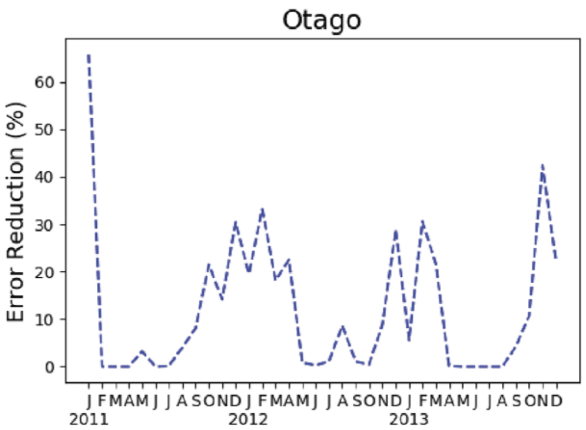
Early Adopters of Inverse Models for Verifying Inventories

- **The UK, Switzerland, and New Zealand were among the first to include atmospheric inverse modeling results as a verification system in national inventory reports.**
  - Early use of inverse model results focused on fluorinated gases and CH_4.
    - Fluorinated species have no natural source interference and there are large uncertainties in the conventional inventories.
    - CH_4 has both natural and anthropogenic sources, but it has a strong atmospheric signal-to-noise ratio and inventories have large uncertainties.

New Zealand CH_4



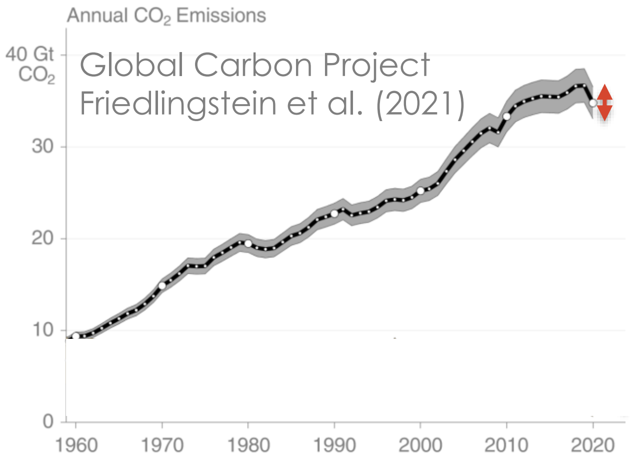
CH_4 Error reduction in the Otago region relative to the bottom-up national inventory



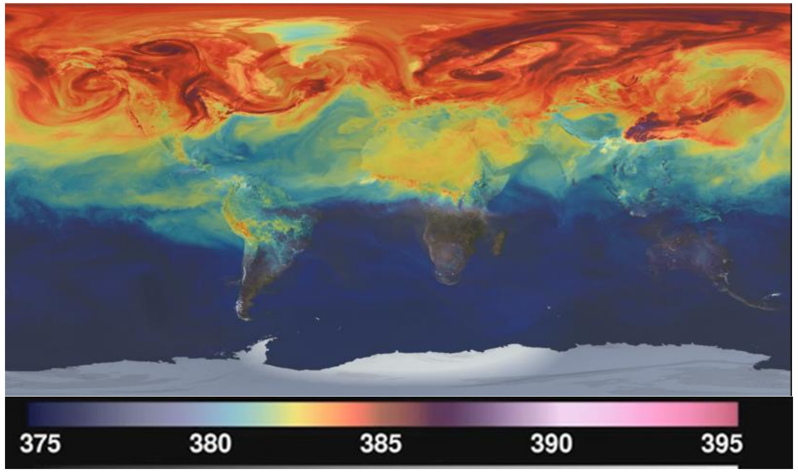
Plots from Geddes et al. (NIWA, 2020)

Early Adopters of Inverse Models for Verifying Inventories

- **CO_2 was not a primary target for early top-down estimates because:**
  - The primary source of CO_2 emissions for most countries is **fossil fuel use**, which has well-tracked ***activity*** and well-characterized ***emission factors***, yielding relatively small uncertainties in inventories.
  - Measurements with high precision and accuracy (< 0.25%) are needed to detect and quantify concentration variations for typical sources & sinks.
- **However:**
  - **AFOLU** emissions have **much larger uncertainties**, but natural processes that both emit & remove CO_2 on a range of scales introduce additional challenges in the **attribution** of top-down results.



Fossil Fuel Use



< 20 ppm (5%) variation pole-to-pole
(NASA Goddard Modeling and Assimilation Office)

Ongoing Improvements in Top-Down CO_2 Flux Estimates

Pilot top-down CO_2 budgets demonstrate new capabilities.

- Rapid improvements as measurement accuracy, resolution, and coverage increase and methods are developed to attribute anthropogenic and natural fluxes.
- Potential role in development and validation bottom-up inventories for **AFOLU** (also called **LULUCF**)
  - AFOLU is a leading source of emissions in many developing countries.
  - Uncertainties in **activity data** and **emission factors** compromise bottom-up AFOLU inventories.

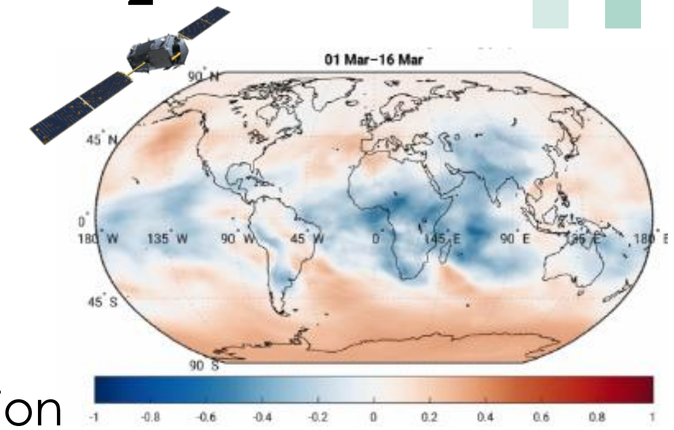
Country	LULUCF MMT CO_2e	Bottom-up Uncertainty	Top-Down Uncertainty
Brazil	403	270	**274**
Indonesia	639	217	**146**
Nigeria	307	68	**45**

Bottom-up LULCF results based on McGlynn et al., Climate Change 2022 https://doi.org/10.1007/s10584-021-03254-2

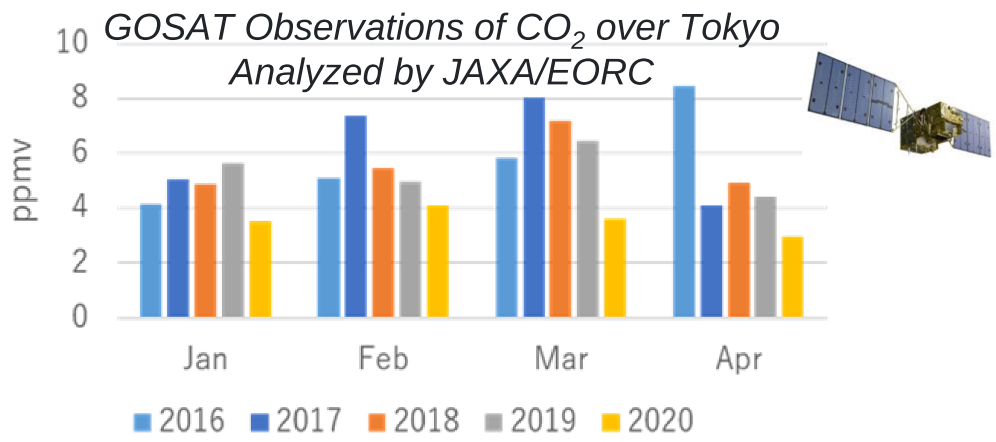
Top-down results from the CEOS Pilot CO_2 Budget (Part 2)

Additional advances in top-down methods anticipated for future global stocktakes

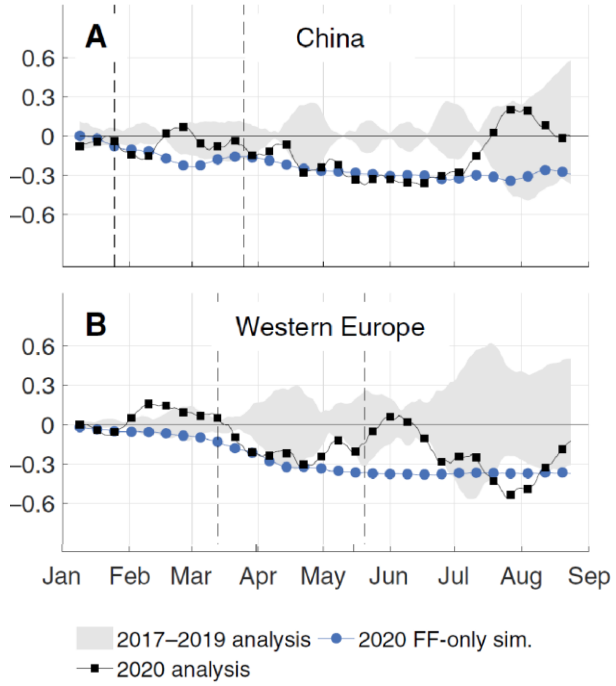
Demonstration of Top-Down Methods – Tracking CO_2 Emissions Reductions due to the COVID-19 Lockdowns



- Regional-scale CO_2 emissions reductions associated with the lockdowns early in the COVID-19 pandemic were derived from OCO-2 observations.
- Urban-scale CO_2 emissions reductions associated with the lockdowns were derived from GOSAT observations.

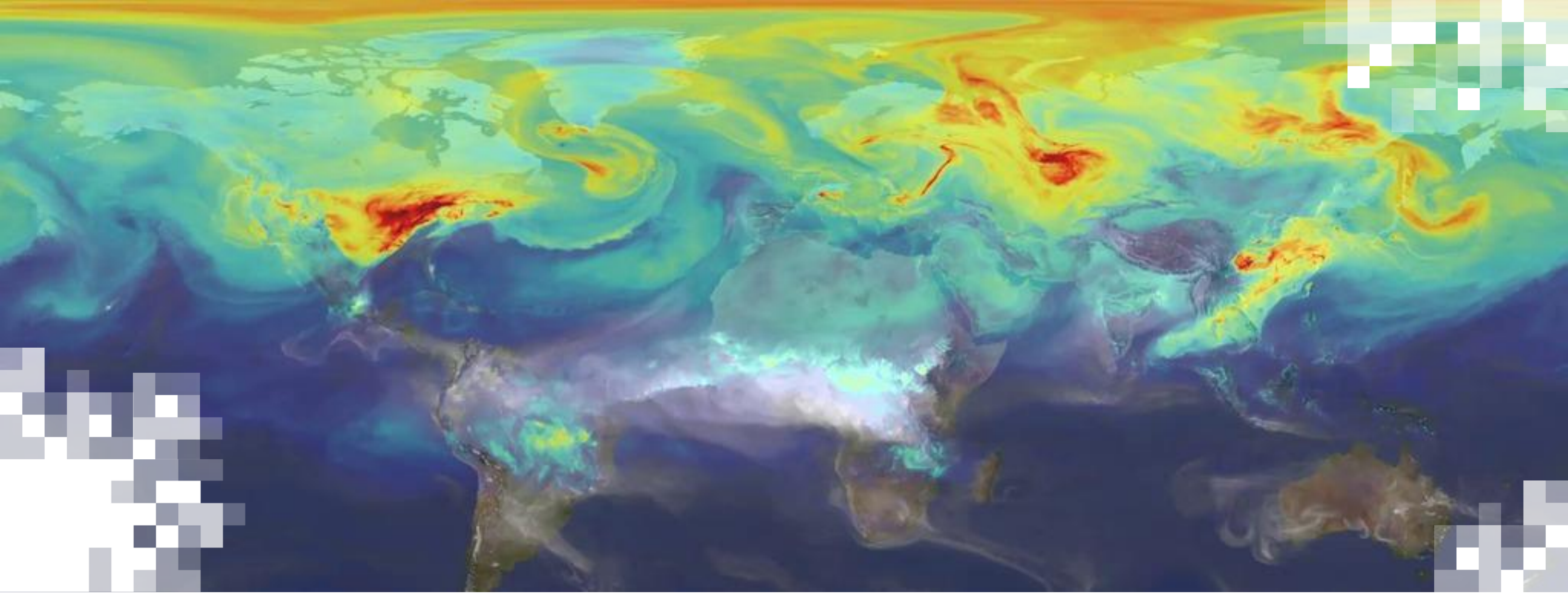


CO_2 emission reductions inferred from atmospheric CO_2 observations (black boxes) agree well with bottom-up estimates derived from activity-based CO_2 emission proxies (blue points) and a background climatology (grey shaded region).



Future atmospheric observations may allow emission monitoring in near-real time.

Figures adapted from Weir et al., 2021. doi: 10.1126/sciadv.abf9415

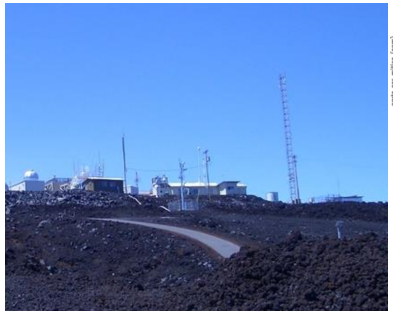


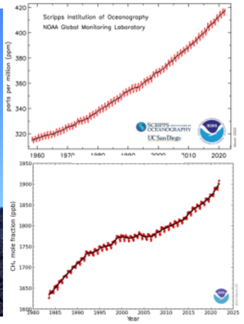
Reconciling Differences in Top-Down Inventories and Bottom-Up Budgets

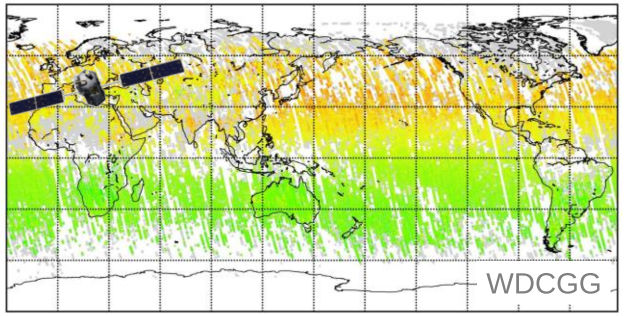
Maximizing the Value of Top-Down CO_2 and CH_4 Budgets

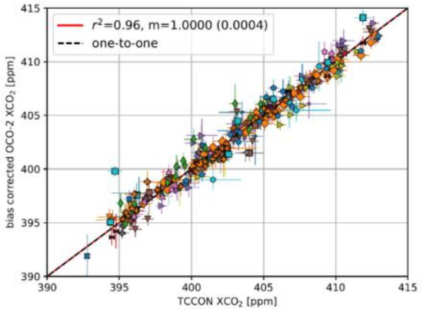
The 2019 IPCC Refinement identifies three critical requirements for top-down methods:

- **Rapidly Improving Atmospheric Observations**

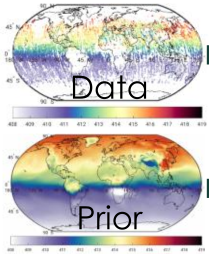


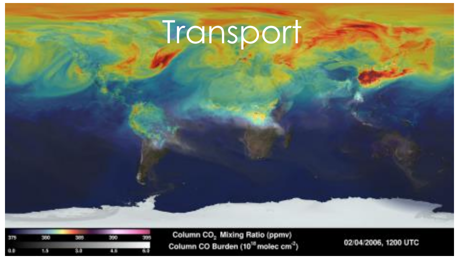






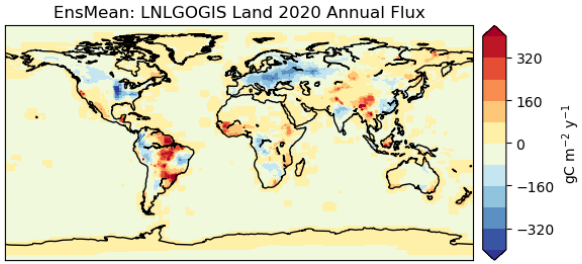
- **Well Validated Atmospheric Inverse Modeling Tools**





Inverse Model

$$\mathcal{J}(\mathbf{x}) = \frac{1}{2}||\mathbf{y} - \mathcal{H}(\mathbf{x})||^2_{\mathbf{R}^{-1}} + \frac{1}{2}||\mathbf{x} - \mathbf{x}_b||^2_{\mathbf{B}^{-1}}$$

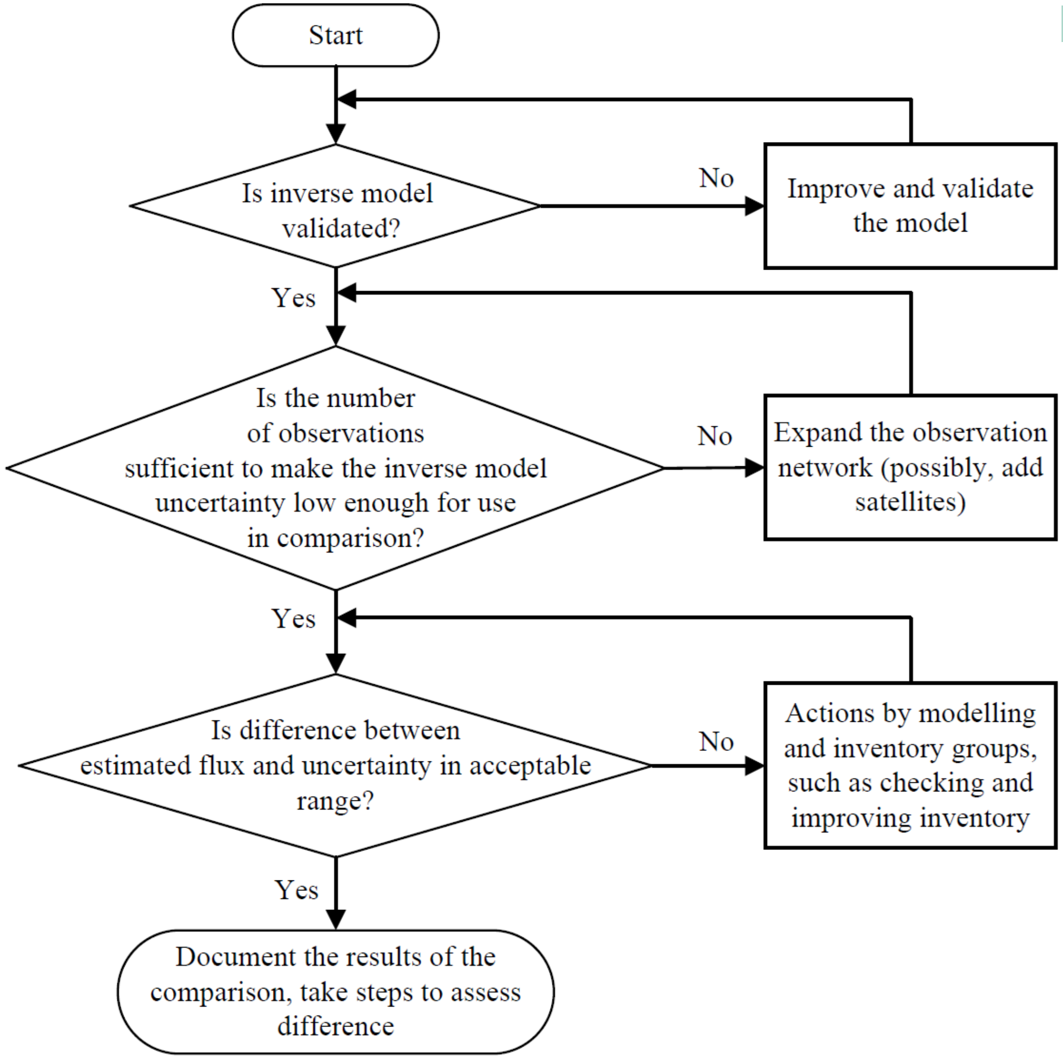


- **Collaboration**
  - Inventory compilers, atmospheric measurement/modeling community, UNFCCC

IPCC Guidelines for Ensuring the Utility of Inverse Model Estimates for Comparison with National Inventories

The **utility** of inverse model estimates depends on their **accuracy and precision** and can be used with more confidence when:

- **Inverse modeling system has been tested and validated against multiple methods**
  - Tests with multiple, well-known tracers
  - Compared results across ensembles of models
- **The number, quality (accuracy/precision), and frequency of measurements are adequate** to resolve known spatial and temporal variability
- **The GHG uncertainty in the inventories is large** (compared to that of inverse modeling results)



2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

Decision tree for establishing utility of an inverse modeling system for verifying national inventories

Reconciling Differences in Top-Down and Bottom-Up Results

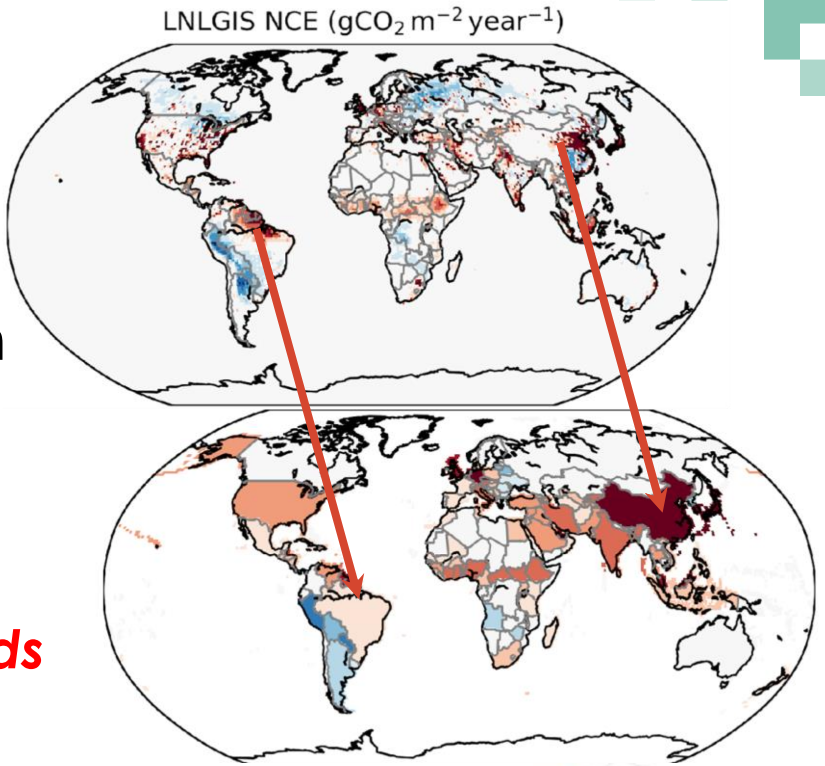
When inverse models and inventory estimates *do not* agree, the IPCC recommends that inverse modelers and inventory compiling groups should collaborate to:

1. Confirm that top-down budgets & inventories represent the **same time periods and areas**
2. Determine what **emission dataset was used as the inverse model prior** and how it compares to the emission inventory
3. Assess how the inverse model treats **anthropogenic and natural emissions** to confirm that the estimates compare with relevant emissions included in the inventory
4. Confirm that **seasonal variability of the emissions** and other effects have been considered in the comparison (impact of included/excluded transient events)
5. Assess the uncertainties and determine whether the discrepancy is **statistically significant**
6. For sub-national scale regions with the larger discrepancies, determine which emissions activities are occurring in that area based on the gridded or regional GHG inventory
7. In the national inventory improvement plan, **prioritize emission sources & regions with larger discrepancies**

2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

Challenges: Measuring the Same Area

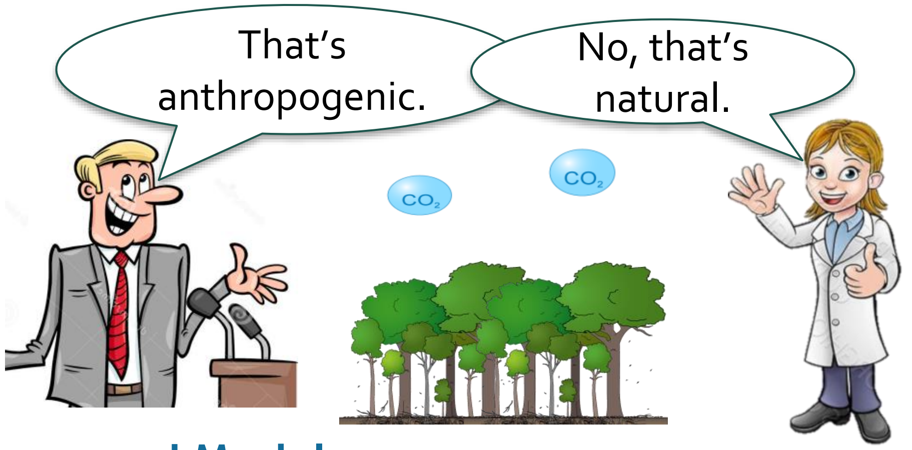
- **Borders**
  - National, land-sea, and biome borders play critical roles in defining bottom-up inventories, but are often difficult to resolve in top-down budgets based on atmospheric inversions.
- **Managed Land vs. Natural Land**
  - Only emissions and removals of GHGs from ***managed lands*** must be reported in national inventories.
    - Emissions from unmanaged lands are not expected to change.
    - Some nations define large areas as *unmanaged*.
  - The borders between managed and unmanaged lands are often difficult to resolve and/or inadequately documented in top-down inverse model results.



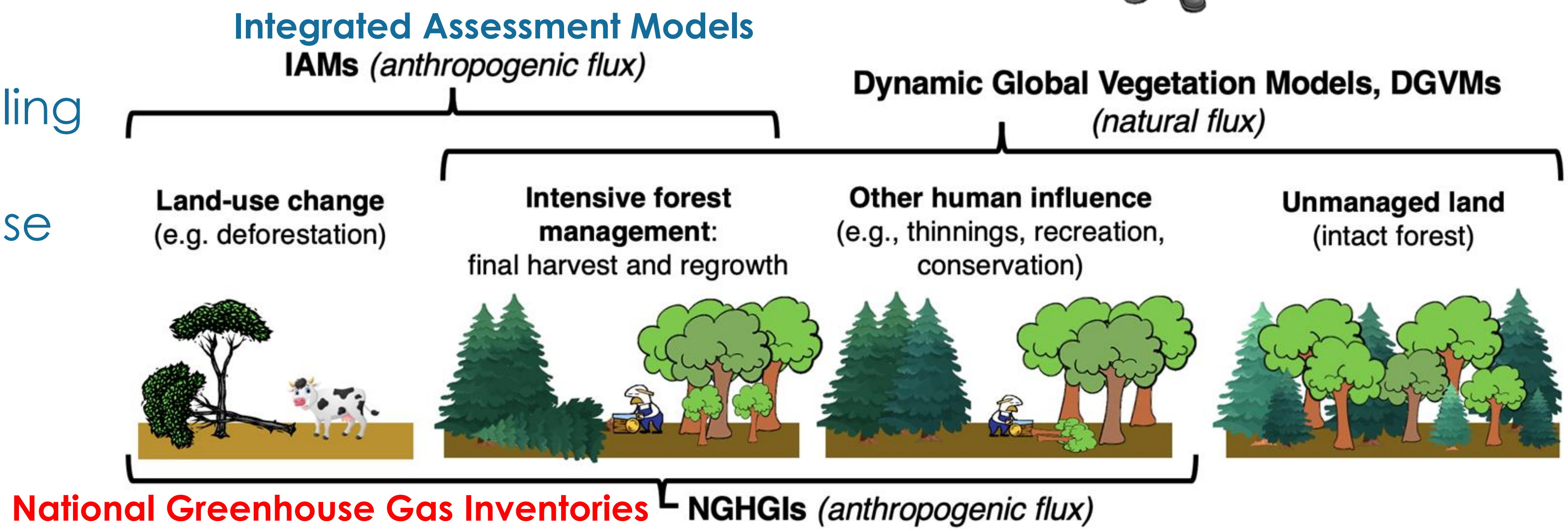
Much of Russia and Canada are not considered ***managed land***.
(Ben Poulter, GSFC, 2021)

Challenges: Differing Definitions of Managed and Natural Lands

The national inventory compilers and the modeling communities have developed different approaches to identifying the *anthropogenic forest CO_2 sink*.



This is mostly a labelling issue, but it must be resolved before these inventories can be compared and combined.



Challenges: Measuring the Same Time Period

Bottom-up estimates of emissions and removals are typically derived from ***Stock-Difference*** or **Gain-Loss** methods.

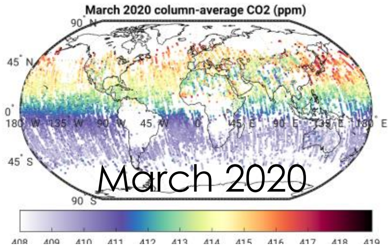
- **Stock-Difference** methods compare measured carbon stocks (e.g., tonnes of coal, above-ground biomass) measured at different times.
  - Accuracy generally benefits most from **multi-year averaging periods**.
- **Gain-Loss** methods consider rates of change of carbon in specific pools (e.g., tree harvest volume or regrowth) over a specified time period.

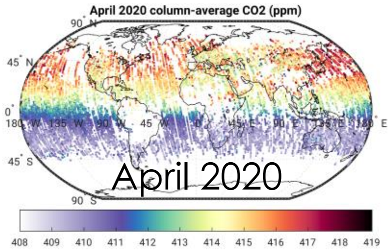
	Stock-Difference	Gain-Loss
Description	Difference in carbon stocks in a particular pool in pre- and post-forest cover change	Net balance of additions to and removals from a carbon pool
Data Requirements	Data needed on forest carbon stocks in key pools before and after conversion	Annual data needed on C losses and gains (e.g., annual tree harvest volume and annual rates of forest growth post-tree removals)
Applications	Appropriate for deforestation and afforestation and for reforestation	Appropriate for forest degradation caused by tree harvest and the regrowth of carbon stocks post-disturbance

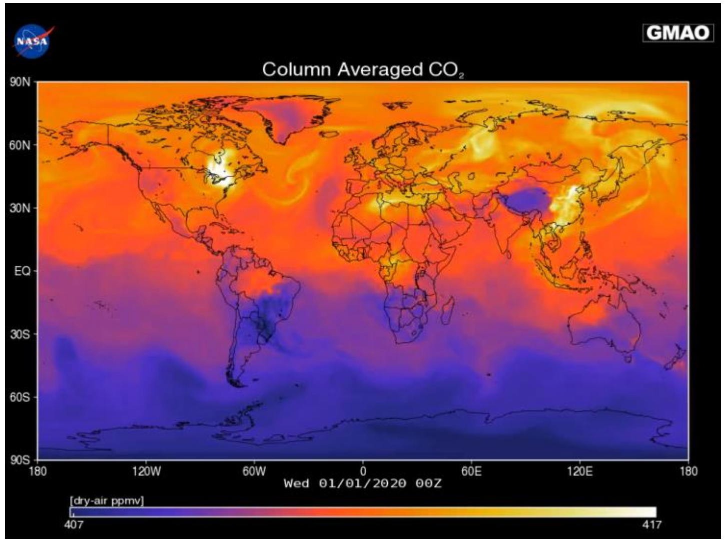
Deforestation/Forest Degradation example from REDD+ training materials by GOFC-GOLD, Wageningen University, World Bank FCPF

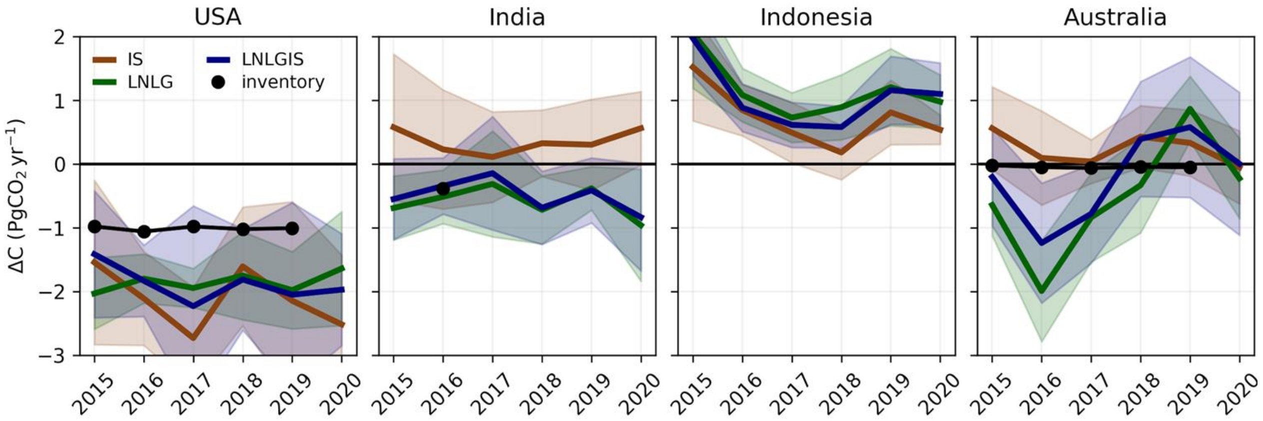
Challenges: Measuring the Same Time Period

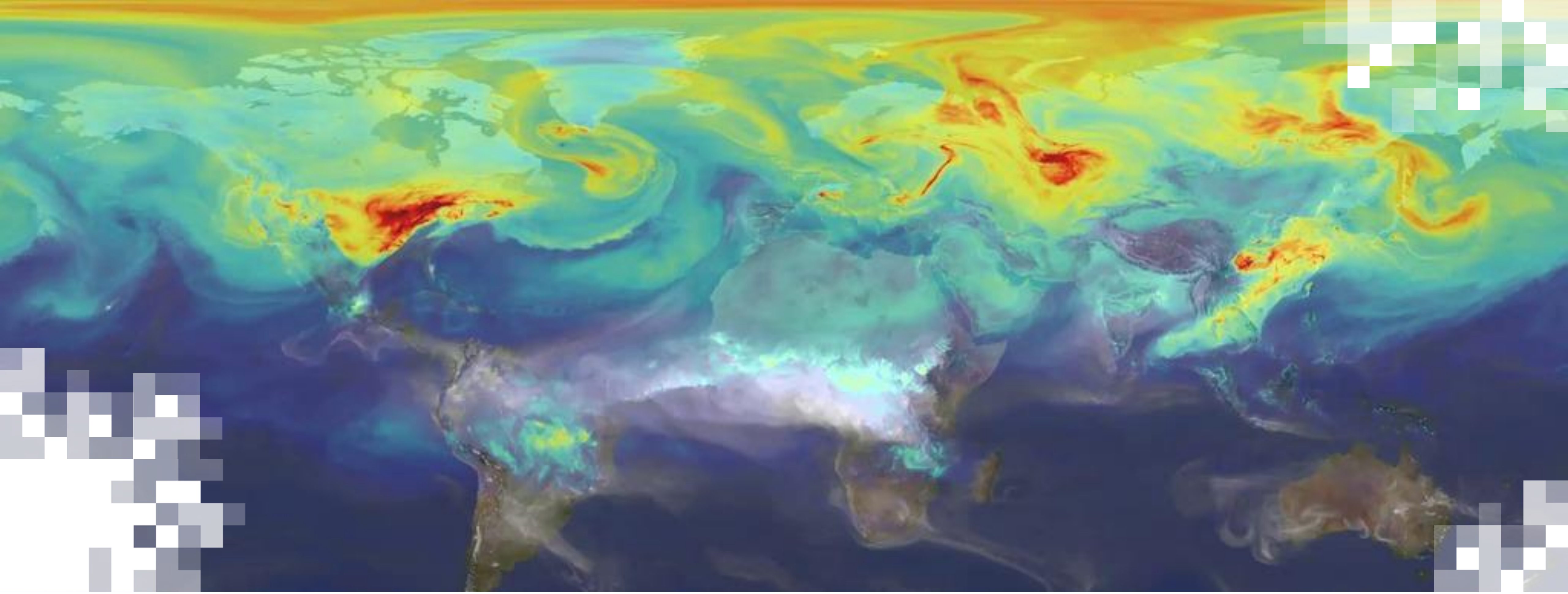
- **Top-down** estimates of fluxes are typically derived from ***snapshots*** of the atmospheric CO_2 or CH_4 field, collected as these gases are transported by winds.
  - Require rapid sampling to resolve time dependence of changes in both CO_2 and CH_4 fluxes and transport by winds
  - Generally more sensitive to **transient events** (floods, droughts, pandemics…)
  - High-resolution, space-based datasets have relatively **short time records**.











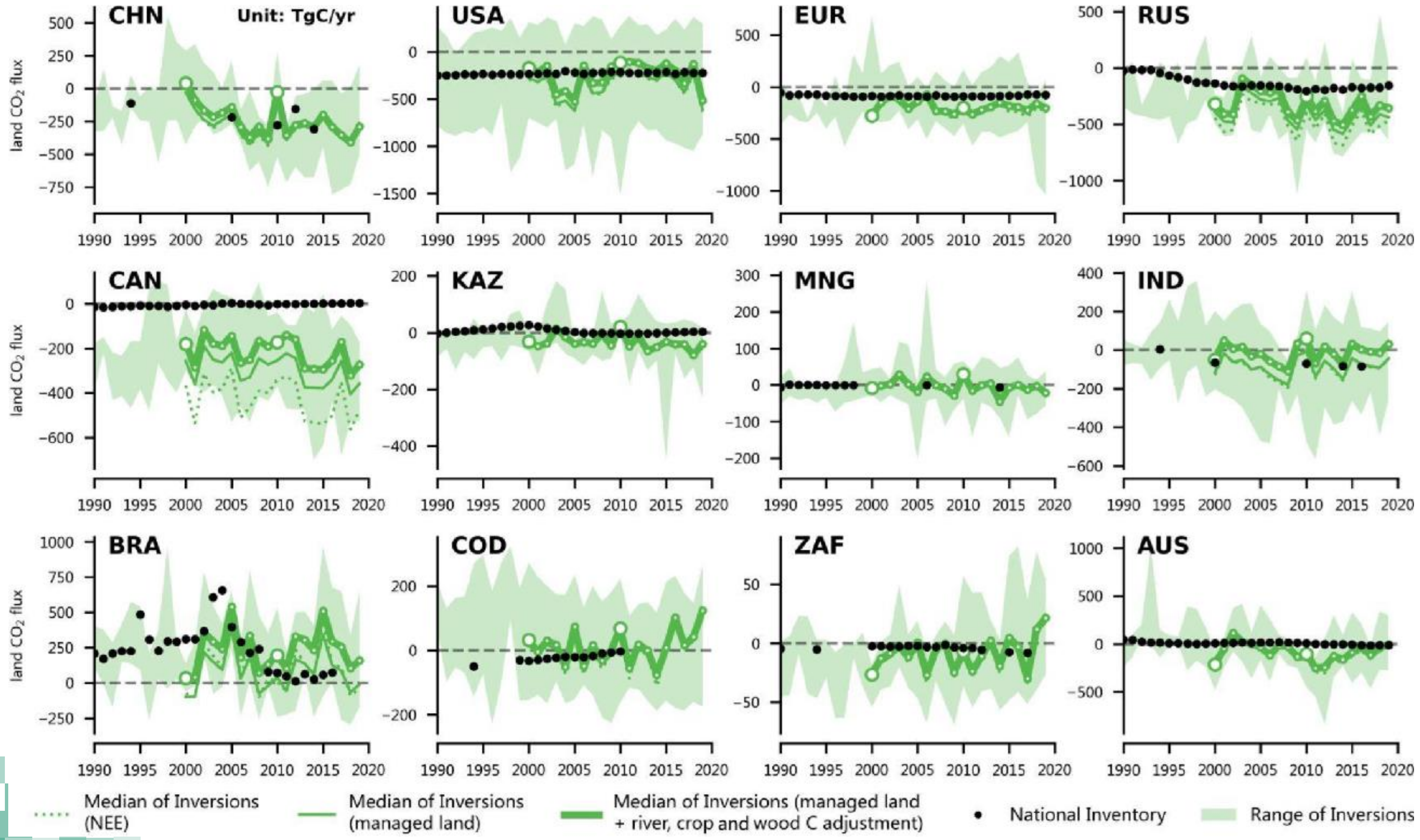
Ongoing Efforts to Compare Top-Down Budgets with Bottom-Up Inventories

Ongoing Efforts by the Science Community

The carbon cycle science community has led pioneering efforts to compare results from top-down atmospheric inverse models and bottom-up inventories.

- **Deng et al.** (2022) introduced a framework for converting Net Ecosystem Exchange(NEE) estimates derived by processing *in situ* and GOSAT data using ensembles of inverse models into products that could be compared to national LULUCF inventories.
- Adopting a similar approach, the Committee on Earth Observations Satellites (**CEOS**) analyzed global Net Biospheric Exchange (NBE) estimates from an ensemble of inverse models constrained by *in situ*, GOSAT, and OCO-2 data to produce **pilot national CO_2 and CH_4 budgets** for use in the first global stocktake.
- The World Meteorological Organization (WMO) Integrated Global Greenhouse Gas Information System (**IG^{3}IS**) held stakeholder consultations compile best practices for tracking LULUCF and Urban emissions using atmospheric measurements.
- **Individual research teams** have used airborne and space-based observations of CO_2 and CH_4 to quantify emissions from intense point sources.

Comparing CO_2 Inventories with Top-Down Atmospheric Budgets

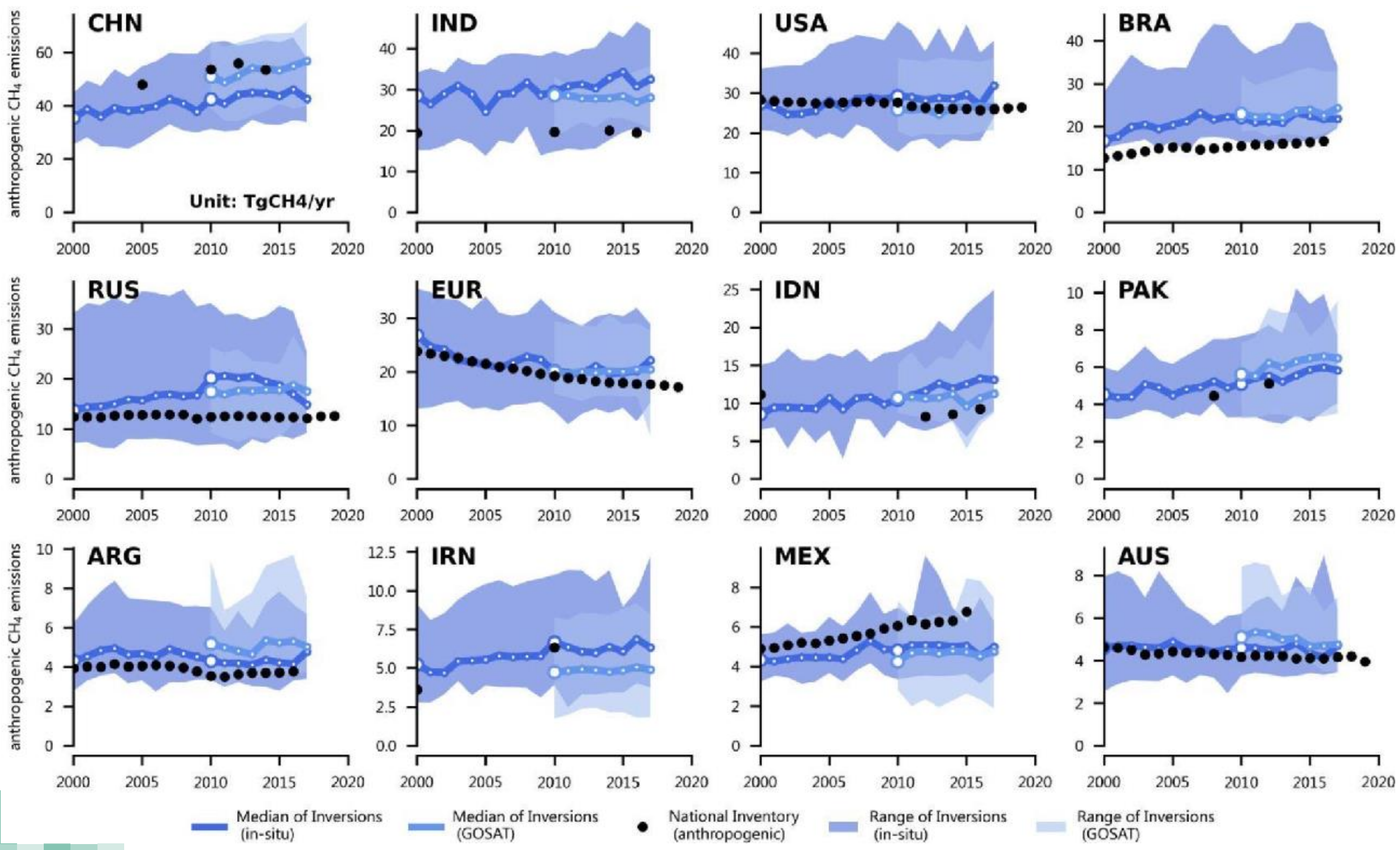


Deng et al. (2022)

For CO_2, the agreement between top-down (green) and bottom up (**black dots**) estimates was generally quite good, although some inventories showed systematic biases and atmospheric inversions show substantially more year-to-year variation than the inventories.

Deng et al., Earth Syst. Sci. Data, 14, 1639–1675, 2022
https://doi.org/10.5194/essd-14-1639-2022

Comparing CH_4 Inventories with Top-Down Atmospheric Budgets

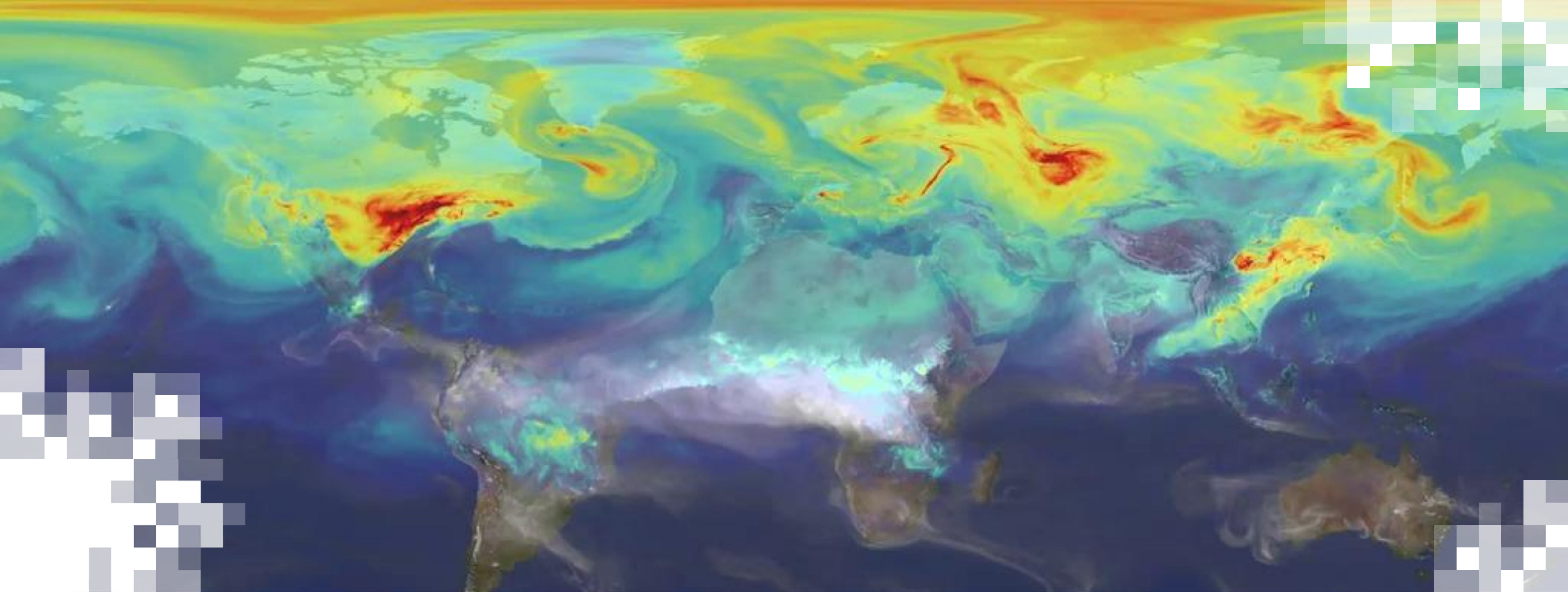


Deng et al.(2022)

For CH_4, both bottom-up (**black dots**) and top-down (**blue lines**) methods indicate that the top 5 emitting countries are responsible for about half of all emissions.

Atmospheric inversions show a wide range of values (**blue bands**) indicating both variability and uncertainty in these estimates.

Deng et al., Earth Syst. Sci. Data, 14, 1639–1675, 2022
https://doi.org/10.5194/essd-14-1639-2022

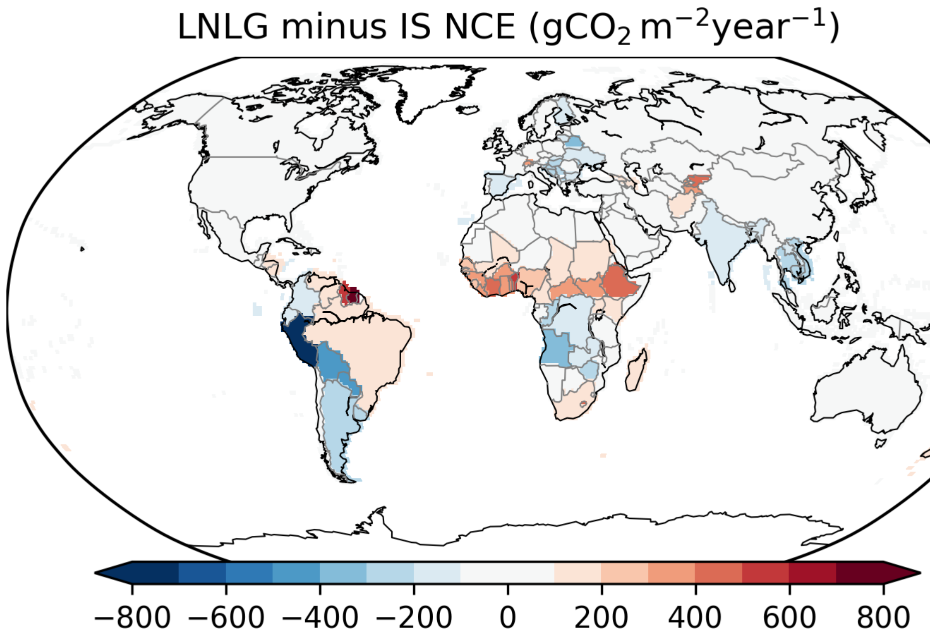


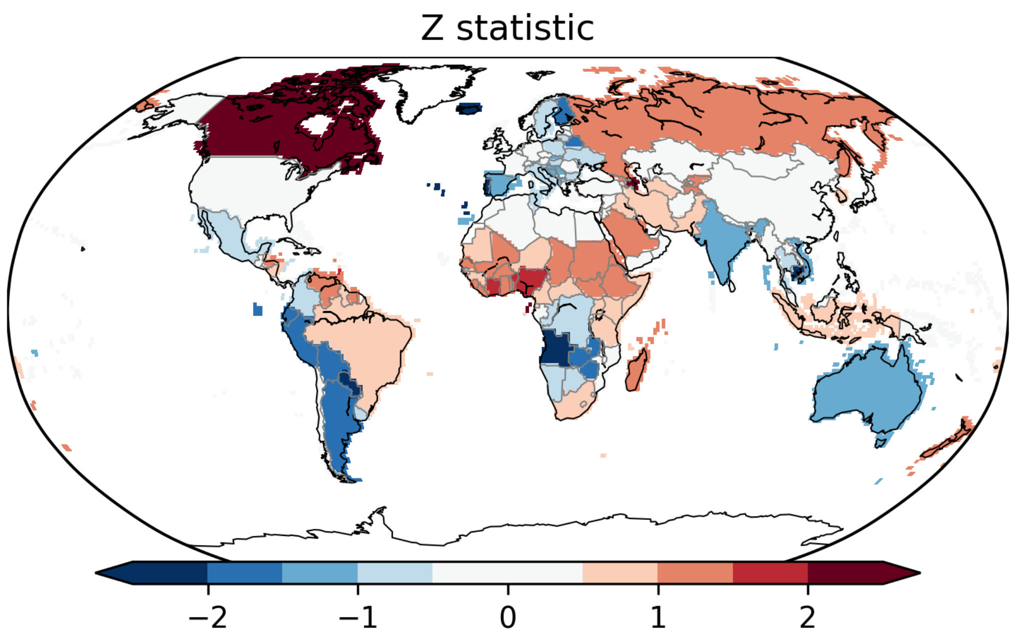
Example: How to Access and Use a Top-Down National CO_2 Budget

Useful metrics: 1. Z-statistic

- Differences between CO_2 budgets between assimilate different CO_2 data (IS vs LNLG).
- Top-down CO_2 budgets are most robust when experiments agree
- The Z statistic measures of how consistent LNLG and IS results are given their uncertainties.

$$Z\ statistic = \frac{\overline{NCE_{LNLG}} - \overline{NCE_{IS}}}{std(NCE_{LNLG} - NCE_{IS})}$$



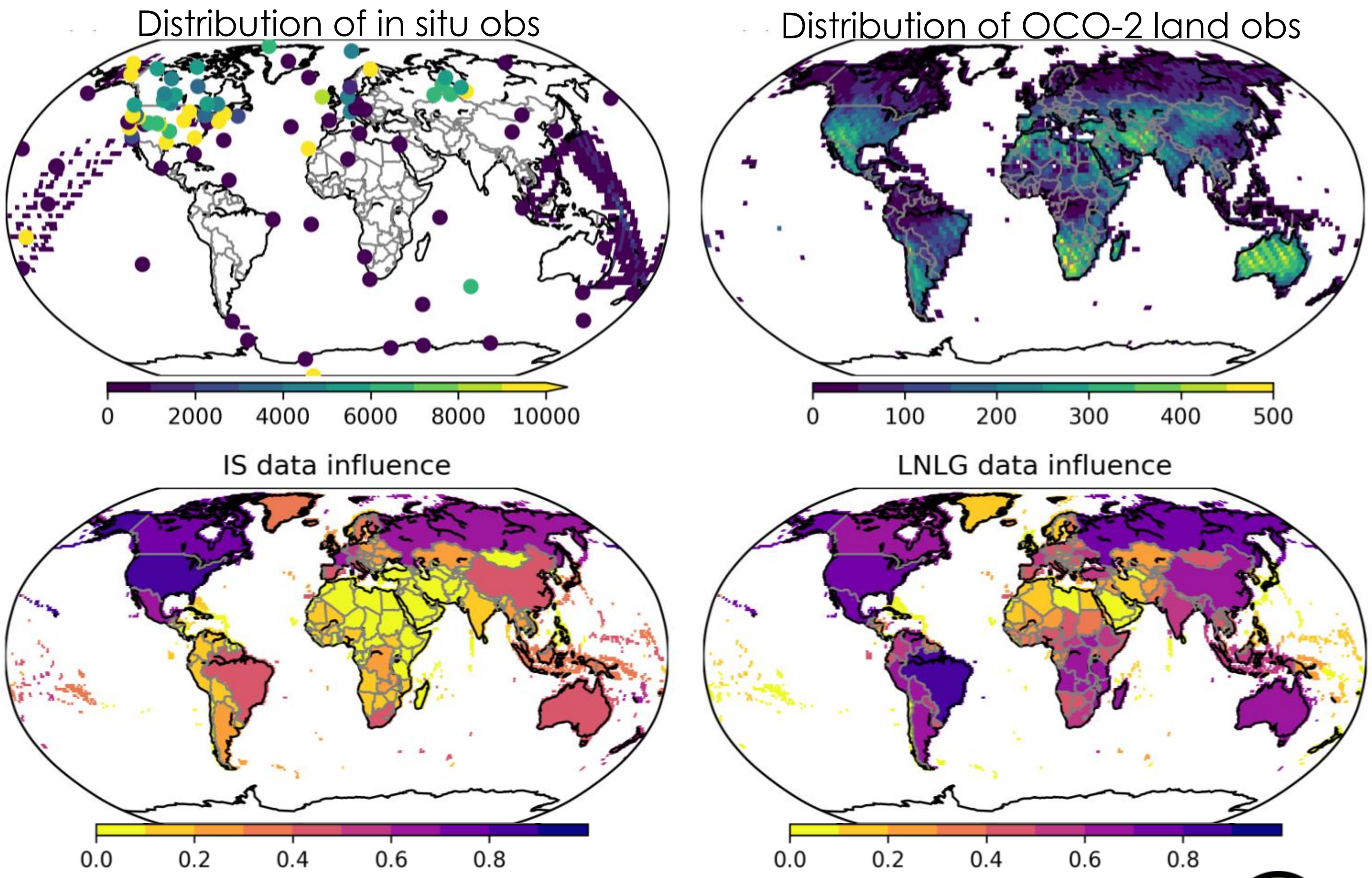


Useful metrics: 2. Influence of Assimilated Data (IAD)

- Fluxes estimates are best captured when CO_2 measurements are nearby
- "**Influence of Assimilated Data (IAD)**" quantifies the impact of data on flux estimates
- IAD measures how much uncertainties in the estimated fluxes are reduced relative to the prior estimate:

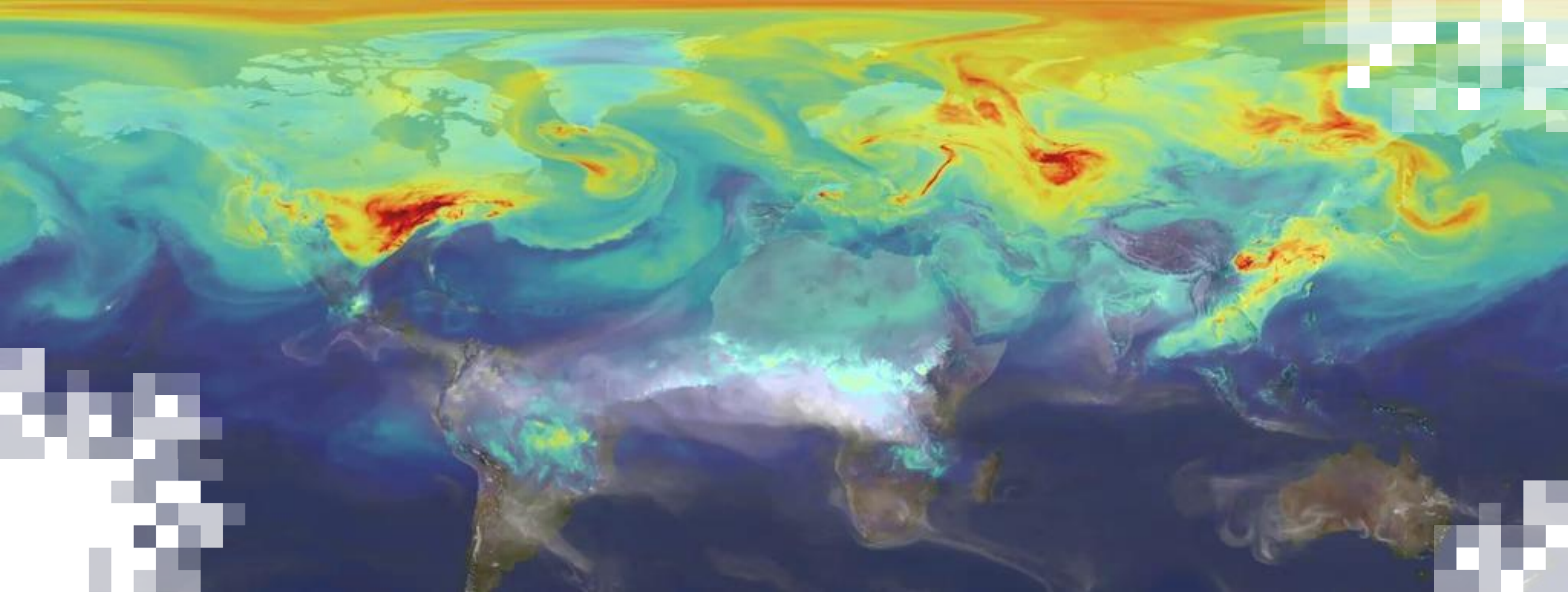
$$IAD = 1 - \frac{posterior\ uncertainty}{prior\ uncertainty}$$

- If IAD = 0 then there was no reduction in uncertainty from the CO_2 data
- If IAD = 1 then CO_2 flux is exactly estimated from the CO_2 data. (e.g., no uncertainty on estimate)



Download the data:

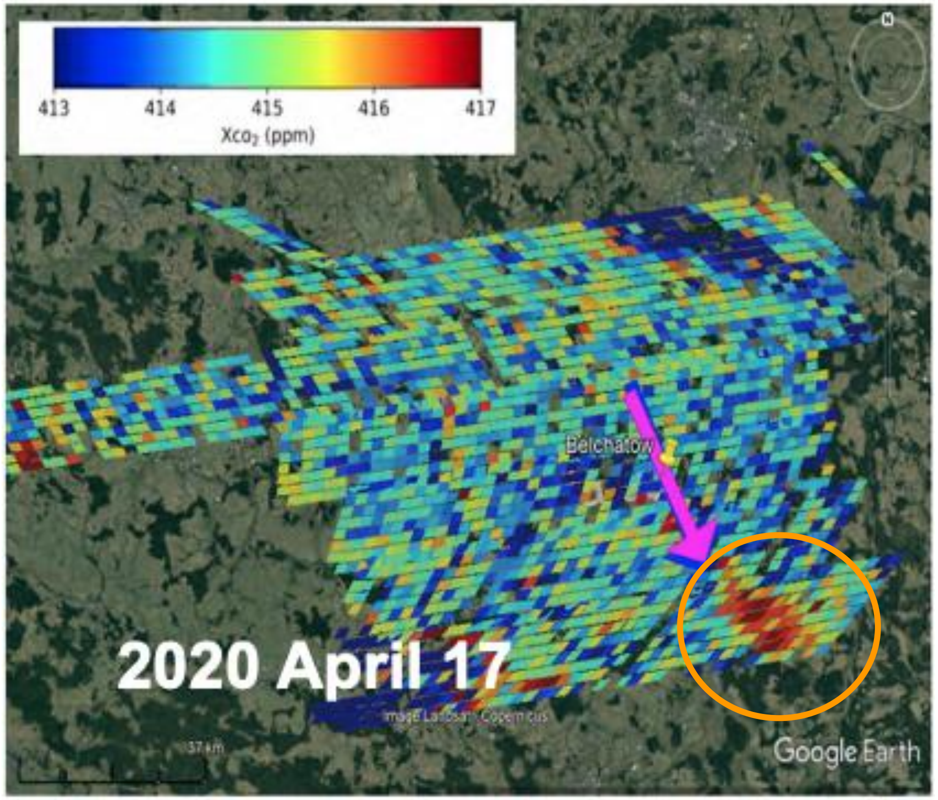
- Dataset hosted on Committee of Earth Observing Satellites (CEOS) website: https://ceos.org/gst/
- Information for a number of satellite-based datasets that inform Global Stocktake activities can be found on the CEOS website
- Pilot CO2 budget dataset is described and can be downloaded here: https://ceos.org/gst/carbon-dioxide.html



Examples of Point Source Detection

Example of a Localized CO_2 Point Source

CO_2 plume detected and quantified at Bełchatów power plant in Poland



Nassar et al. (2021)

Top-down and bottom-up results for a large, coal-fired power plant - April 17, 2020

Bottom-up emission (Q) estimate

Q_{bottom} = Power generation (MW) x Emission factor

Q_{bottom} = 103 $ktCO_2$ /day

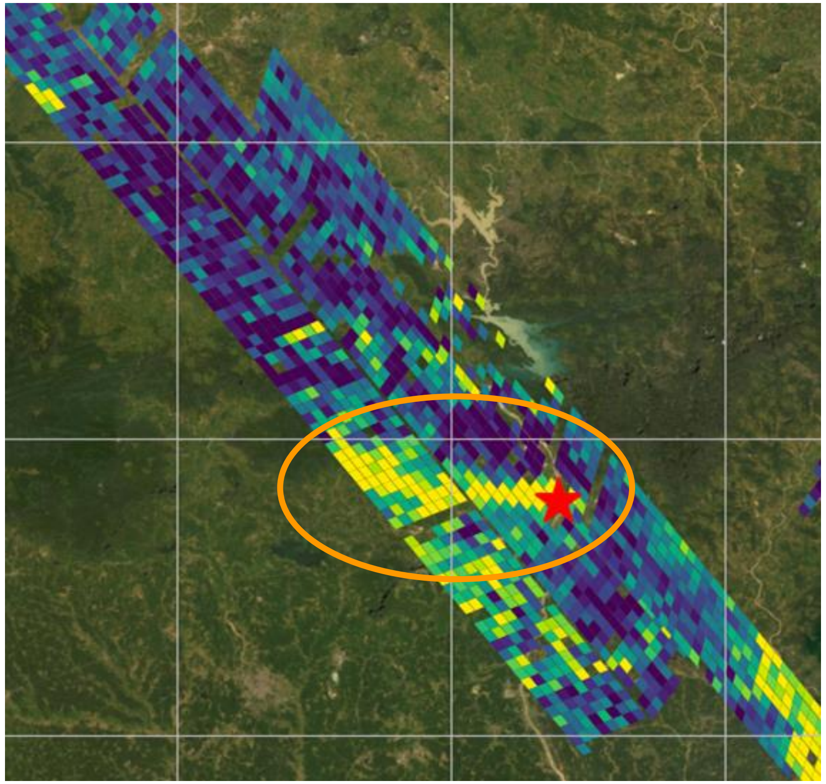
Top-down emission estimate from OCO-3 satellite

Q_{top} = 98.2 ± 11.9 $ktCO_2$ /day

Good agreement at this site suggests proper emission factors used at this site and good satellite data quality.

Example of a Localized CO_2 Point Source

CO_2 plume detected at Korba power plant, Chhattisgarh, India (Dec 26, 2021)



https://ocov3.jpl.nasa.gov/sams/

What about places where there is less certainty regarding power plant emission factors?

Q_{bottom} = Power generation (MW) x Emission factor

Q_{top} = 34.7 ktCO_2 /day

Single, but ideally multiple, overpasses of satellite with emission quantification can reduce uncertainty in emission and activity factors at this site.

Future high-resolution, space-based measurements of CO_2 and CH_4 will provide time-resolved monitoring of local sources such as large urban areas and large fossil fuel-powered power plants.

Using Localized CH_4 Point Sources to Improve Inventories

"Ultra-Emitters" Detected by Sentinel 5p TROPOMI

Lauvaux et al. (2022)

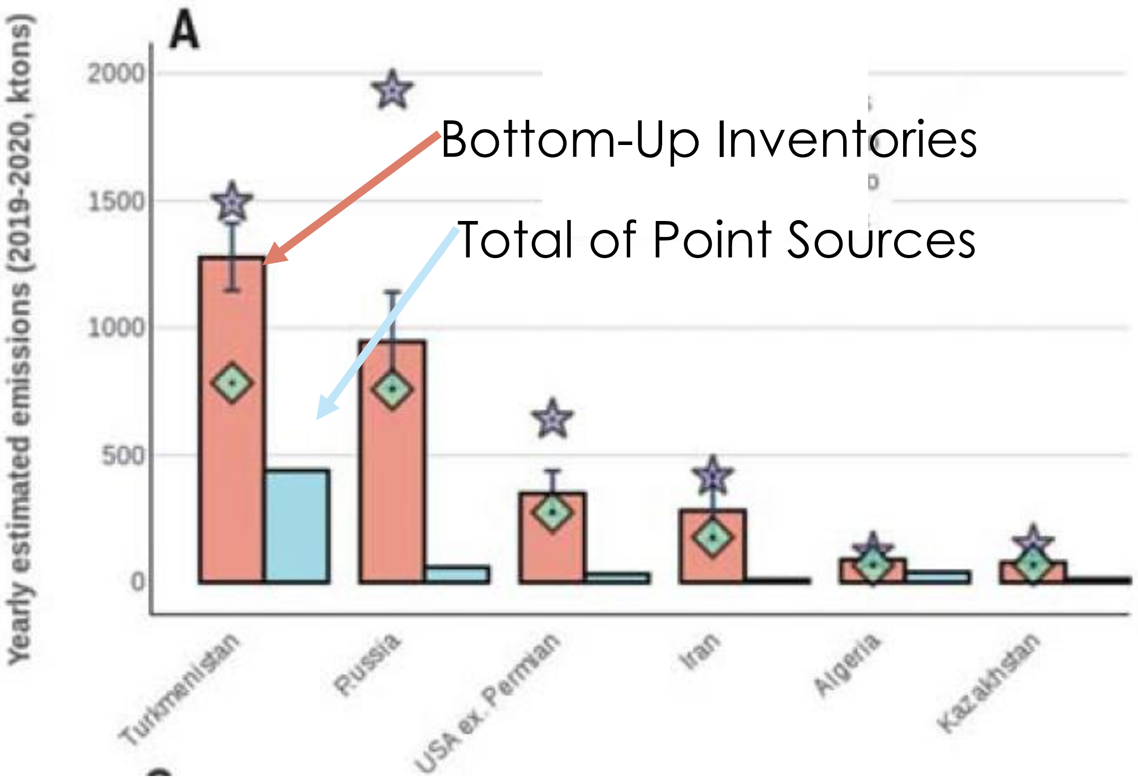
Review:

- Localized CH_4 point sources often result from events not traditionally included in bottom-up inventories (e.g., oil/gas leaks, malfunctions, or short-lived maintenance events).

- These emissions are often neglected, but can be a significant fraction of CH_4 budgets.

Using Localized CH_4 Point Sources to Improve Inventories

Comparison of national-scale bottom-up inventories to aggregated "ultra-emitters"



Lauvaux et al. (2022)

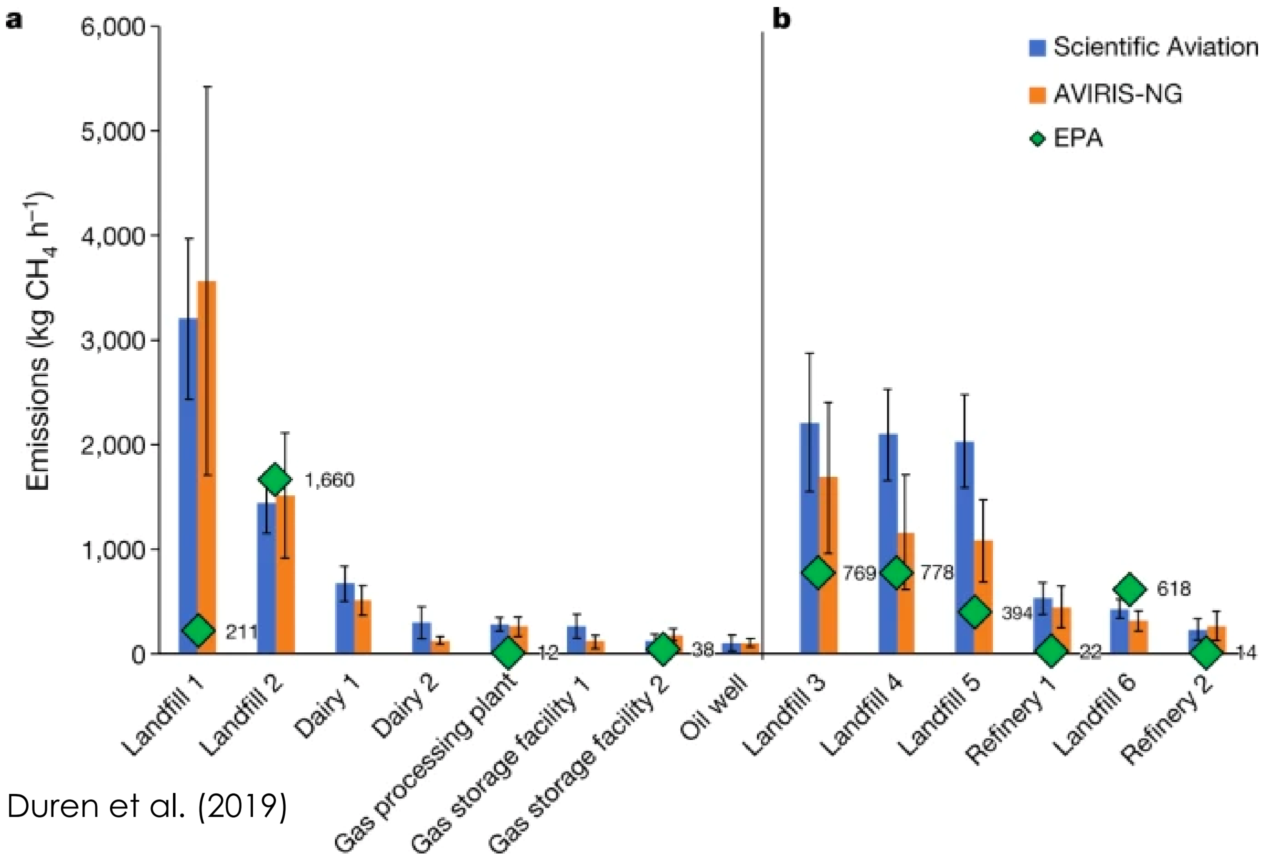
The first step is to contextualize the issue.

"How much CH_4 is emitted from localized sources in my country?"

"How does this compare to my national inventory?"

Using Localized CH_4 Point Sources to Improve Inventories

Comparison of top-down and bottom-up estimates of CH_4-emitting infrastructure in California



Duren et al. (2019)

At the facility-scale, can employ similar methods for CO_2 point sources:

“What would a bottom-up inventory for my refinery predict for CH_4 emissions?”

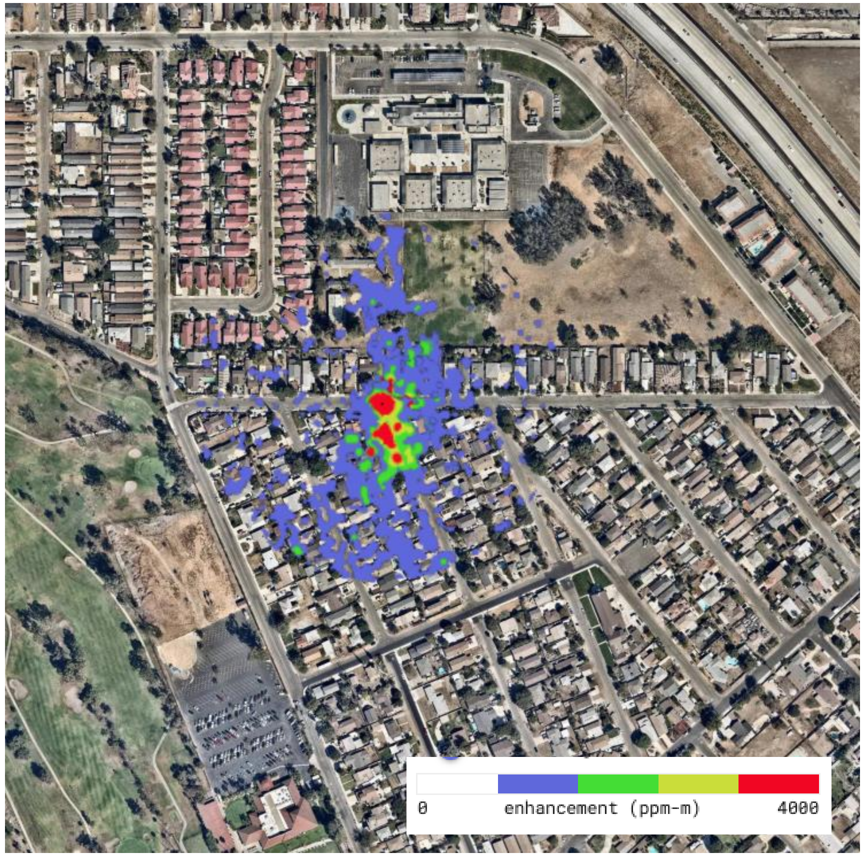
“What is the atmosphere telling me?”

“Is there a discrepancy? If so, is it due to emission factors, seasonality, operations, or measurement noise?”

Multiple overpasses with atmospheric measurements will continue to reduce uncertainty.

Localized CH_4 Data Can Be Used to Identify Hazards

Gas Line Leak in Chino Hills, CA



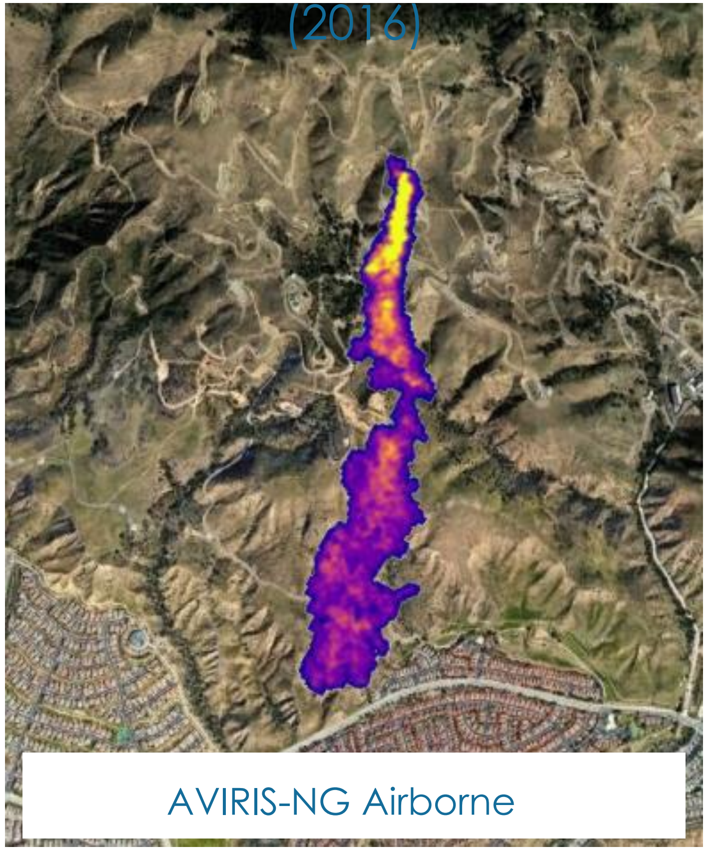
A gas leak was detected in a residential neighborhood with the AVIRIS-NG airborne imaging spectrometer.

The local gas company was contacted and pipeline was fixed within 24 hours.

Follow-up flights verified that the leak was fixed.

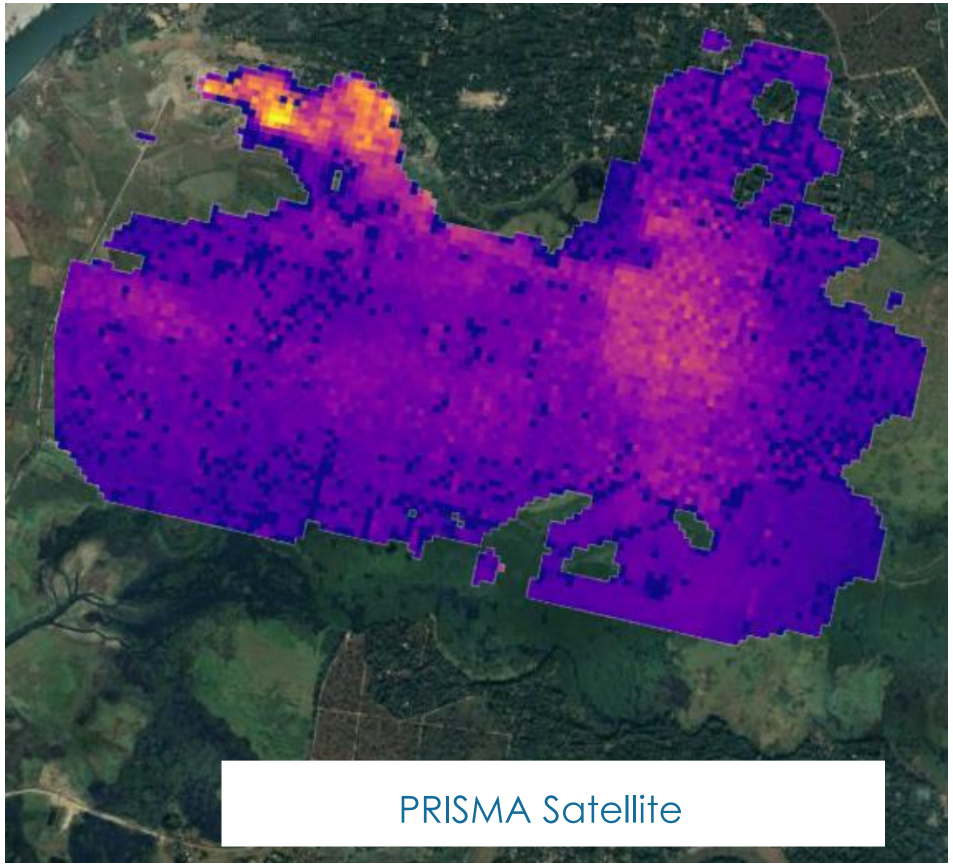
Localized CH_4 Data Identifies Large Anomalous Events and Impacted Communities

Gas Blowout in Los Angeles (2016)



Thorpe et al. (2020)

Gas Blowout in Assam, India (2020)



Cusworth et al. (unpublished)

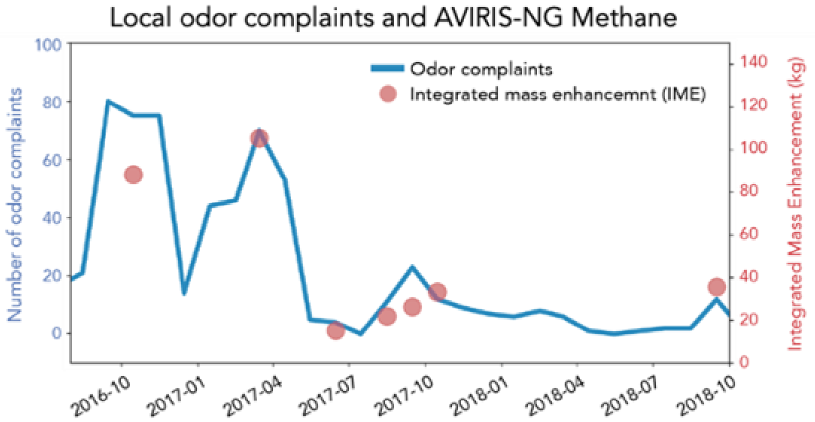
- Quantification of emissions from individual events

- Maps of plumes allow for understanding of affected communities. Connection to air quality.

Localized CH_4 Data Can Validate Changes to Infrastructure

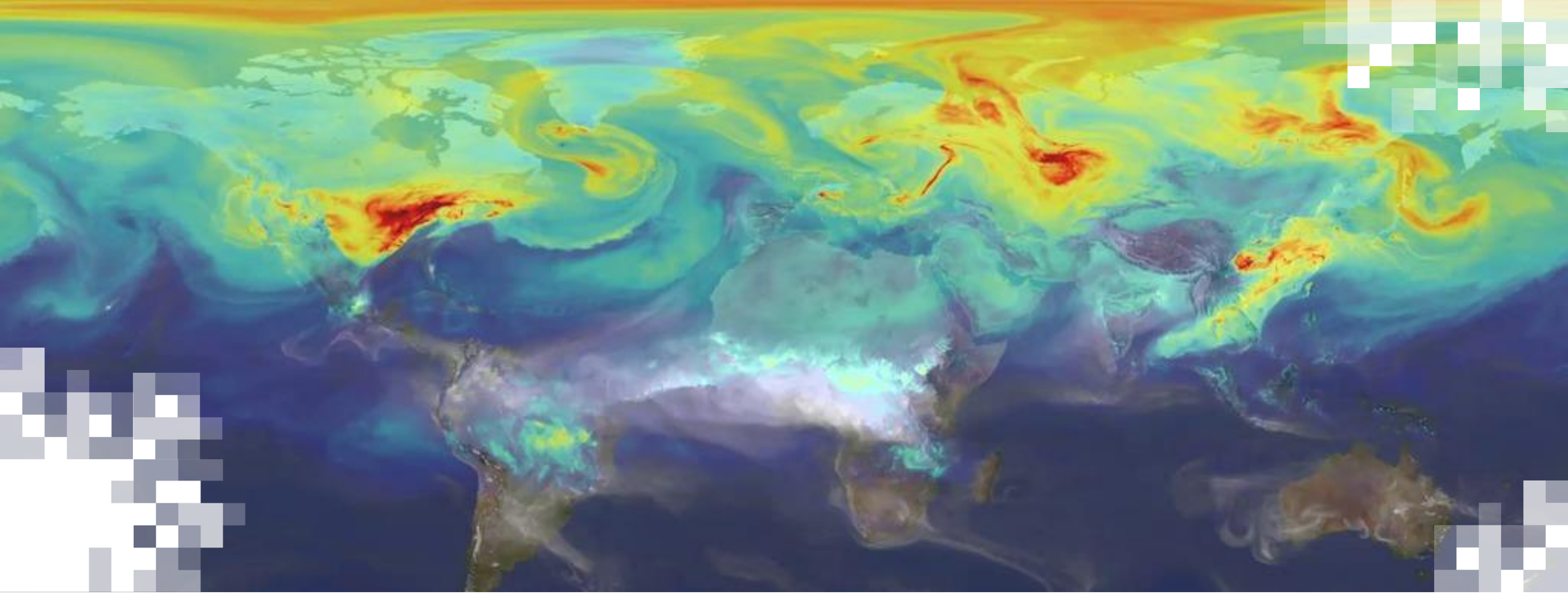
CH4 plume over landfill before and after infrastructure improvements

Cusworth et al. (2020)



Case Study at a Landfill:

- Large plumes observed with airborne AVIRIS-NG.\
- Data shared with operators and enforcement agency
- Large investments to infrastructure in following year
- Return flights saw significantly reduced methane. Landfill received fewer odor complaints as well.



Emerging Opportunities and Gaps

Opportunity – Using Top-Down Results to Refine Emission Factors

- Can we combine high-resolution maps of **activity** with **top-down CO_2 and CH_4 fluxes** inferred from atmospheric inverse models to produce regional-scale maps of ***emission factors*** for use in bottom-up inventories of the AFOLU sector?

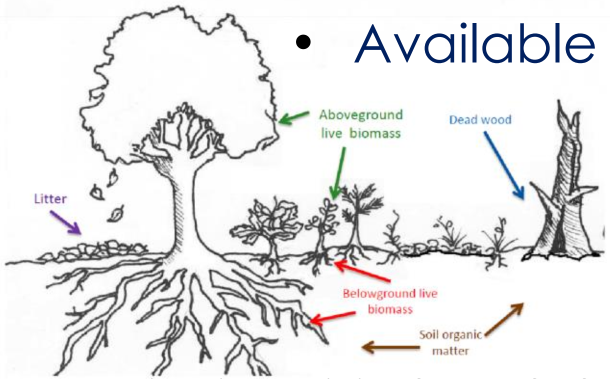
Typical Stock-Change Approach for Estimating Bottom-Up Emissions Factors for Deforestation

$$EF = (C_{bio,pre} - C_{bio,post} - C_{wp} + ([CS_0 - CS_D]/D)) \times \frac{44}{12} + E_{oth}$$

Where:

EF	= Emission factor, t CO_2-e ha^{-1}
$C_{bio,pre}$	= C stock in biomass prior to forest change, t C ha^{-1}
$C_{bio,post}$	= C stock in biomass post-deforestation, t C ha^{-1}
CS_O	= Initial or reference soil organic carbon,
CS_D	= Soil organic carbon at default time D, t C ha-1
D	=Default time period to transition to a new equilit value (20 year)
C_{wp}	= Carbon stored in long term wood products, t C
44/12	= Conversion factor for C to CO_2
E_{oth}	= Emissions of non-CO_2 gases, such as CH_4 & N_2(released during burning, t CO_2-e ha^{-1}

- Which carbon pools are included?
- How do we assess carbon change in each carbon pool?
  - Above-Ground Biomass
  - Below-Ground Biomass
  - Soil Carbon
- Available field measurements?



This is hard.

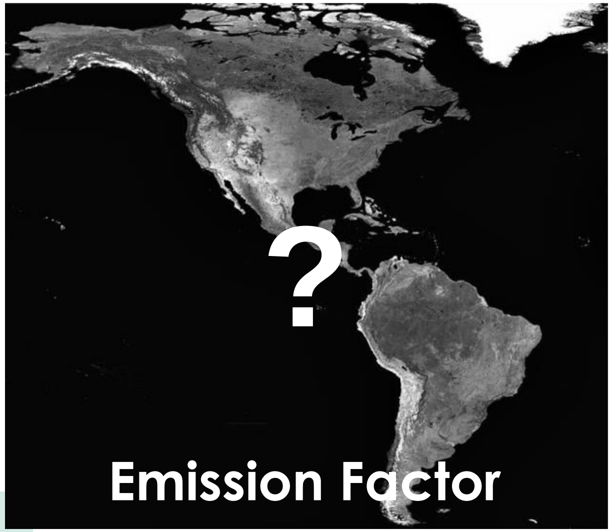
Adapted from Module 2.3: Estimating emission factors for forest cover change, GOFC-GOLD, Wageningen University, World Bank Forest Carbon Partnership

Deriving Improved Emission Factors from Top-Down Budgets

Recall: **ΔFlux (tCO_2/yr) = Activity (hectares converted) × Emission Factor (tCO_2/hectare)**

Rearranging: **Emission Factor (tCO_2/hectare) = ΔFlux (tCO_2/yr) ÷ Activity (hectares converted)**

- Atmospheric measurements provide constraints on the emissions and removals (**ΔFlux**).
- In principle, these data can be combined with high spatial resolution maps of **Activity**. They provide a spatially- and temporally-resolved constraint on emission factors.



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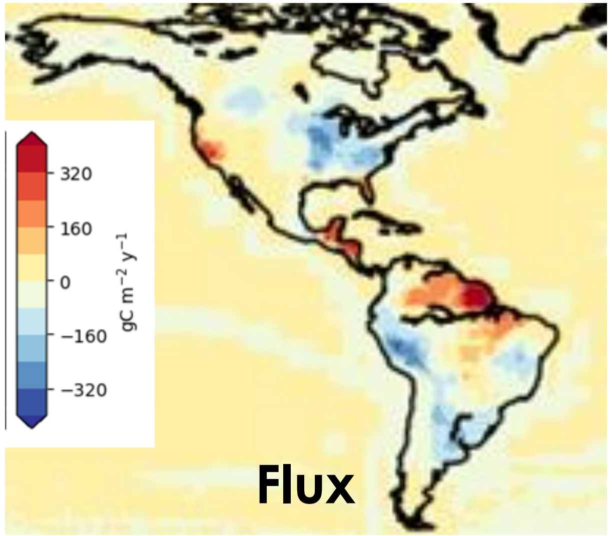

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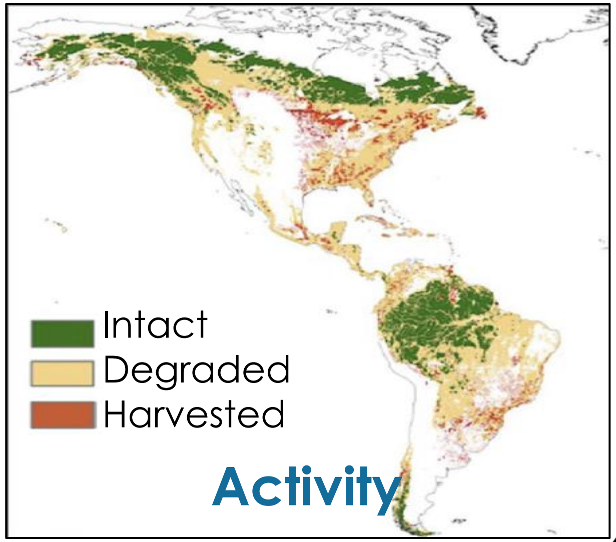


Closing the CO_2 Budget Using Atmospheric Measurements

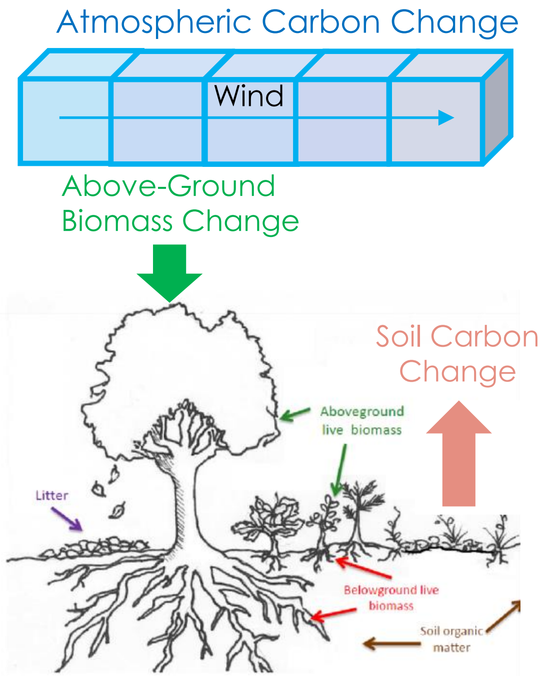
Atmospheric measurements can be combined with inventory data to complete the budget for individual components that are difficult to quantify in bottom-up inventories, such as **soil carbon**.

- Prior to 2015, the global land sink was estimated as a residual of fossil fuel emissions, ocean sink, and the atmospheric uptake:

land sink = emissions (fossil fuel and LUC) – atmospheric growth rate - ocean sink

- Improved measurements and models now provide independent estimates of the land sink, but this ***residual*** approach is still useful for estimating some components of the system that are difficult to measure directly, such as **soil carbon**.
  - If we have adequate constraints on above-ground biomass and reliable atmospheric inversions:

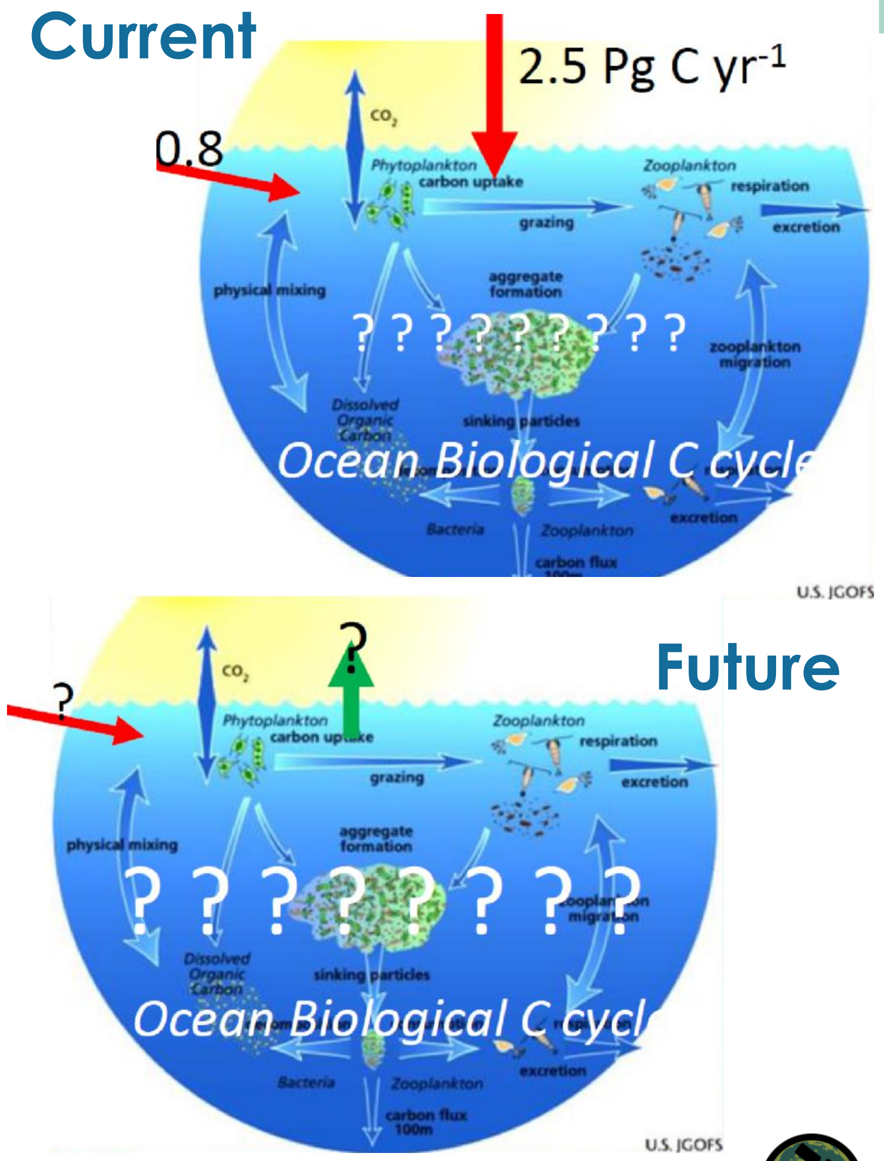
soil carbon change = atmospheric change - above-ground biomass change



A Critical Gap: Monitoring the Ocean Carbon Sink

How will the ocean sink change in response to human activity and climate change?

- Will the ocean sink continue to remove more than ***25%*** of anthropogenic CO_2?
- What is the role of biology in the ocean carbon cycle and how will it change in the presence of increasing ***ocean acidification*** and ***climate change***?
- How will the exchanges of carbon between the land, ocean, and atmosphere evolve over time?
- How are humans altering the ocean carbon cycle and what are the feedbacks?



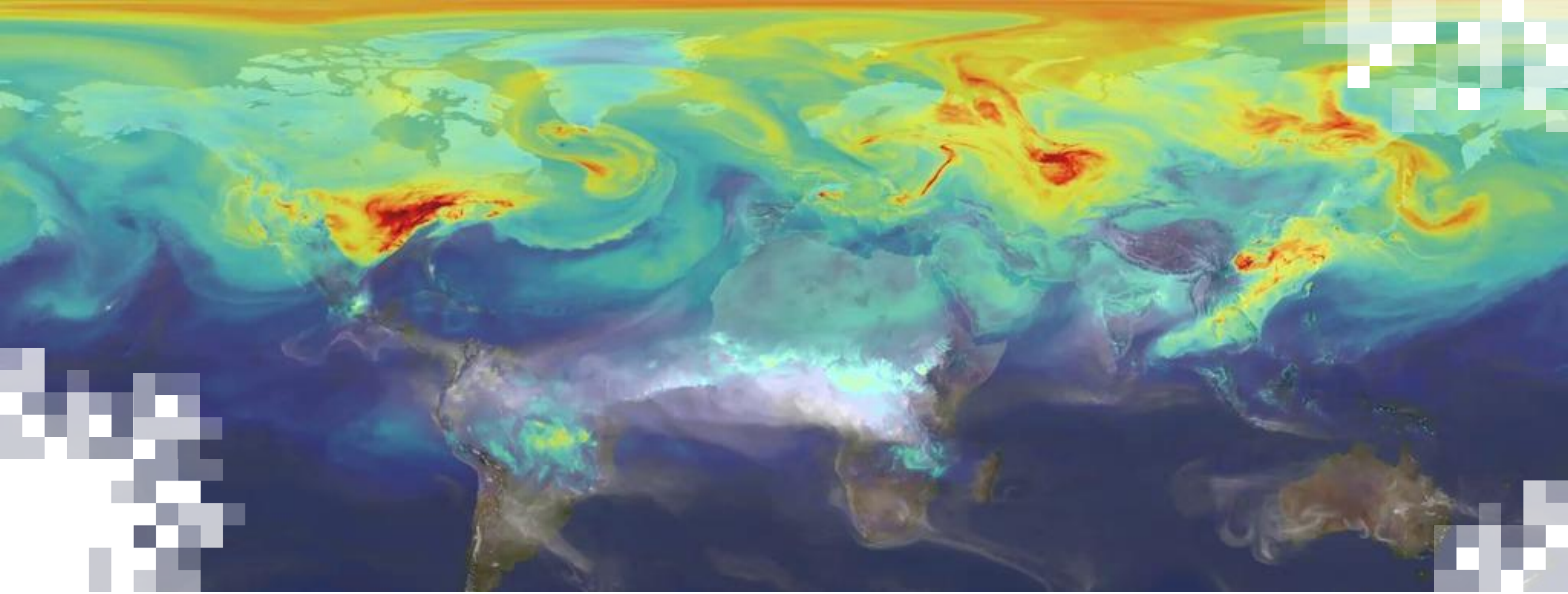
Answers to these questions are critical to the climate mitigation goals of the Paris agreement.

Global Ocean Observing System

The Need to Track Changes in the Ocean Sink

- When integrated over the industrial age:
  - The **land sink** associated with intact forests and other natural parts of the terrestrial biosphere has roughly balanced sources associated with LUC.
  - The **ocean** has been a cumulative net sink of anthropogenic carbon emissions.
- From 1750 to 2010, the ocean has cumulatively absorbed excess carbon equivalent to about **45%** of industrial-era fossil fuel emissions, or about 30% of the total anthropogenic emissions, including land use change.
- Oceans are currently absorbing about 26% of anthropogenic fossil fuel emissions.
- Interestingly, CO_2 emissions and removals by the ocean:
  - Are not included in the inventory reports submitted to the global stocktakes
  - Must be determined from *in situ* (ship, buoy, drone) sensors because space-based CO_2 observations do not yet have adequate precision and accuracy to resolve fluxes

The ocean sink is a GAP not addressed by bottom-up or top-down methods.



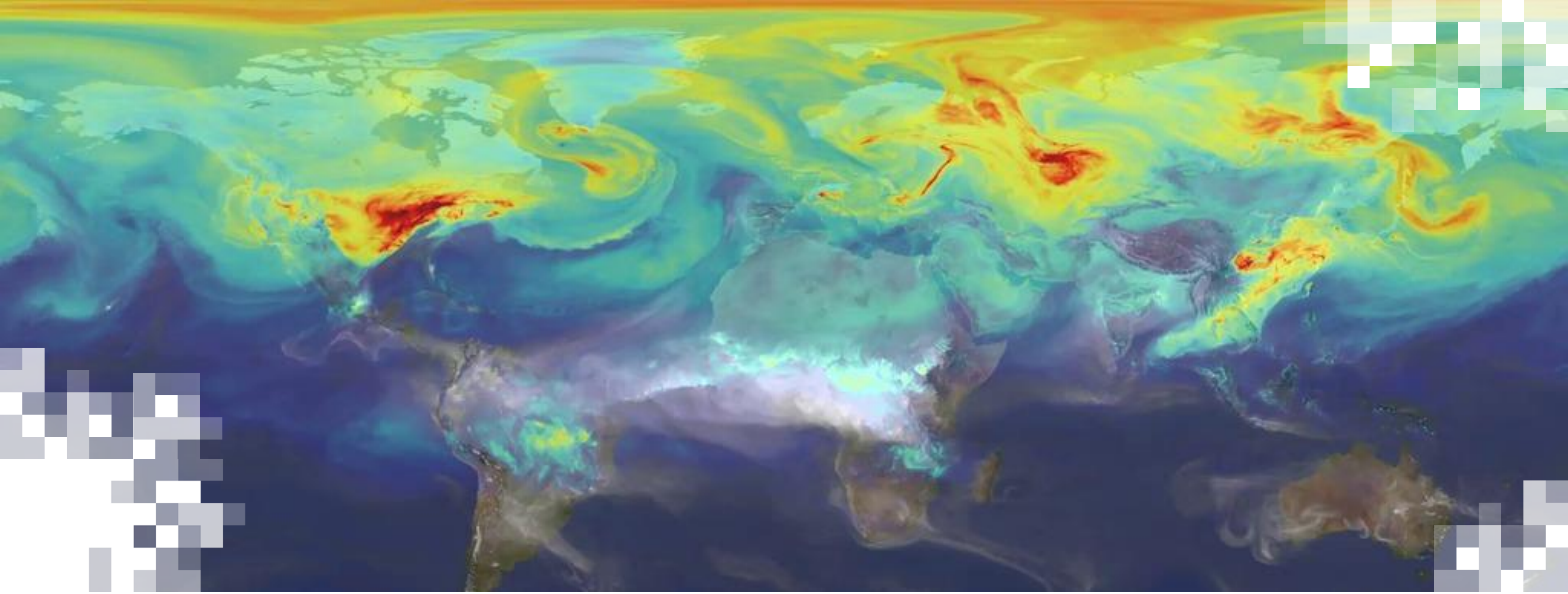
Ensuring Transparency and Assessing Collective Progress Towards the Goals of the UNFCCC and the Paris Agreement

Ensuring Transparency of Top-down Data and Methods

- **Document CO_2/CH_4 concentration data acquisition, analysis, & validation methods**
  - Measurement approach (precision, accuracy, resolution and coverage)
  - Retrieval model capabilities/limitations (forward, instrument, and inverse models)
  - Priors and other assumptions and input data sets used
  - Traceability of validation approach to accepted accuracy standards
- **Document inverse modeling tools and products**
  - Model architecture (assimilation, inverse methods), spatial, and temporal resolution
  - Source of meteorological fields, prior concentrations, and fluxes
  - GHG measurement dataset (in situ, remote sensing, land or ocean only, land + ocean)
- **Document uncertainties and best practices for uncertainty propagation**
  - Measurement uncertainties
    - Precision, accuracy, and representation (spatial/temporal sampling) errors
  - Inverse model uncertainty quantification approach
    - Range fluxes predicted within ensemble, input/prior uncertainty propagation

Assessing Collective Progress Toward the Goals of the UNFCCC and Paris Agreement

- Atmospheric measurements of CO_2, CH_4, and other GHGs provide direct constraints on their atmospheric abundances and trends over time.
  - These data also provide the input needed by the climate modeling community to assess the impacts of GHG changes on surface and atmospheric temperatures and other climate variables.
- Regionally, comparisons of top-down budgets and bottom-up inventories show:
  - Fraction of the **total net emissions** and removals captured by the inventories
  - Fraction of the fluxes originating from the **ocean**, **unmanaged land**, and **transient events**, which are usually excluded from inventory reports
- Atmospheric CO_2 and CH_4 flux estimates can also be combined with high-resolution activity maps to yield improved regional-scale estimates of emissions factors from the land biosphere.



In Summary…

Key Takeaways

- **Rapid**, **deep**, and **sustained** reductions in greenhouse gas emissions are essential to limit global warming to 2°C above pre-industrial levels.
- The global stocktakes provide a means of tracking progress toward these goals.
- Bottom-up national inventories and top-down atmospheric budgets provide complementary information about greenhouse gas emissions and removals.
  - It should be possible to combine top-down CO_2 and CH_4 budgets with bottom-up national inventories to produce a more complete & transparent global stocktake.
  - This is clearly still a **work in progress**.
- Here, we have reviewed the advantages, challenges, and progress to date in efforts to compare and combine bottom-up inventories and top-down budgets.
- We have also introduced new opportunities for using top-down atmospheric CO_2 and CH_4 budget to facilitate the development and assessments of future national inventories.

Thank You!