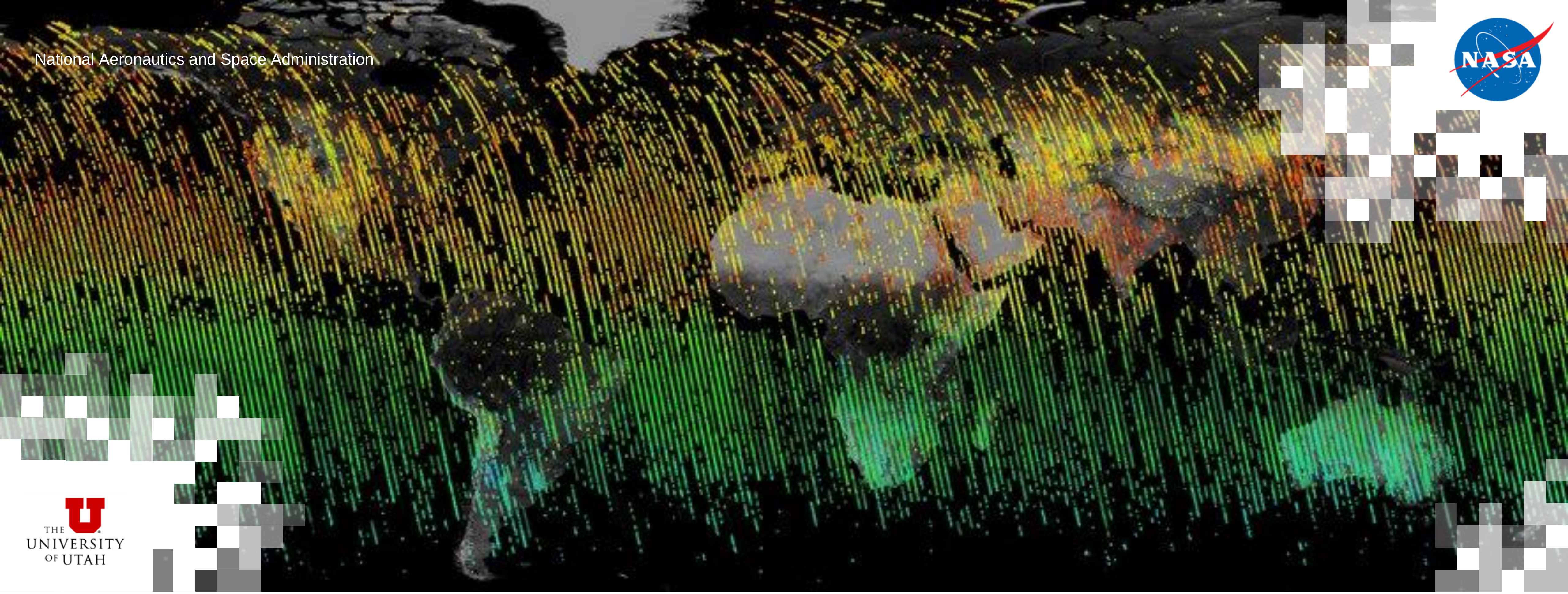


Measuring Atmospheric Carbon Dioxide from Space in Support of Climate Studies: Global and Regional Carbon Cycle Studies

Abhishek Chatterjee, OCO-3 Project Scientist, OCO-2 Deputy Project Scientist, Jet Propulsion Laboratory/Caltech

May 31, 2022

Webinar Agenda

Part 1: An Introduction to XCO_2 with OCO-2 and OCO-3

- EDT (UTC-4:00)
- Tuesday, May 24, 2022
- Trainers: Vivienne Payne (JPL)
- Background of the XCO2 measurement and how it is measured
- Description of the OCO-2/OCO-3 sensors
- Characteristics, limitations and validation of the measurement
- Q&A

Part 2: A Demonstration on how to Access and Visualize OCO-2/OCO-3 Data

- EDT (UTC-4:00)
- Thursday, May 26, 2022
- Trainers: Karen Yuen (JPL)
- Use of Jupyter Notebook to access, search, filter and display XCO_2 data
- Q&A

Part 3: XCO_2 in Support of Global and Regional Climate-Related Studies

- EDT (UTC-4:00)
- Tuesday, May 31, 2022
- Trainers: Abhishek Chatterjee (JPL)
- Global and regional carbon flux estimation, and carbon cycle response to climate variability and changes in anthropogenic emissions
- Q&A

Part 4: XCO_2 in Support of Local and Regional Climate-Related Studies

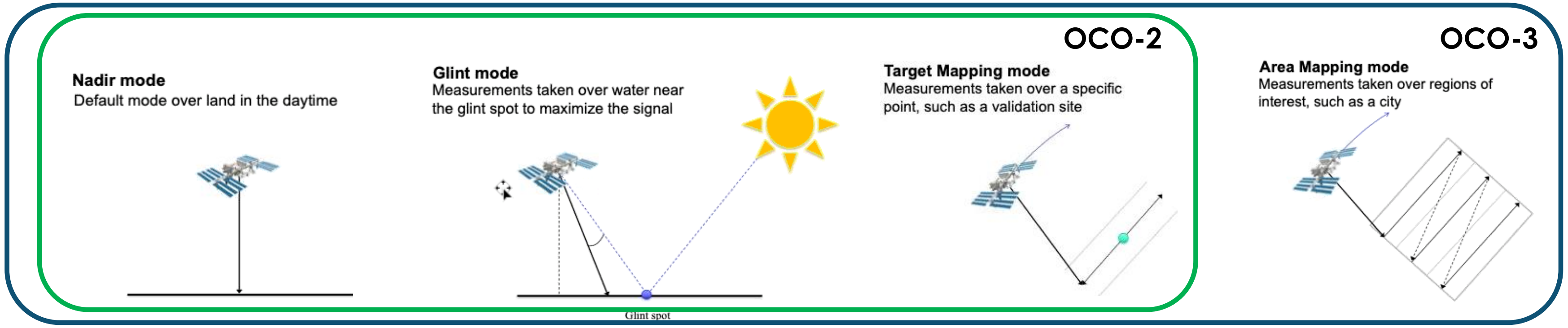
- EDT (UTC-4:00)
- Thursday, June 2, 2022
- Trainers: John Lin (University of Utah)
- Climate impacts from localized emissions, air quality, and urban density
- Q&A

Overview

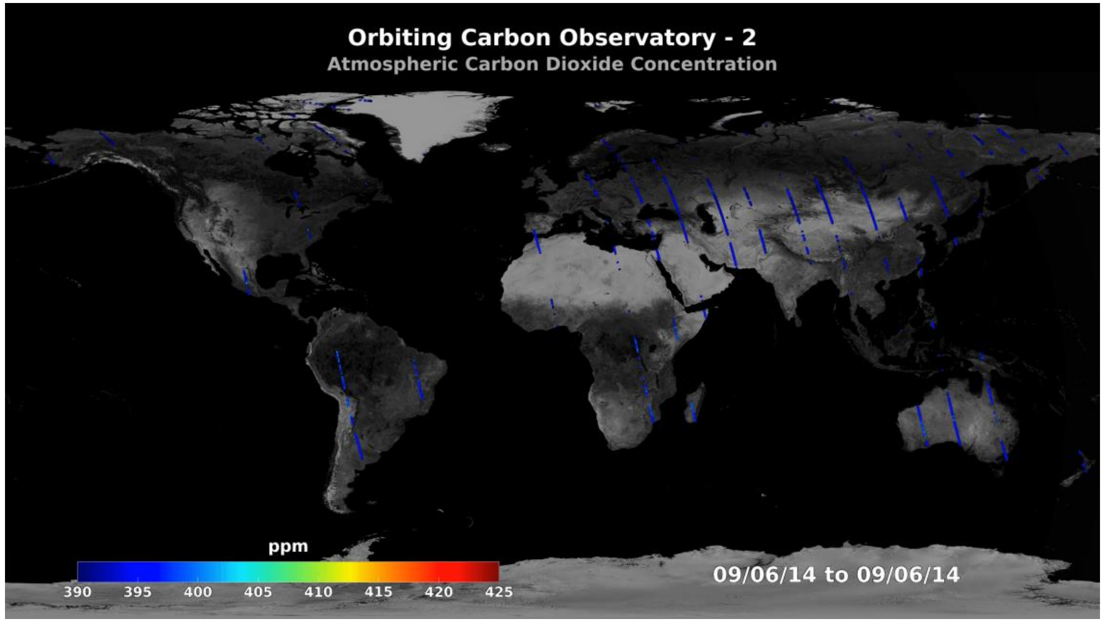
- Recap of OCO-2 and OCO-3 XCO_2 measurements
- Overview of the carbon cycle
- Higher-order products (Level 3 XCO_2 and Level 4 CO_2 Fluxes)
- Global and regional carbon cycle studies
  - Constraining CO_2 flux exchange between land and ocean surfaces & the atmosphere
  - Carbon cycle response to climate patterns and variability
  - Carbon cycle response to anthropogenic perturbation
- Summary

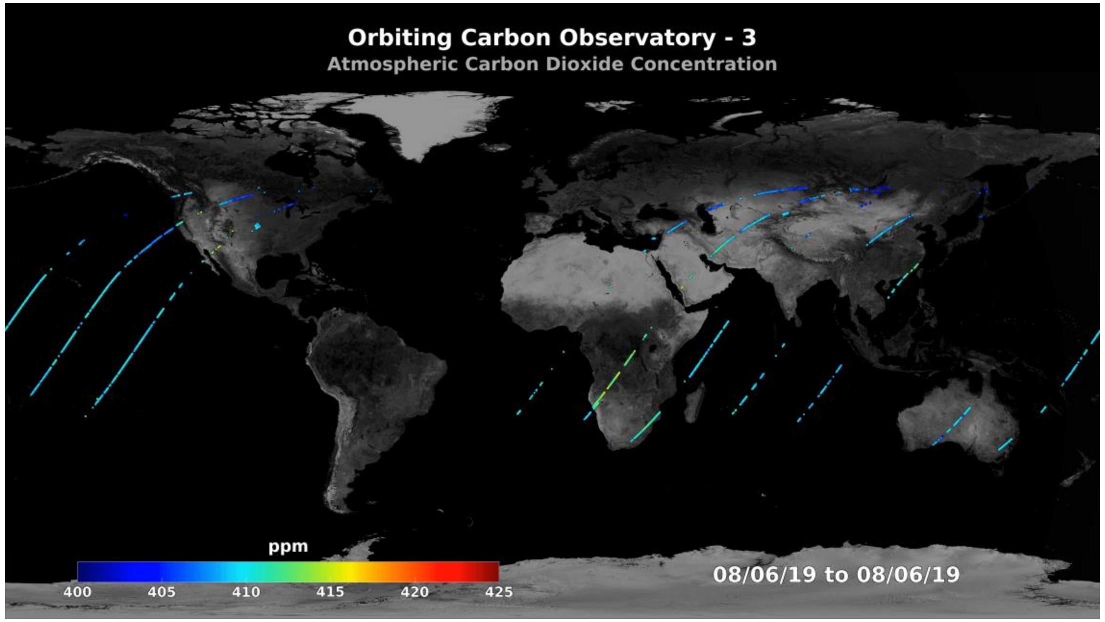
Recap of OCO-2 and OCO-3 XCO_2 Measurements

- OCO-2 launched on July 2014 (data record spans 7.5+ years) and OCO-3 launched in May 2019 (data record spans 2.5+ years)
- Mission Objectives:
  - Retrieve estimates of the column-averaged dry air mole fraction of carbon dioxide (XCO_2) at regional scales (>1,000 km) and with precision better than 0.25% (1 part per million)
- Data Collection:
  - Both OCO-2 and OCO-3 collect data in Nadir, Glint, and Target (specific locations on the ground) modes
  - OCO-3 has a 4th mode: Snapshot Area Mapping (SAM)
    - Enabled by utilizing the Pointing Mirror Assembly (PMA)
    - Targeted to a specific location and then slew to sweep across a region of ~100 km x ~100 km

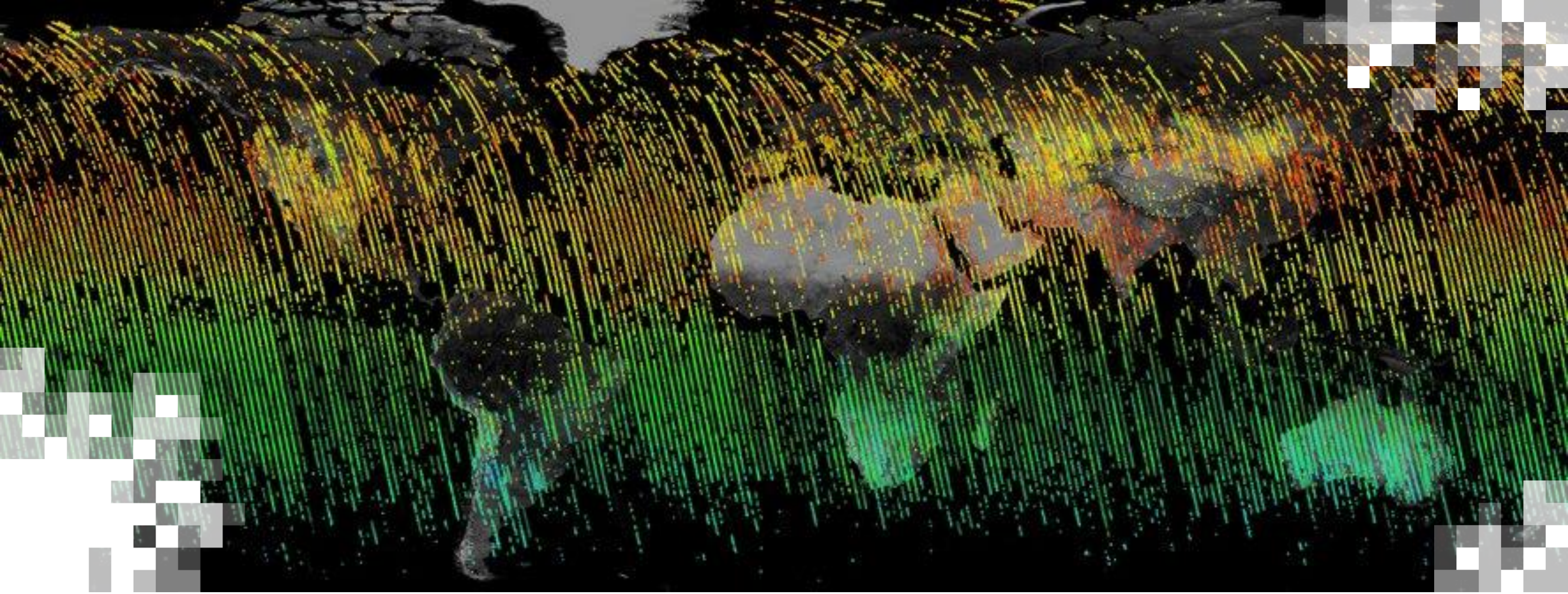


Recap of OCO-2 and OCO-3 XCO_2 Measurements



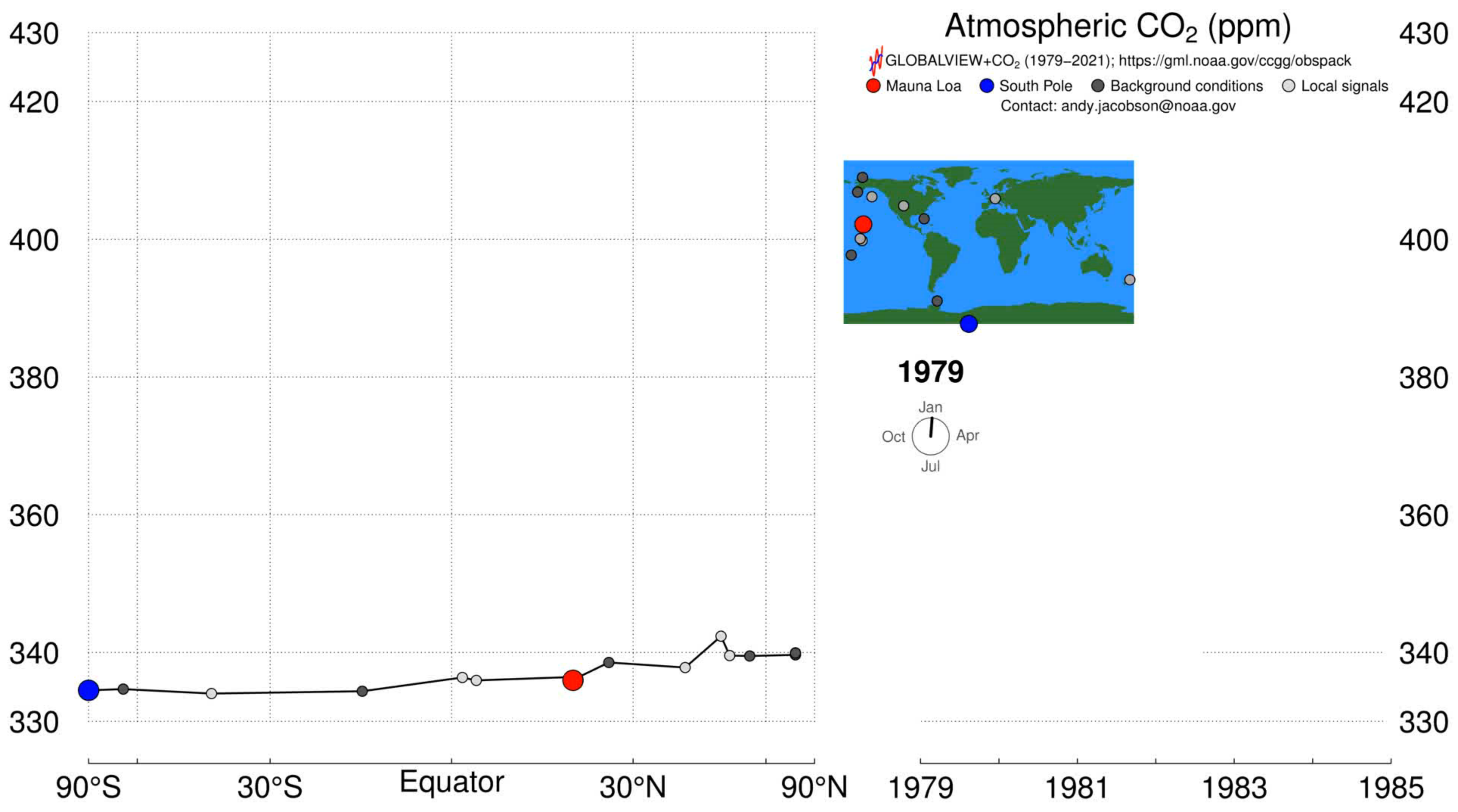


- Data are being used to study (400+ publications since 2014) -
  - Global and regional carbon cycle interactions, response of the carbon cycle to climate patterns, and extreme regional events including droughts, floods, and wildfires.
  - Quantification of CO_2 emissions from human activities, including large power plants and urban centers.



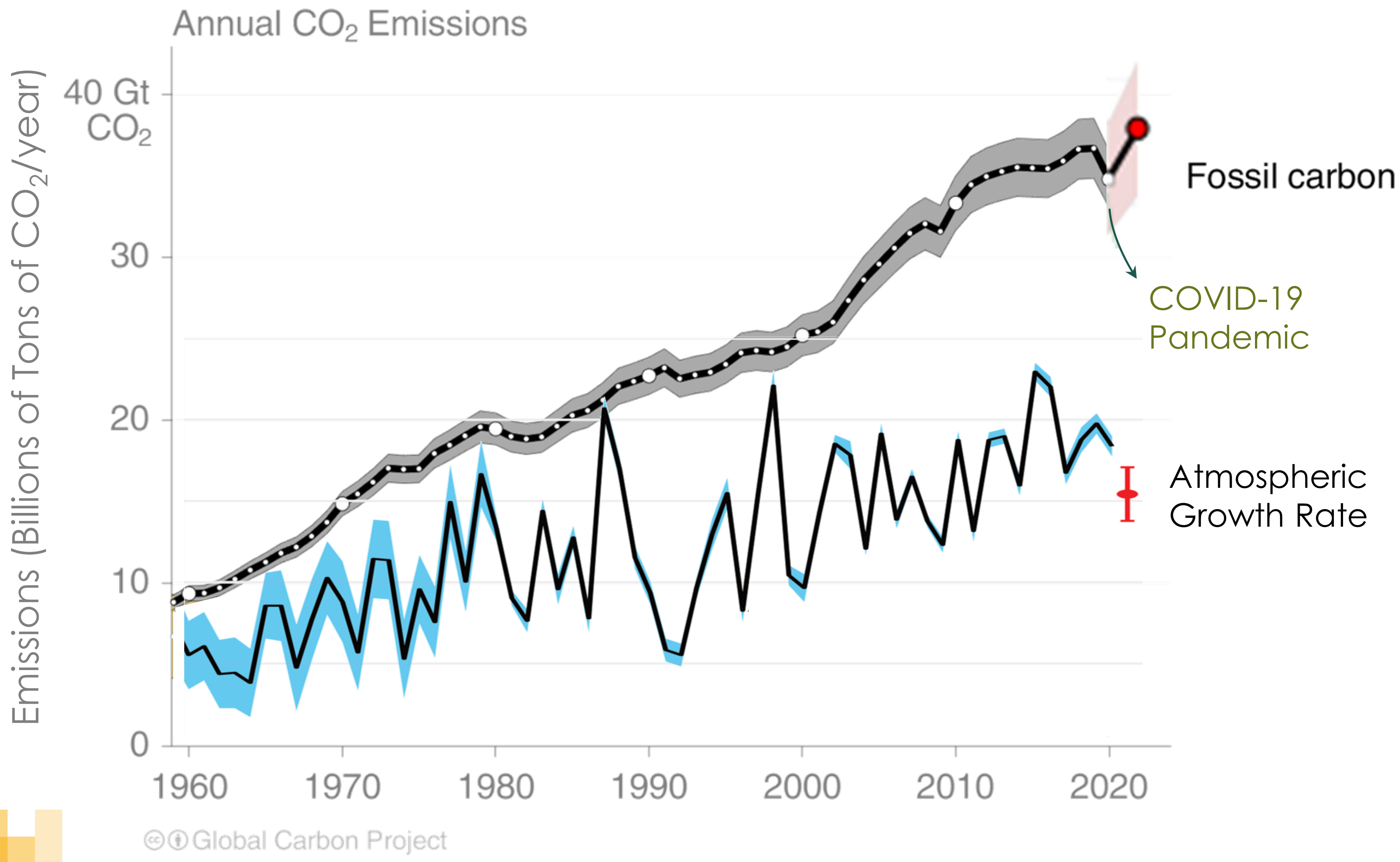
Overview of the Carbon Cycle

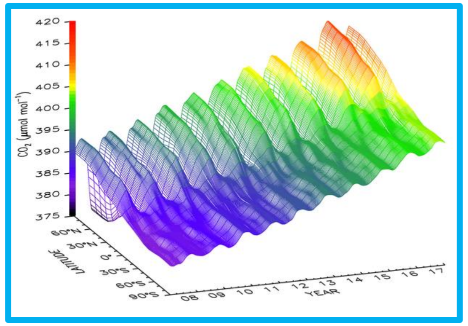
Atmospheric CO_2 Concentrations



https://gml.noaa.gov/ccgg/trends/history.html

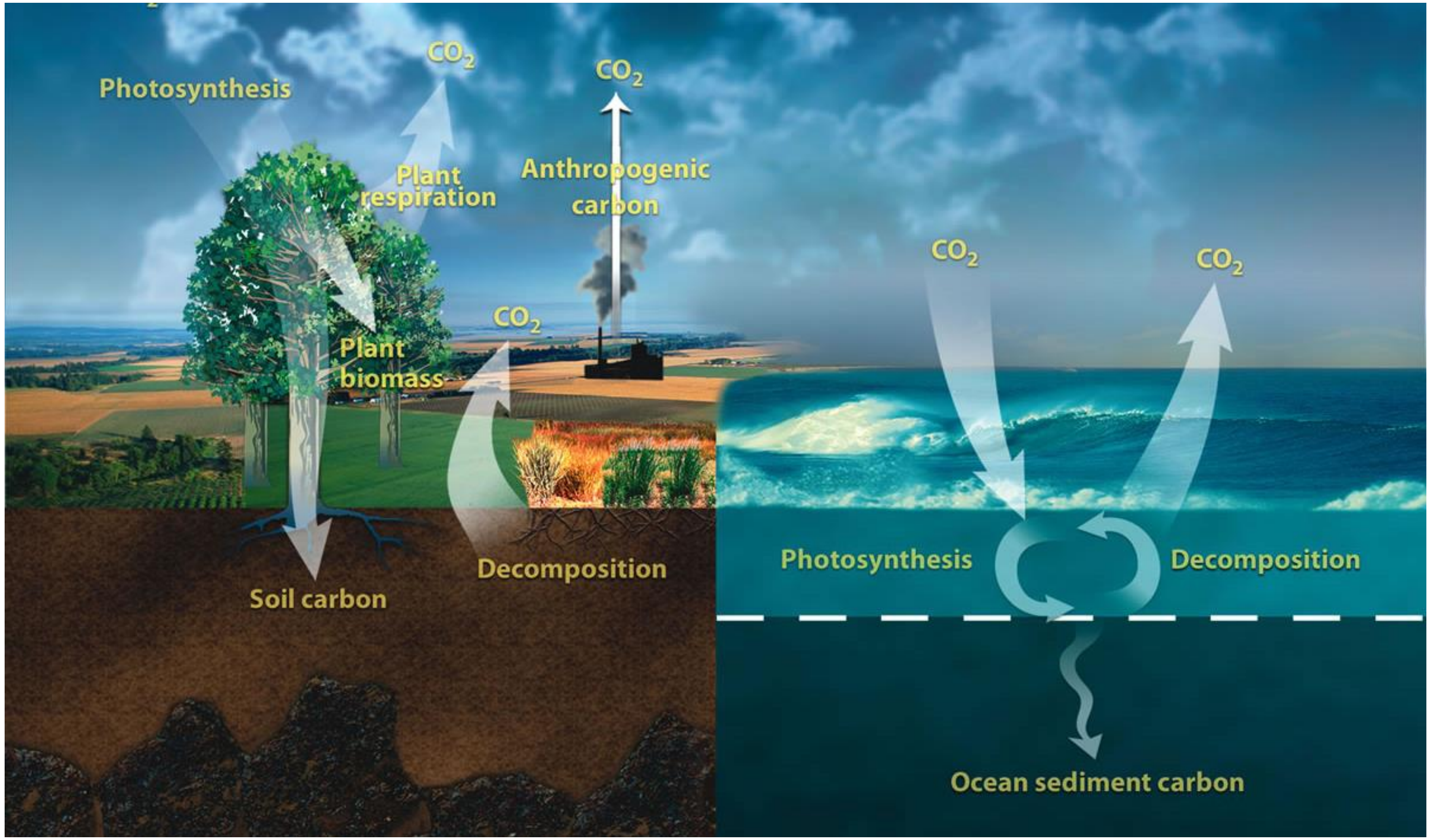
Human Activities Impact CO_2 Concentrations





Adapted from Global Carbon Budget 2021 & ARSET Training on Global Stocktake

Earth’s Carbon Cycle



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

Gross CO_2 Fluxes:

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

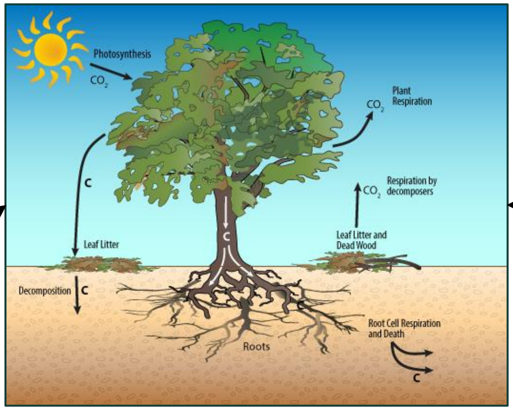
Ocean
- Emissions ~330 Pg CO_2 yr^{-1}
- Removals ~340 Pg CO_2 yr^{-1}

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)

Carbon Cycle Operates at Various Spatial and Temporal Scales

Tree Scale

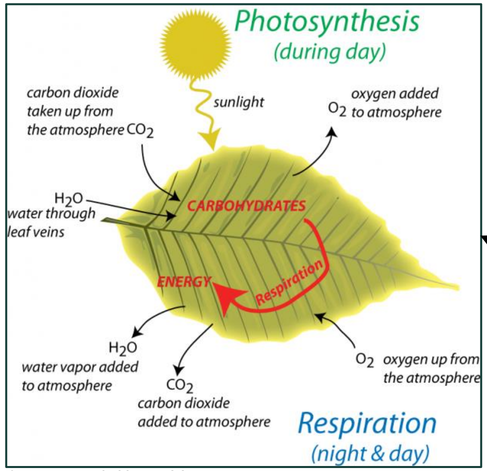


Source: https://serc.carleton.edu/eslabs/carbon/1a.html

Regional Scale

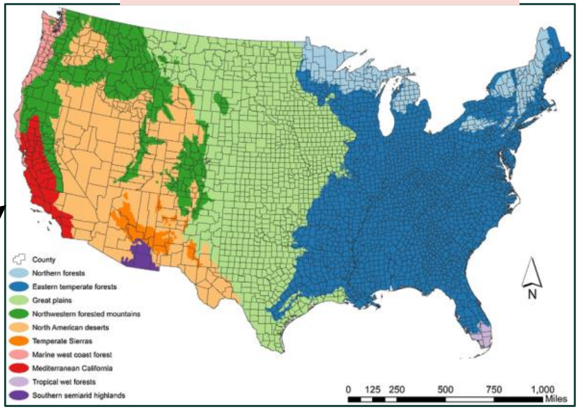
Source: https://www.flickr.com/photos/whsieh78/40393541904/, University of Minnesota, Department of Soil, Water and Climate

Leaf Scale



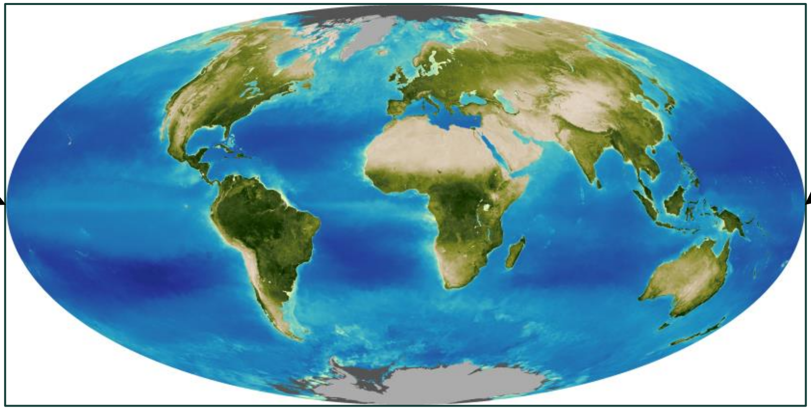
Source: https://www.e-education.psu.edu/earth103/node/1020

Country/ Continental Scale



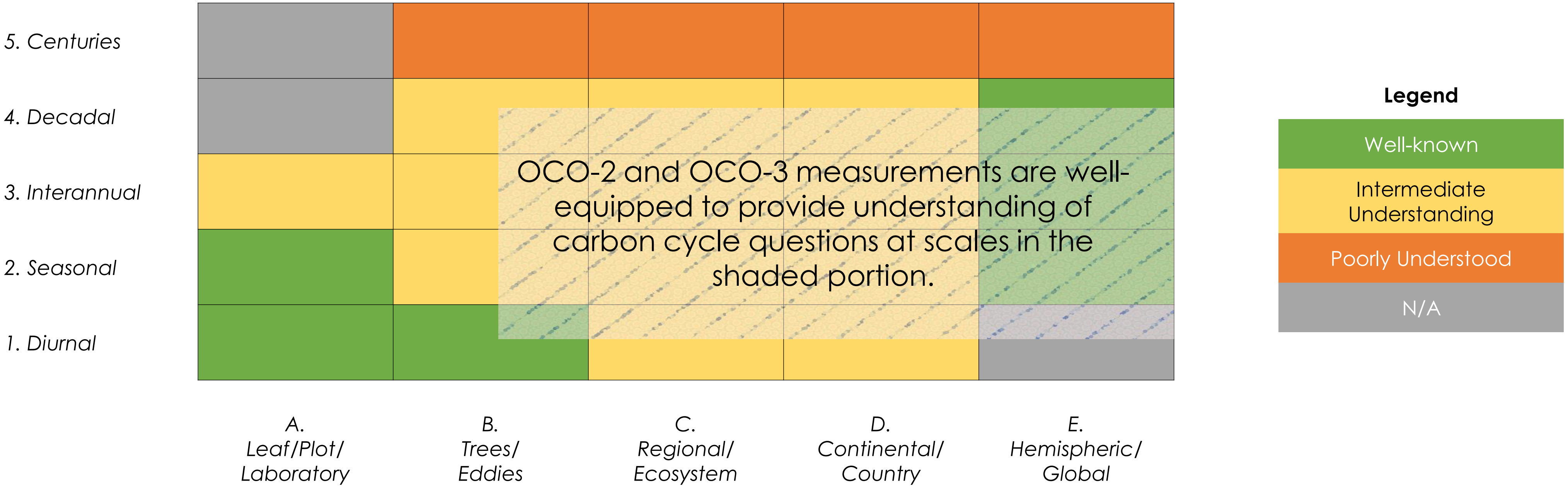
Source: Pickard et al. (2017), DOI:10.1016/j.landurbplan.2016.07.014

Global Scale

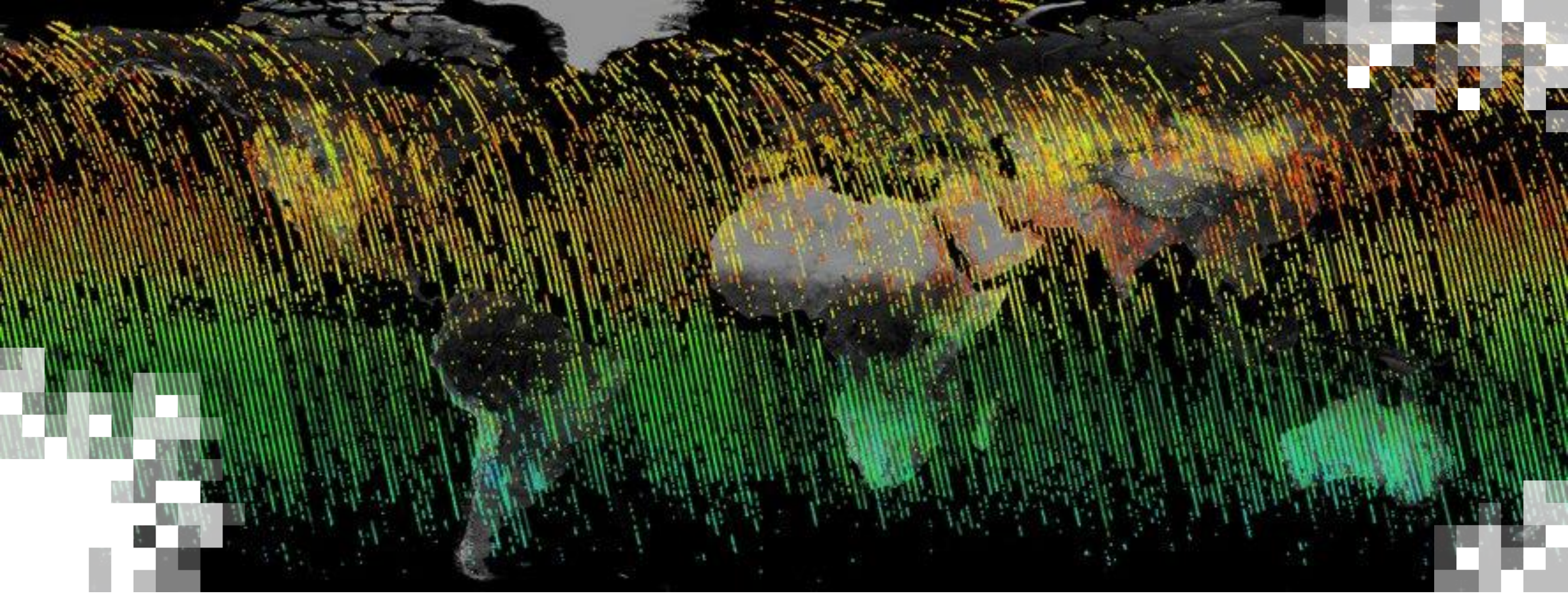


Source: https://earthobservatory.nasa.gov/images/38889/global-biosphere

The Most Pressing Questions in Carbon Cycle Science



Carbon Cycle Science Questions	*Grids*	*Carbon Cycle Science Questions*	*Grids*
Marine physical - biogeochemical coupling	A1, B1	**Disturbance & recovery**	B3, B4, C3, C4, D3, D4
Coastal & inland processes	B2, C2	**Contemporary net carbon sink**	D2, D3, D4, E2, E3, E4
Phenology	A1, A2, A3	**Land and ocean carbon budgets**	D3, D4, E3, E4
Ecosystem physiology - weather interactions	B1, B2	**CO_2, N-fertilization, ocean acidification trends**	A4, B4, C4
C cycle response to water stress events	C1, C2, C3	**Permafrost carbon loss and emissions**	C5, D5
C cycle response to climate variability	B2, B3, C2, C3, D2, D3	**Land use, land management trends**	B4, B5, C4, C5
Ecosystem ⇆ atmosphere flux quantification	B2, B3, C2, C3	**Migration of biomes**	C5, D5



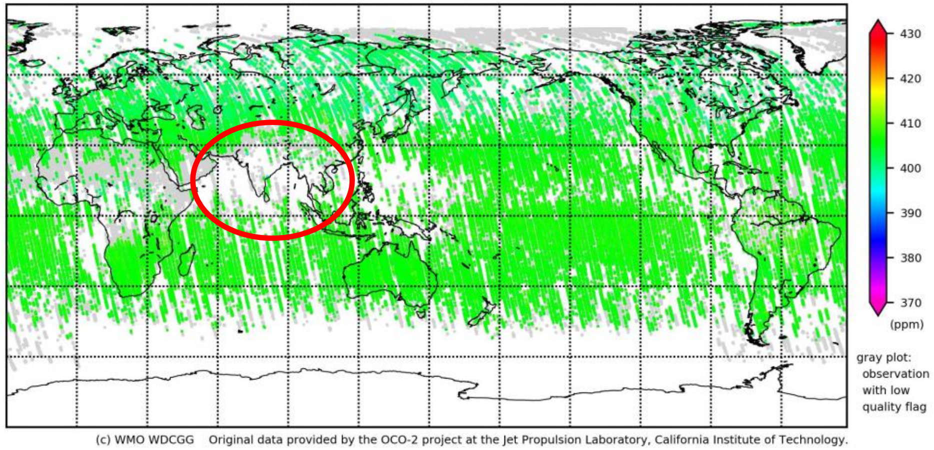
Higher-Order Products
(Level 3 XCO_2 and Level 4 Carbon Fluxes)

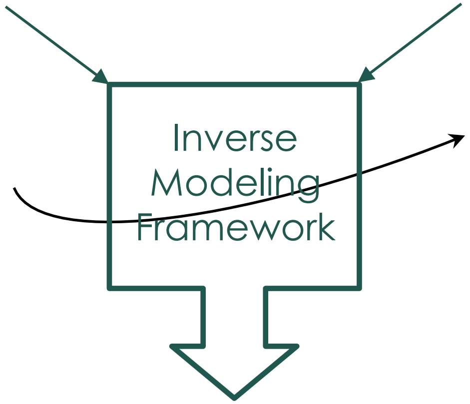
Higher-Order Products From Level 2 XCO_2 Data

- **Level 2** products have "gaps" – missing soundings due to cloud cover, thick aerosol layer, etc. These are also reported in units of concentrations (ppm).
- **Level 3** product - maps XCO_2 to one part per million (ppm) accuracy over the Earth's surface, typically in grids that are ∽50 – 100 km in latitude and ∽ 50 – 100 km in longitude. Think of this as 'gap-filled' maps.
- **Level 4** product - maps the distribution of CO_2 sources and sinks (fluxes in gC m^{-2} yr^{-1}) over the Earth's surface, typically in grids that are ∽ 100 – 500 km in latitude and ∽ 100 – 500 km in longitude. Can be generated from both Level 2 or Level 3 data via a mathematical framework known as 'inverse modeling'.

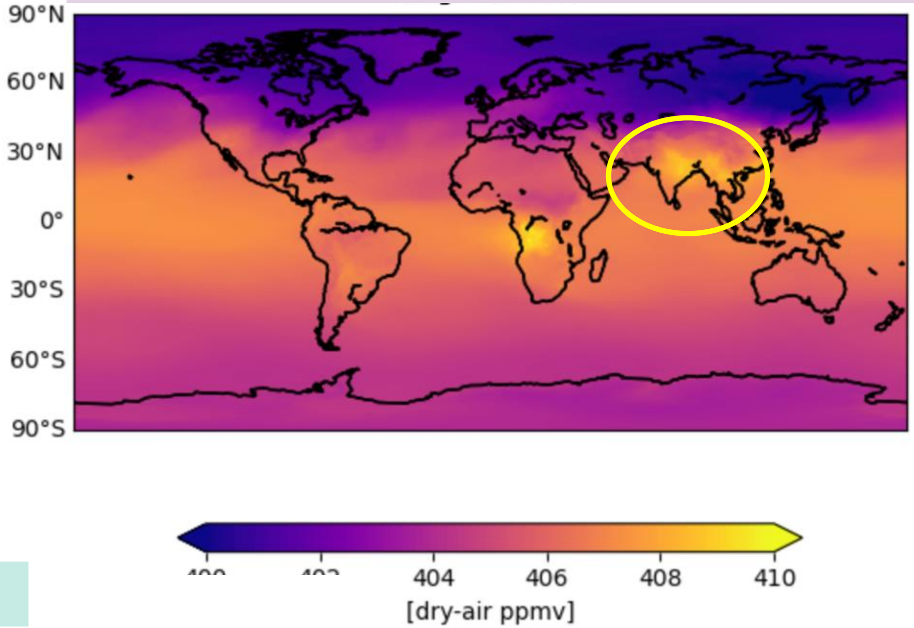
Higher-Order Products From Level 2 XCO_2 Data

Level 2 Product (August 2018)

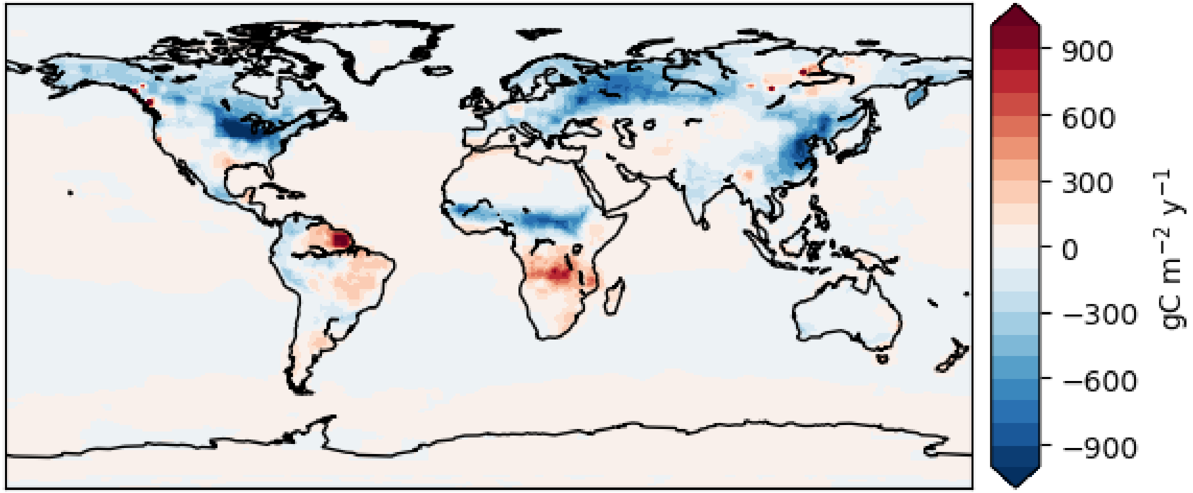




Level 3 (Aug 2018) – Gap-Filled XCO_2 Product



Level 4 (Aug 2018) – CO_2 Flux Product



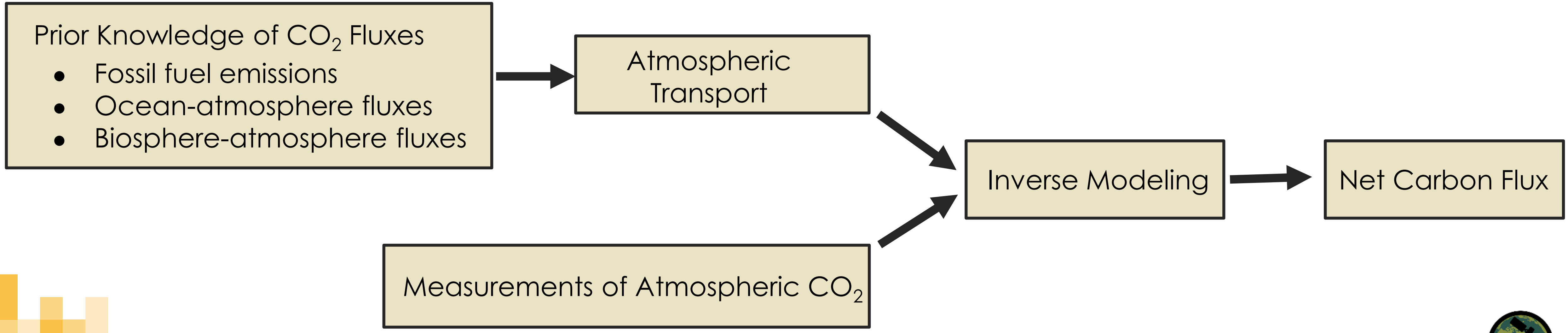
Inverse Modeling

Inverse Modeling:

- Inverse modeling allows us to estimate the CO_2 flux that agrees with observed atmospheric CO_2 concentrations.

Framework:

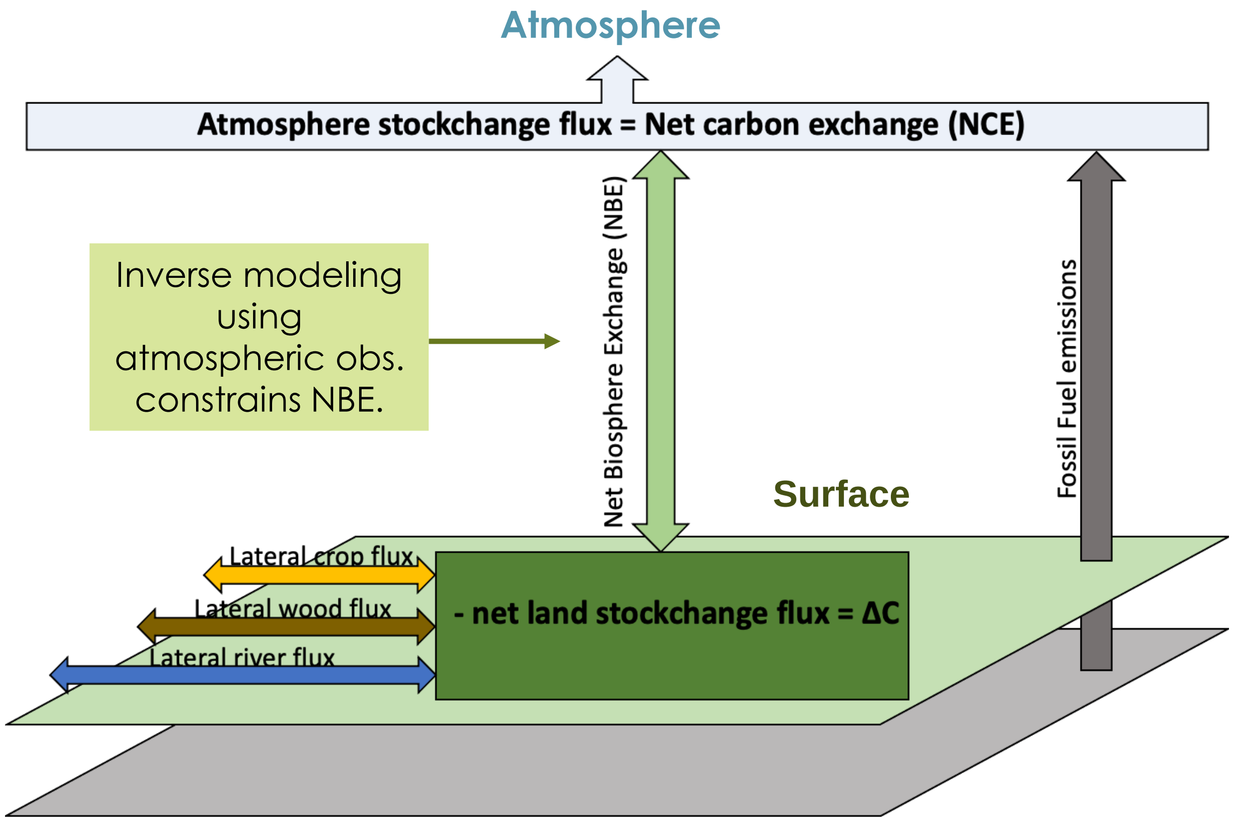
- Simulate atmospheric CO_2 using prior estimate of surface-atmosphere fluxes and realistic winds.
- Compare "measurement" of model atmosphere with real measurements.
- Correct flux estimates to make model atmosphere agree with real measurements, within uncertainties.



Terminology

- **Net Biosphere Exchange (NBE):** Net flux of carbon between the terrestrial biosphere and the atmosphere, including biomass burning. Includes both anthropogenic processes (e.g., deforestation, reforestation, farming) and natural processes (e.g., climate-variability-induced carbon fluxes, disturbances, recovery from disturbances).
- **Fossil Fuel and Cement Emissions (FF)**: The burning of fossil fuels and release of carbon due to cement production, representing a flux of carbon from the geologic reservoir to the atmosphere.
- **Terrestrial Net Carbon Exchange (NCE)**: Net flux of carbon between the surface and atmosphere. For e.g., land NCE can be defined as: **NCE** = **NBE** + **FF**

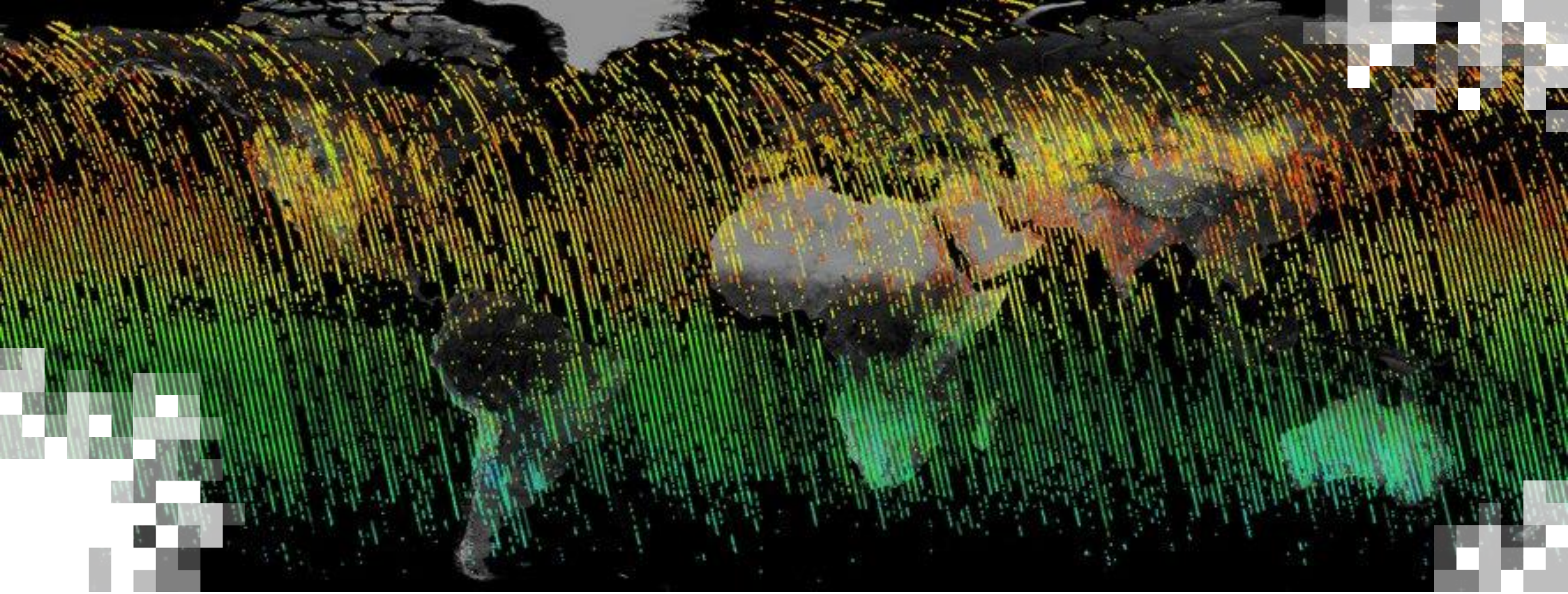
Schematic of NCE, NBE, and Other Carbon Fluxes



Adapted from NASA's ARSET Training on Global Stocktake

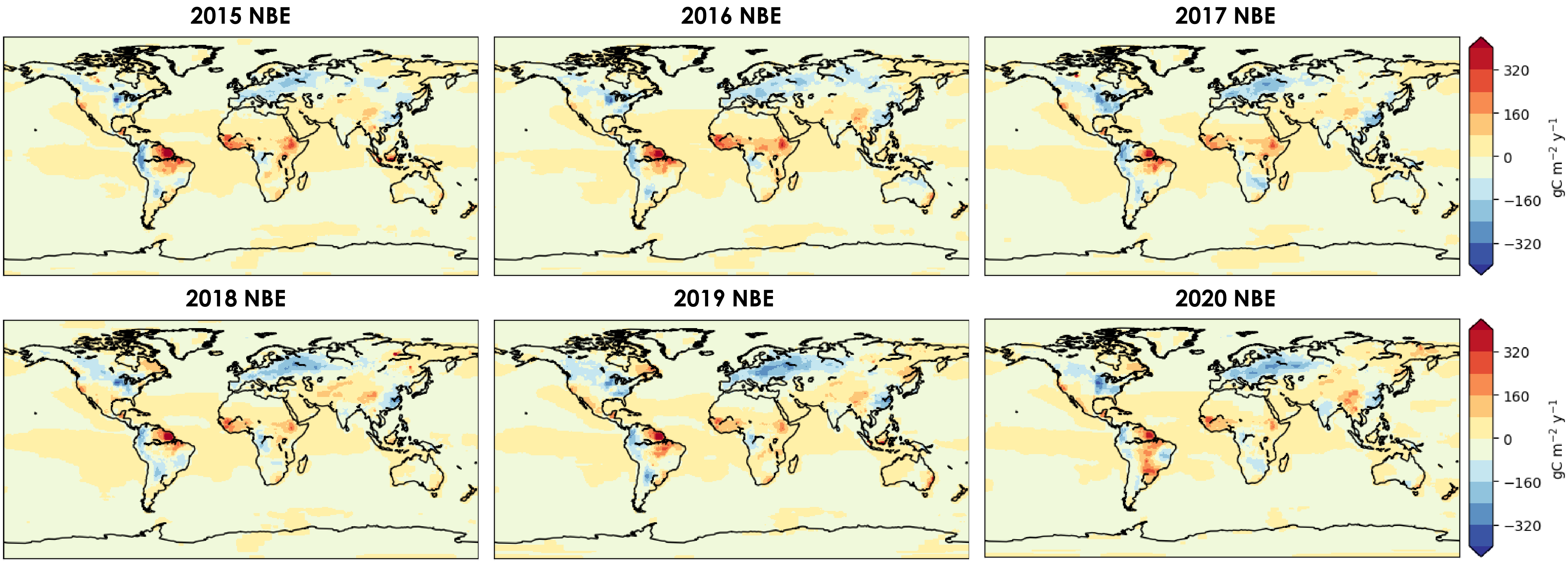
Studies Conducted with Level 2, Level 3, or Level 4 Data

- What is the net CO_2 flux exchange between the land and atmosphere, or the ocean and atmosphere -
  - At global to continental scales
  - At regional scale, for e.g., South Asia
  - At country level scale, for e.g., US, Brazil, India, etc.
- How did the carbon cycle respond to –
  - The 2015 -2016 El Nino
  - The 2019-2020 bushfires in Southeast Australia
- What was the impact on atmospheric CO_2 concentrations due to the COVID-19 pandemic?



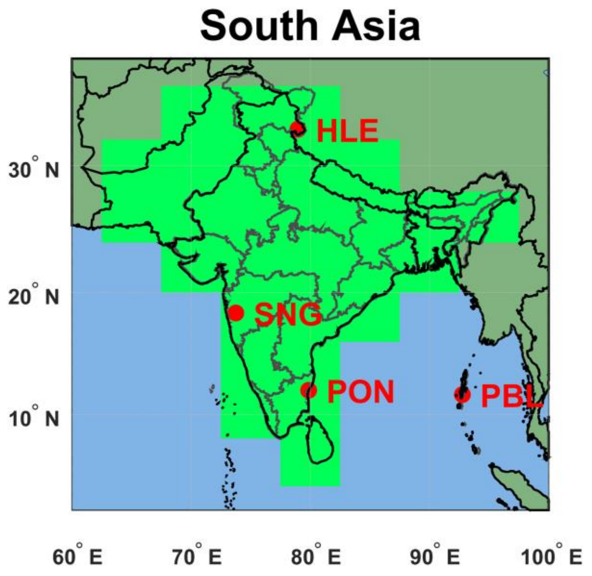
Global and Regional CO_2 Flux Exchange Between Land/Ocean and Atmosphere

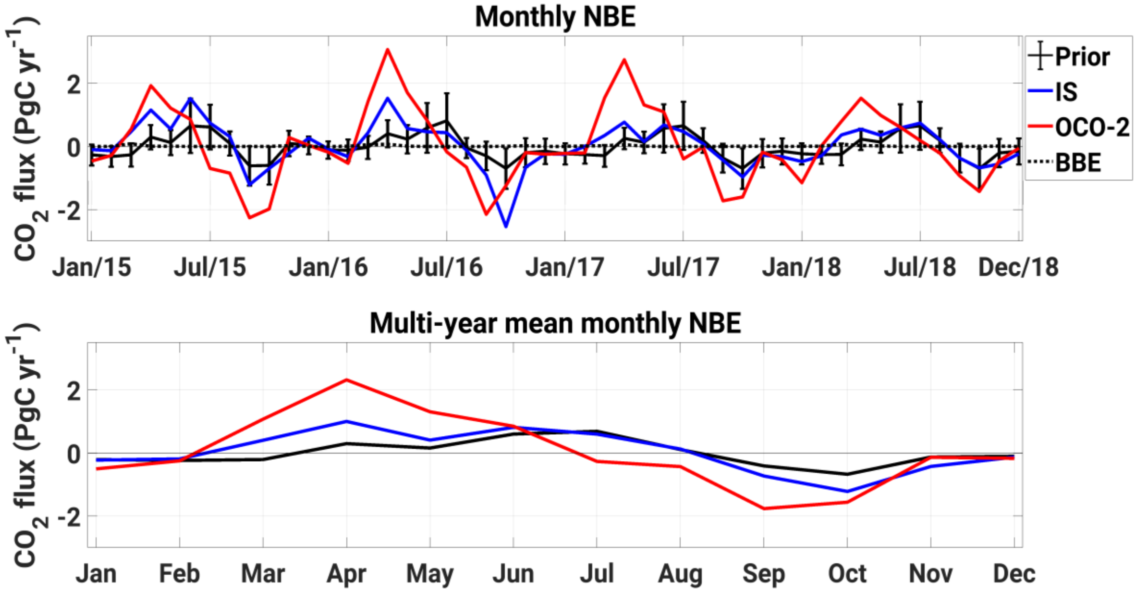
Net CO_2 Flux Exchange Between Land-/Ocean- Atmosphere

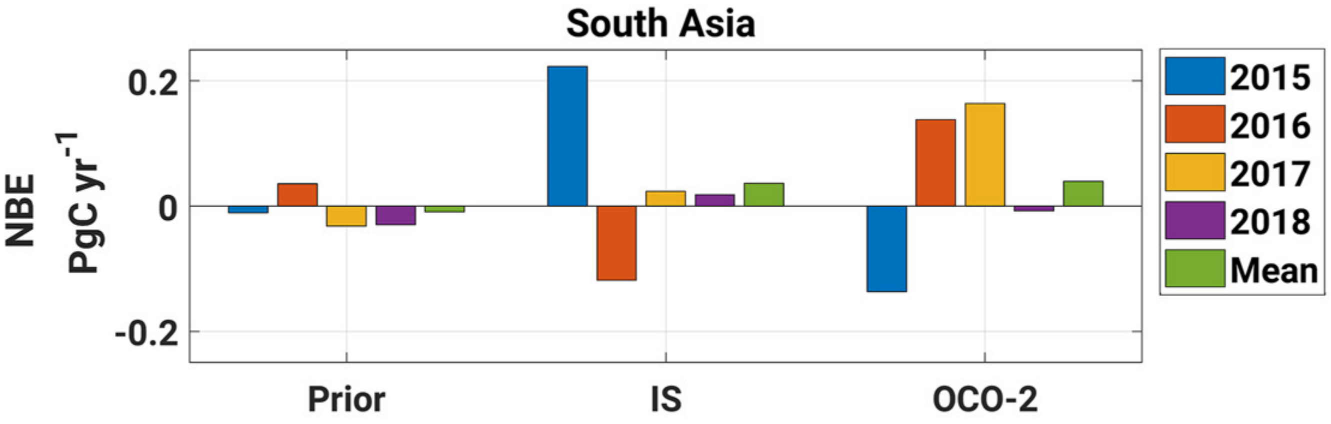


- **Blue** = Carbon uptake by the land and the ocean, **Red** = Carbon release by the land and the ocean
- Note the interesting action happening over the tropical land areas – we will revisit this shortly!
- OCO Science Team routinely generates these estimates – see Crowell et al. (2019), Peiro et al. (2022)

What about CO_2 Flux Exchange at Regional Scales?







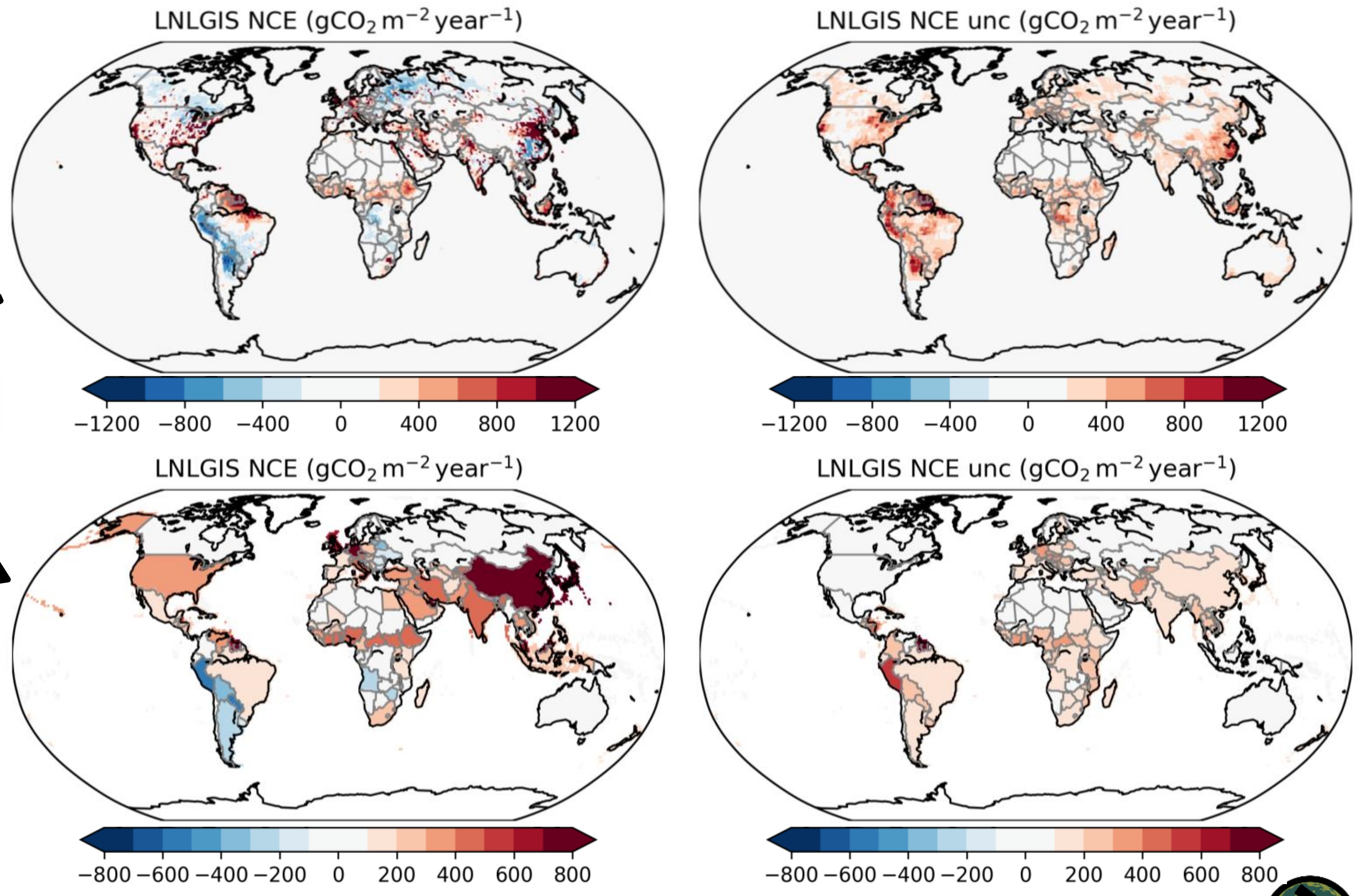
- OCO-2 provides vital information over data-starved regions, such as South Asia, where we do not have many atmospheric CO_2 measurements from ground-based sites.
- CO_2 fluxes estimated from OCO-2 show lower annual sink but larger seasonal amplitude and a phase-shift in seasonality compared to estimates from the in-situ network.
- See Philip et al. (2022)

CO_2 Flux Exchange at Country Scales

- One can estimate the **Net Carbon Exchange (NCE) = Fossil Fuel + Net Biosphere Exchange**
- Estimates provided on a 1° x 1° grid
- Aggregated to country totals
- See ARSET Training on [Global Stocktake]() for significance of these estimates and maps

Net Carbon Exchange (NCE) for 2015–2020

Mean | **Uncertainty**



NCE fluxes Aggregated to Country Totals

Contribution to the UNFCCC Global Stocktake

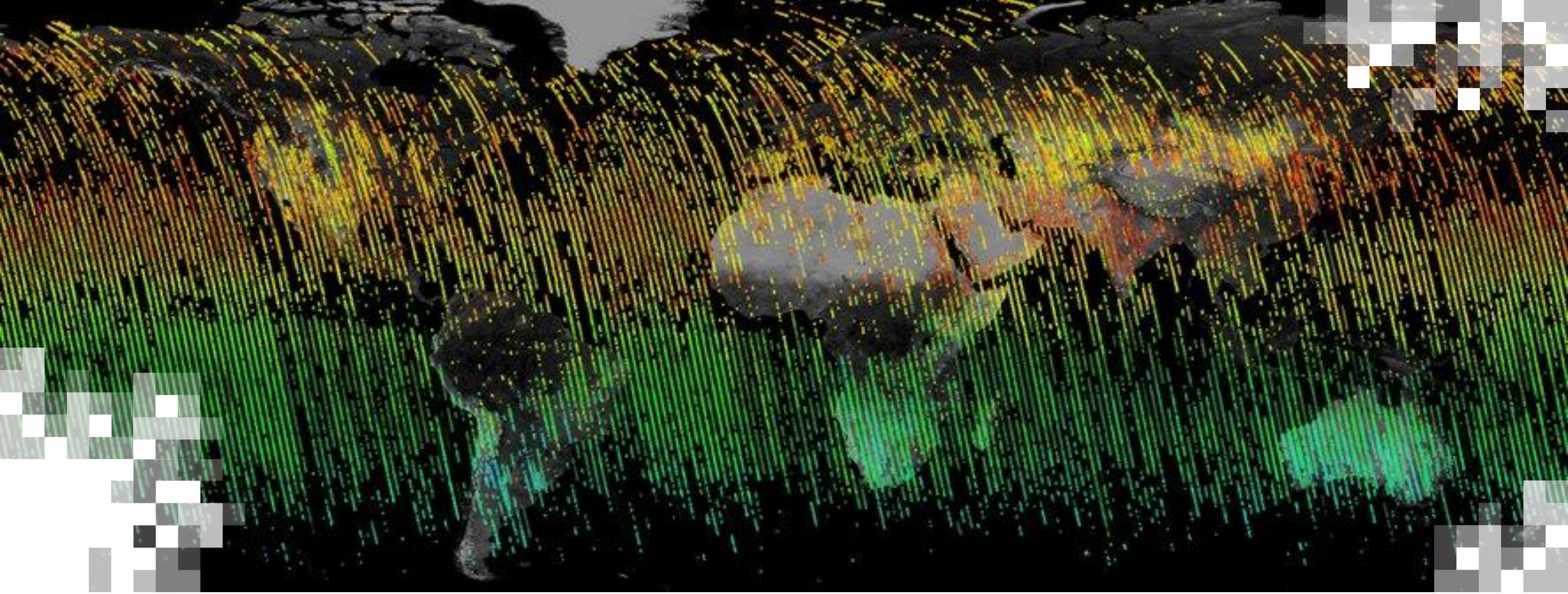
Global Top-Down CO_2 Budgets

- Pilot global CO_2 budgets derived from flux products being developed by the OCO-2 Model Intercomparison Project (OCO-2 MIP)
  - Combine in situ CO_2 measurements and column-averaged CO_2 dry air mole fraction (XCO_2) estimates from OCO-2 to predict fluxes and stock changes

These top-down atmospheric CO_2 budgets complement bottom-up inventories to support a more complete, accurate, & transparent global stocktake (GST) as defined in:

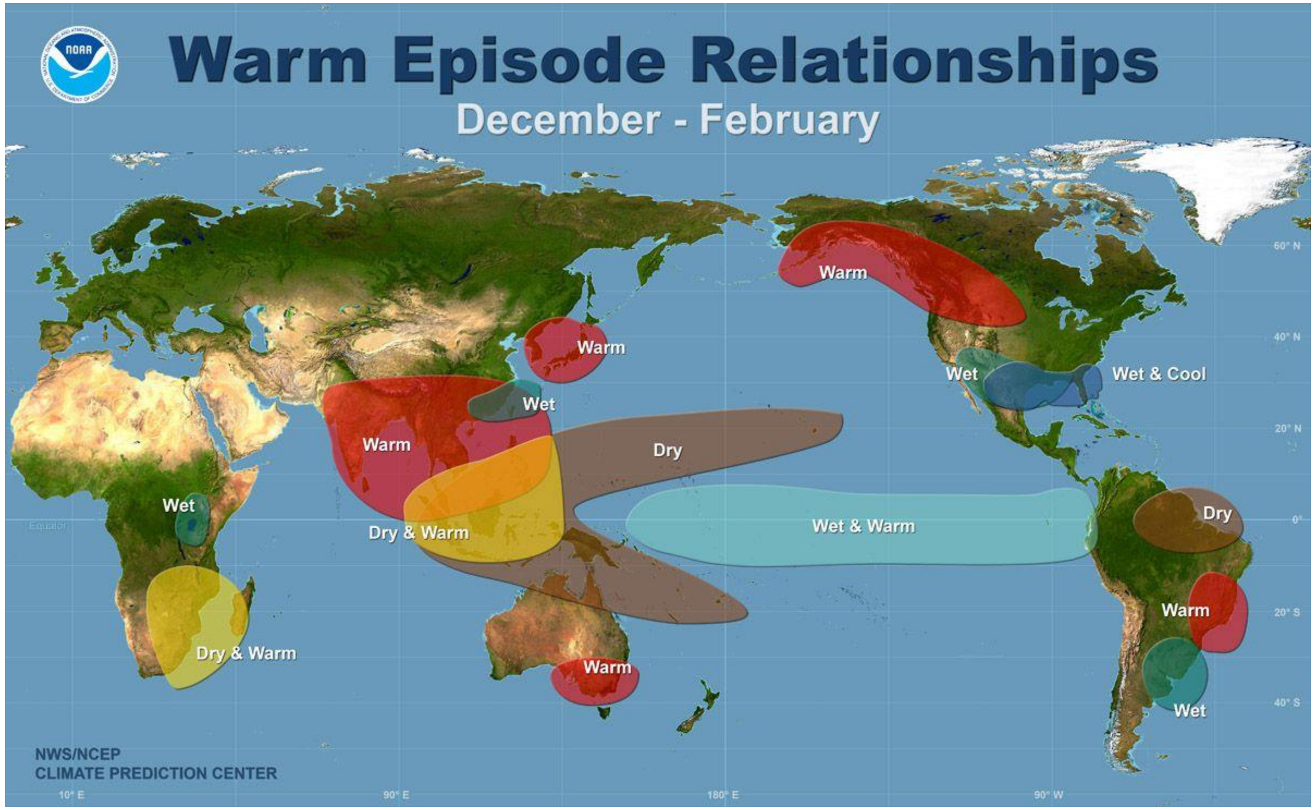
- **Article 14 of the Paris Agreement**

See ARSET Training on **Atmospheric CO_2 and CH_4 Budgets to Support the Global Stocktake**



Carbon Cycle Response to Climate Patterns & Variability

What is an El Niño ?

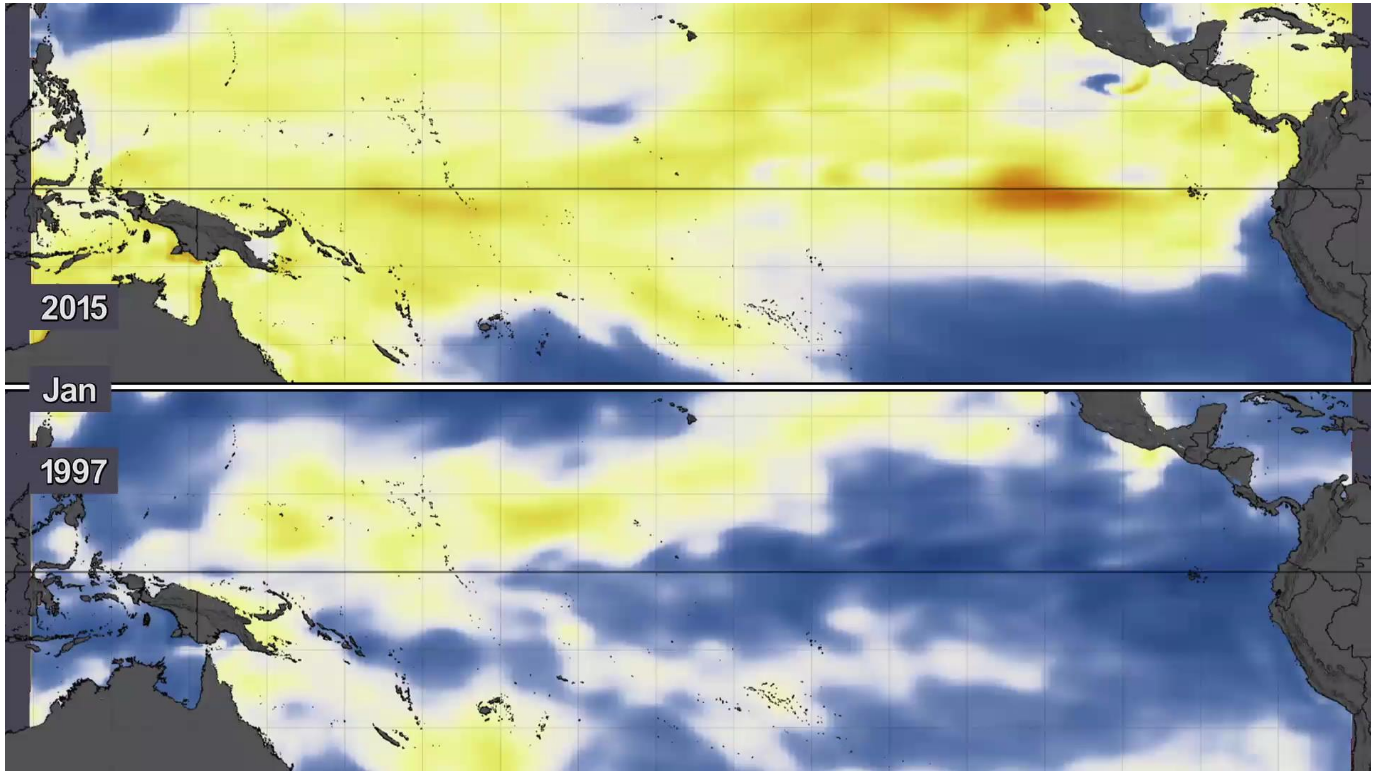


- a climate pattern that describes unusual warming of surface waters in the eastern tropical Pacific Ocean
- "warm phase" of a larger phenomenon called the El Nino-Southern Oscillation (ENSO)
- occurs irregularly at 2-7-year intervals
- impacts ocean temperatures, speed and strength of ocean currents, health of coastal fisheries, and weather from tropics to extra-tropics

For *attendees*: lots of great resources on the web, e.g., climate.gov/enso, https://www.pmel.noaa.gov/elnino/what-is-el-nino

Carbon Cycle Response to the 2015-2016 El Niño

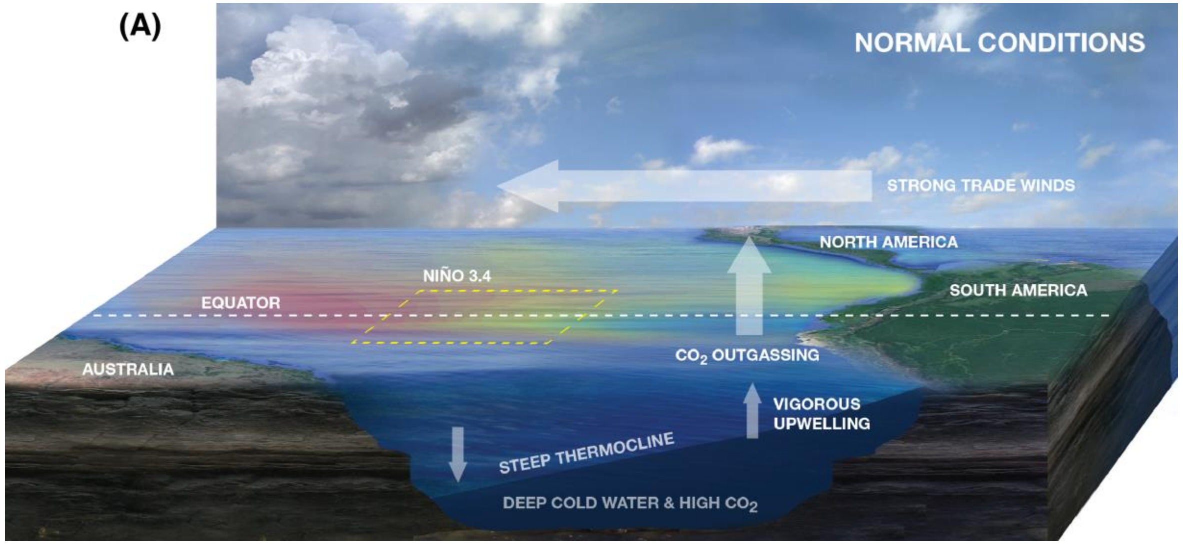
Sea Surface Temperature Anomalies



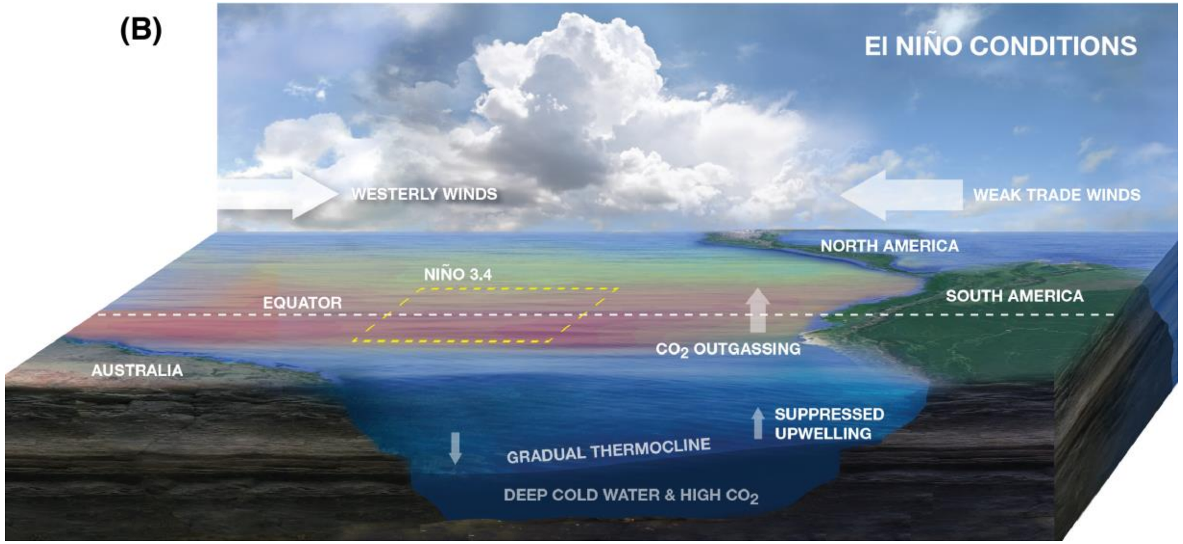
- Correlations between atmospheric CO_2 growth rate and El Niño and La Niña activity have been reported since the 1970s – see Chatterjee et al. (2017).
- ENSO is a big driver of inter-annual variability in the carbon cycle. Studying the response of CO_2 to ENSO → how feedbacks between the physical climate system and global carbon cycle operate.
- Understanding causal mechanisms, especially separating the influence of the marine and the terrestrial components have been challenging due to limited observations over the Tropical Pacific and surrounding regions.

Carbon System in the Tropical Pacific

(A)

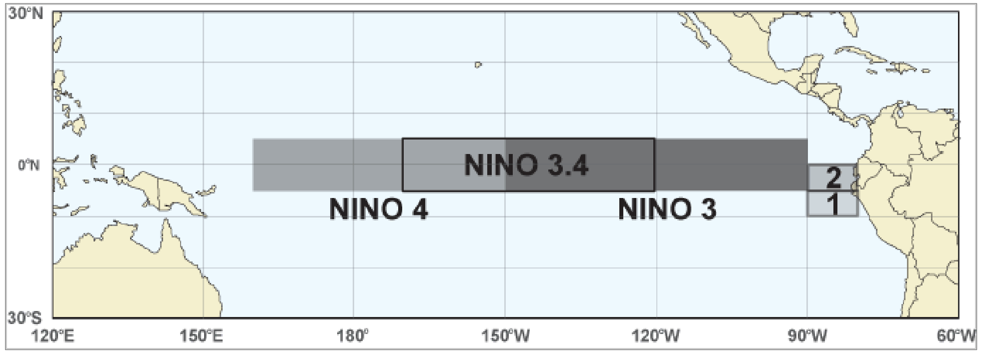


(B)



- **Normal Conditions:** Upwelling of cold, sub-surface waters that have high potential pCO_2 + inefficient biological pump → strong CO_2 outgassing.
- **El Niño Conditions:** Deepening of thermocline, reduction in upwelling, weakening of trade winds + more efficient biological pump → decreases CO_2 outgassing by 40-60%.

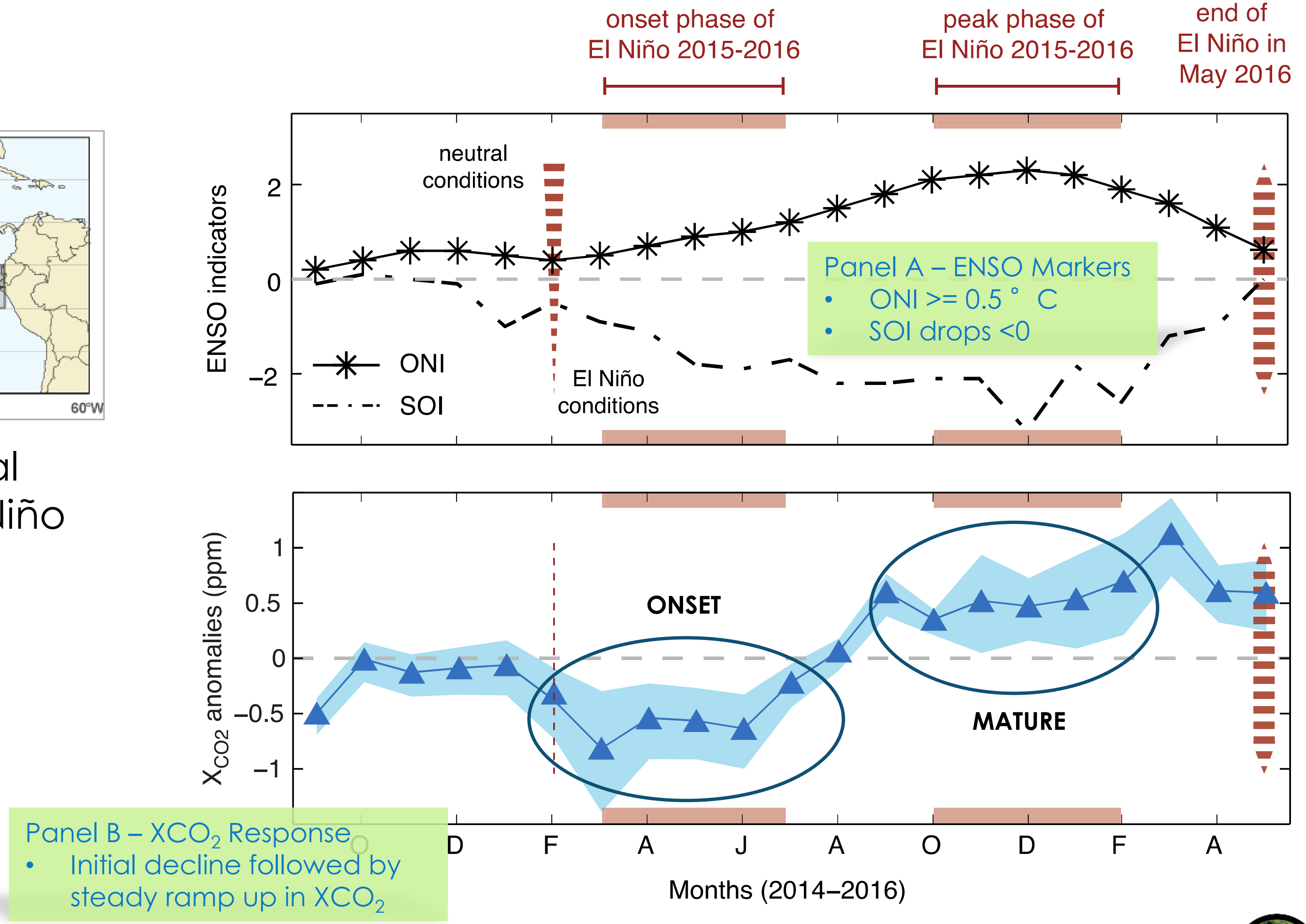
Observable Trends During the 2015 – 2016 El Niño



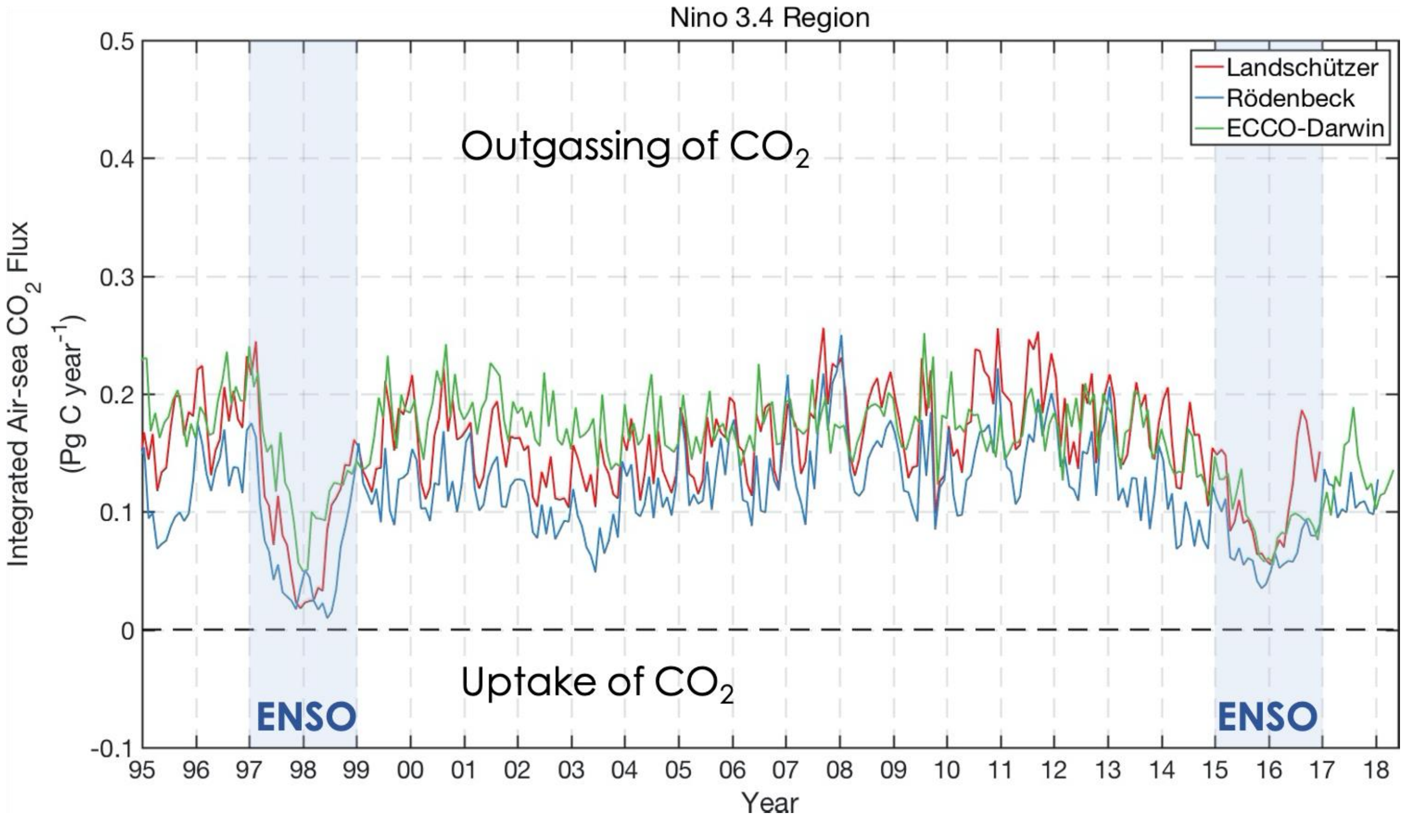
Time-series showing the temporal evolution of X_{CO2} anomalies over Niño 3.4 region

Sep 2014 – May 2016

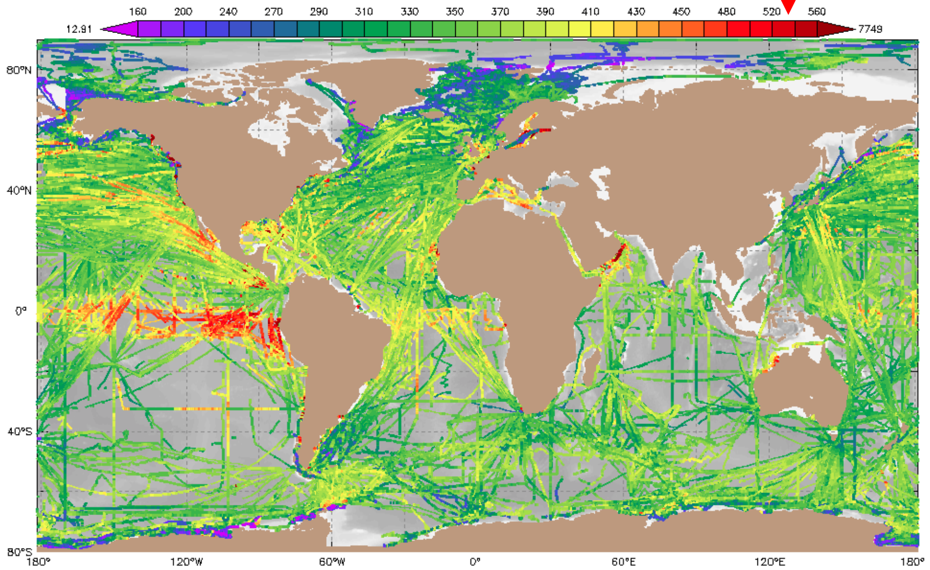
Chatterjee et al. [2017]



Reduction in CO_2 Outgassing from the Tropical Pacific



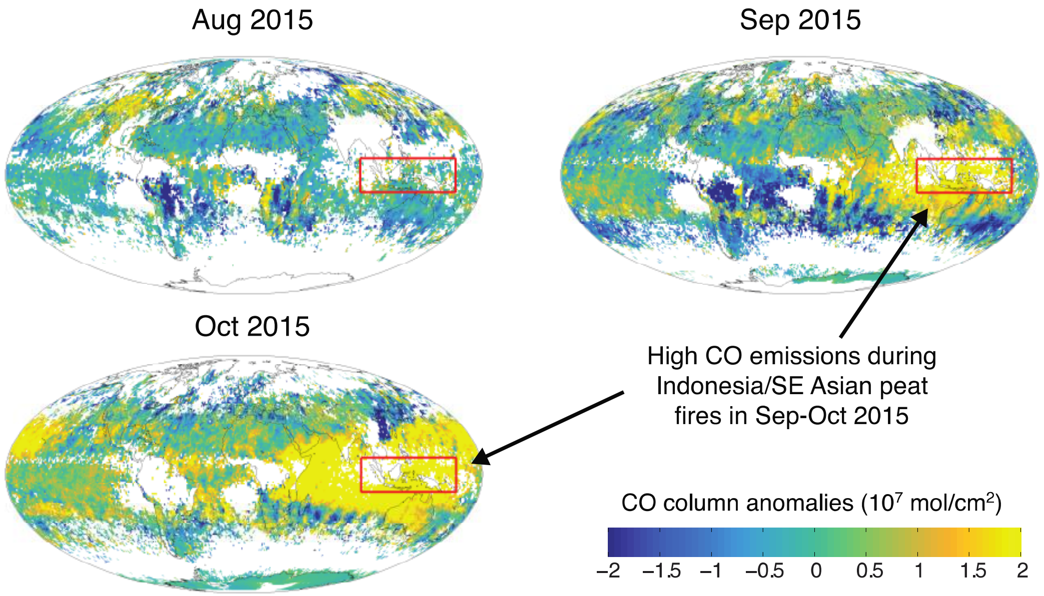
OCO-2-Based Flux Estimate (PgC)	Model Ensemble Mean (PgC yr^{-1})	PMEL Shipboard, Data-Based Estimate (PgC)
0.20 ± 0.07	0.12 ± 0.06	0.22 - 0.26



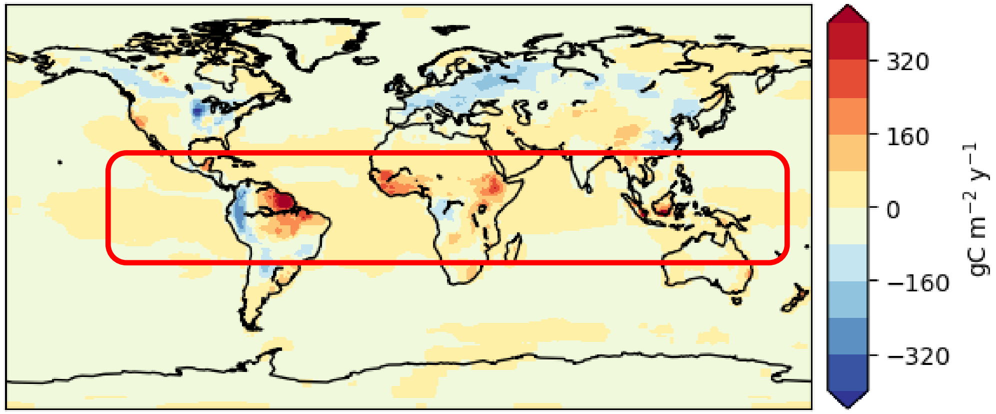
What Caused the Increase in Atmospheric CO_2?

Changes in Tropical Land Fluxes

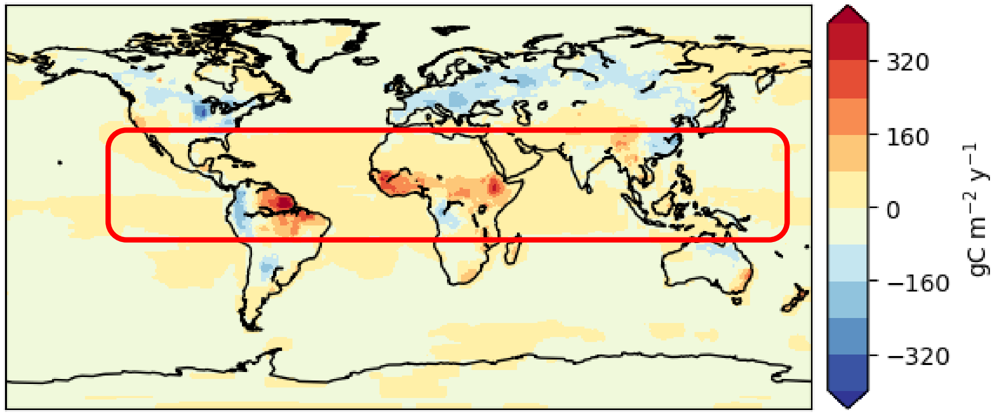
- Increase in emissions from biomass burning
- Warmer and drier climate across the Tropical lands – overall reduction in biospheric uptake



2015 Net Annual Flux (OCO-2)



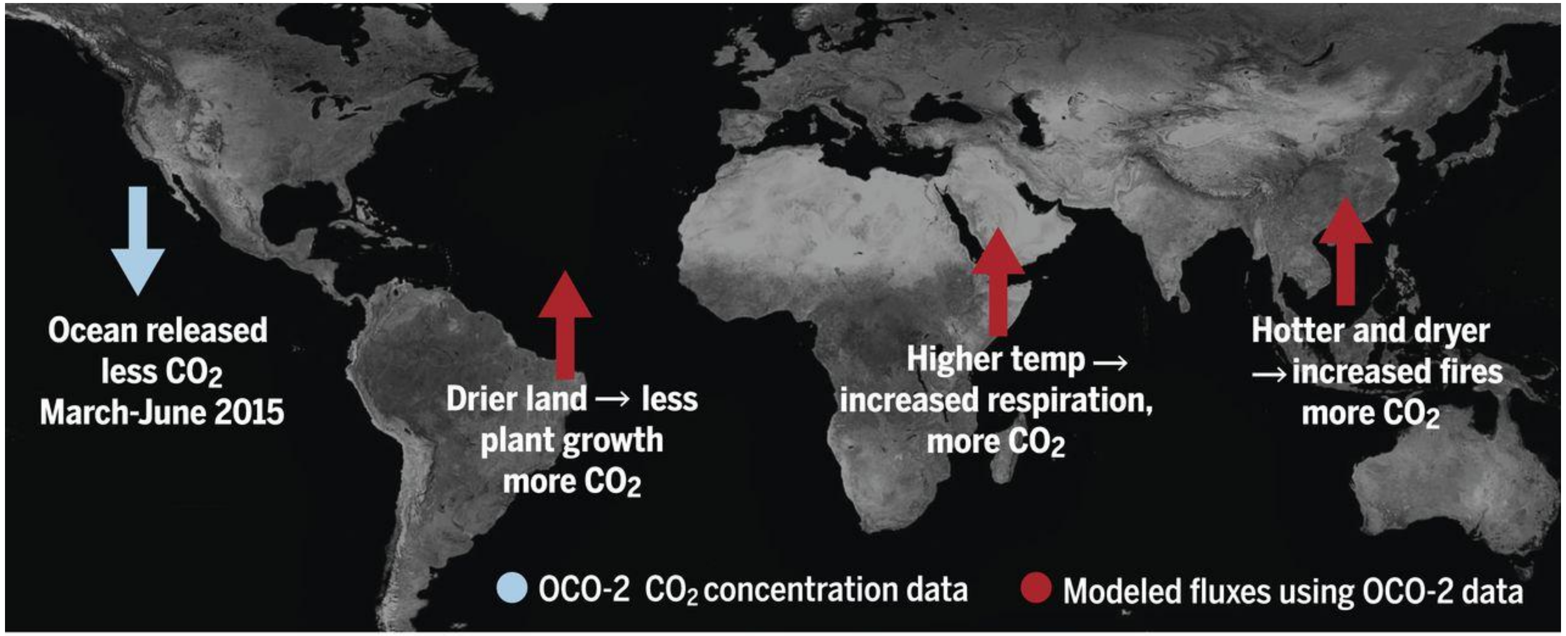
2016 Net Annual Flux (OCO-2)



Also see Chatterjee et al. (2017), Liu et al. (2017), Patra et al. (2017)

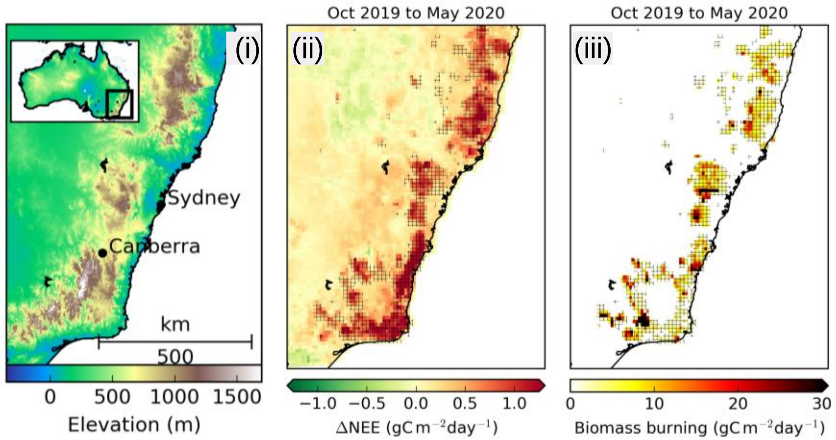
Additional Reading on Unique Findings from OCO-2

- In 2017, we had a special issue in Science Magazine (Vol. 358, Issue 6360). OCO-2 provided the first and unique insights into El Niño's effects on CO_2 fluxes, detection of CO_2 emissions from point sources, and measurement of terrestrial photosynthesis.

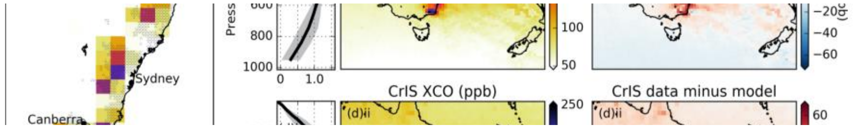


Carbon Cycle Response to 2019-2020 Bushfires in SE Australia

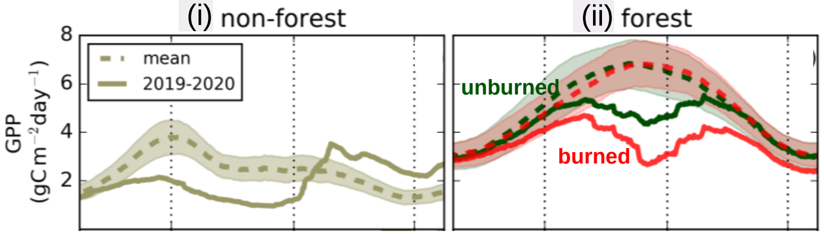
(a) Geography and maps of CO2 flux anomalies



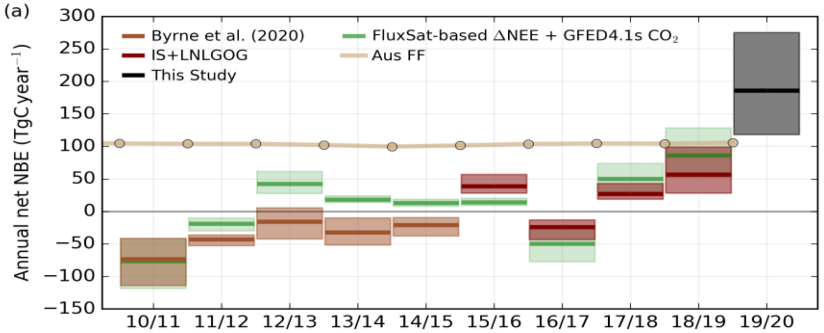
(b) Timeseries of prior (red) and posterior (blue) CO emissions

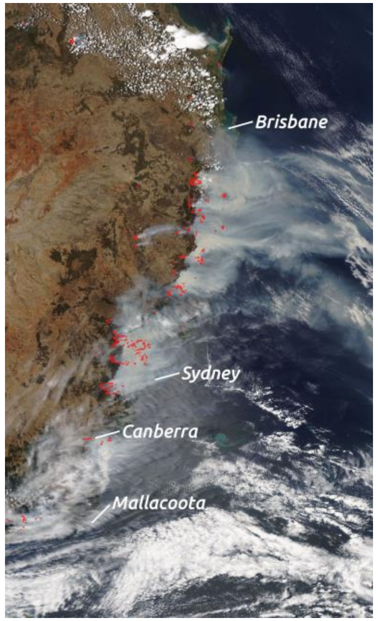


(c) Timeseries of GPP for 2019/20 and mean year



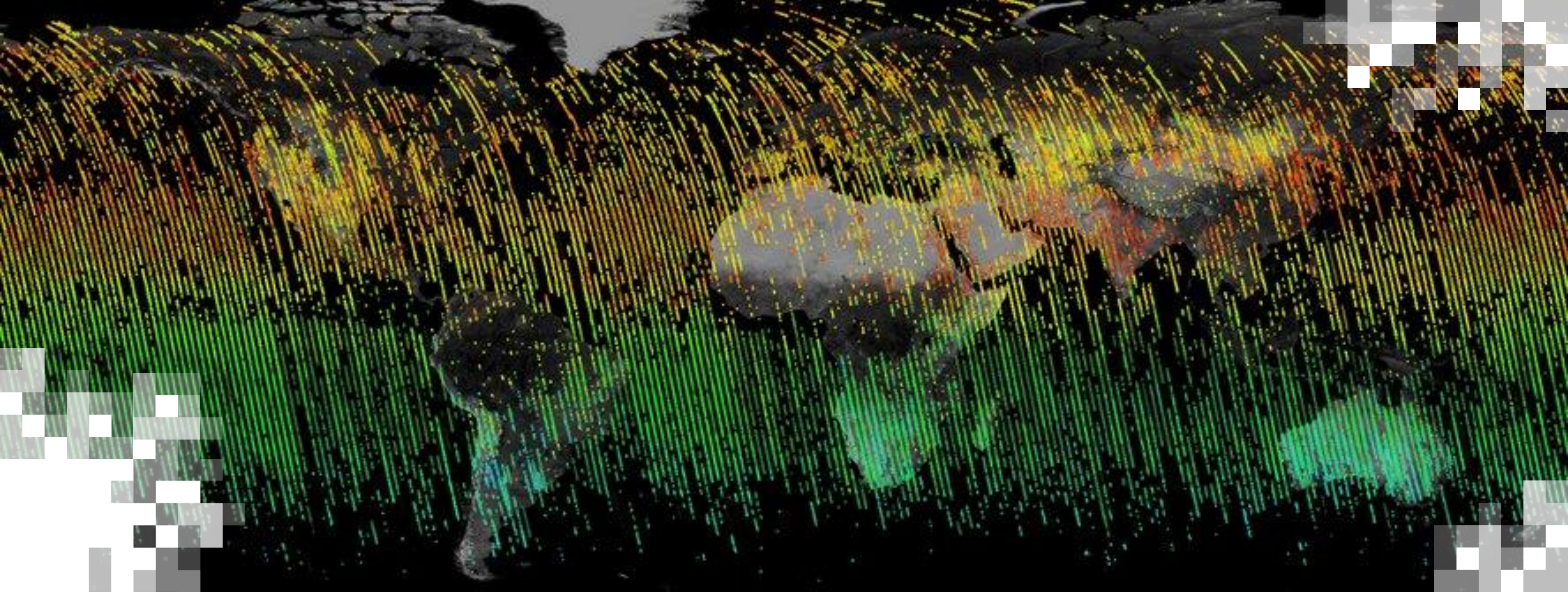
(d) Net annual NBE fluxes from 2010/11 to 2019/20





NASA Satellite Imagery from Dec. 2019

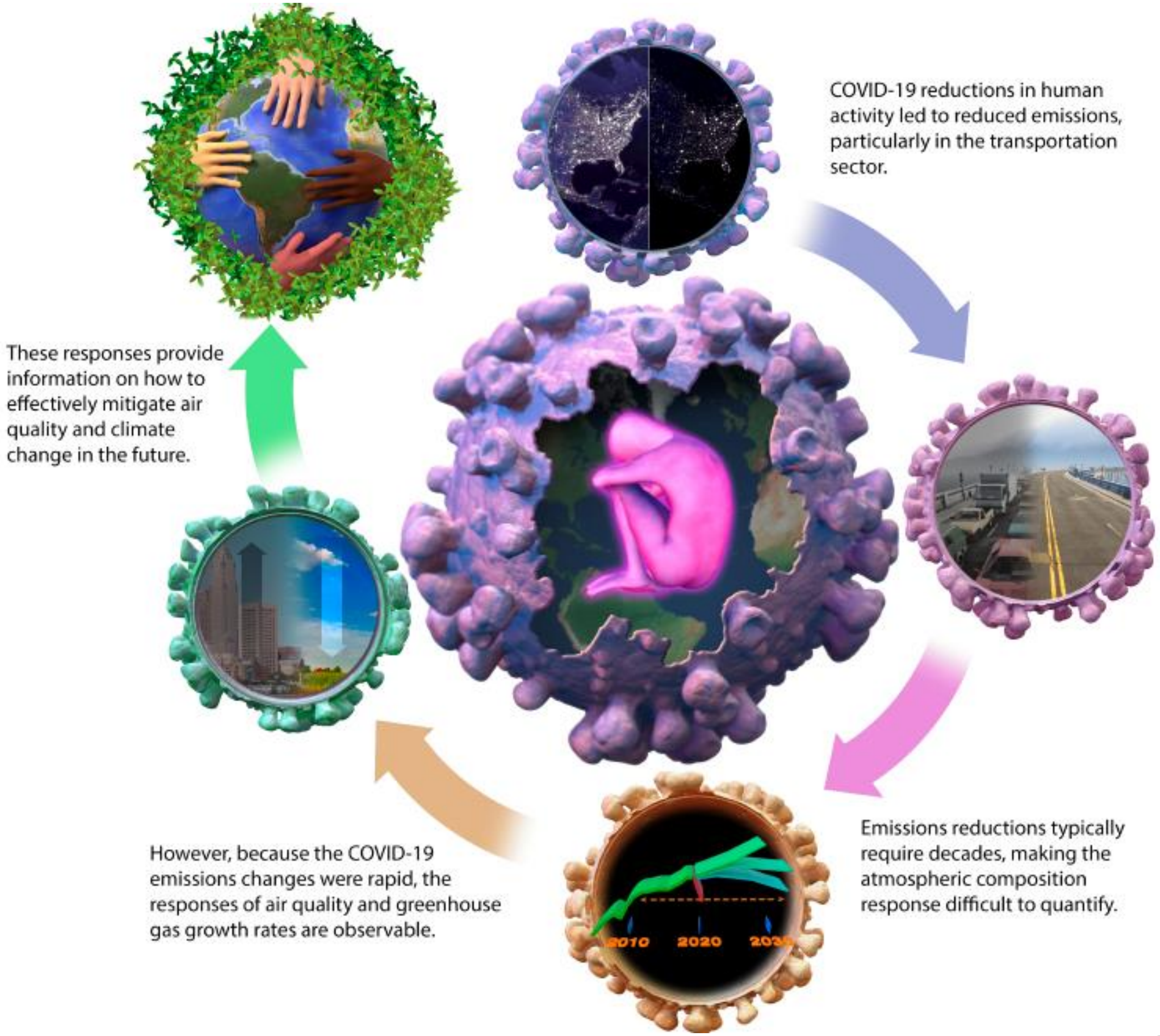
- 2019 was the hottest and driest year on record for Southeast Australia, leading to bushfires of unprecedented extent.
- See Byrne et al. (2021) for a detailed analysis using the OCO-2 data.
- Surface-atmosphere CO_2 flux anomalies due to extreme events can be tracked from space – in addition, we can use data from missions like OCO-2 and OCO-3 to quantify differences in carbon cycle responses between vegetation types and burned/unburned ecosystems.



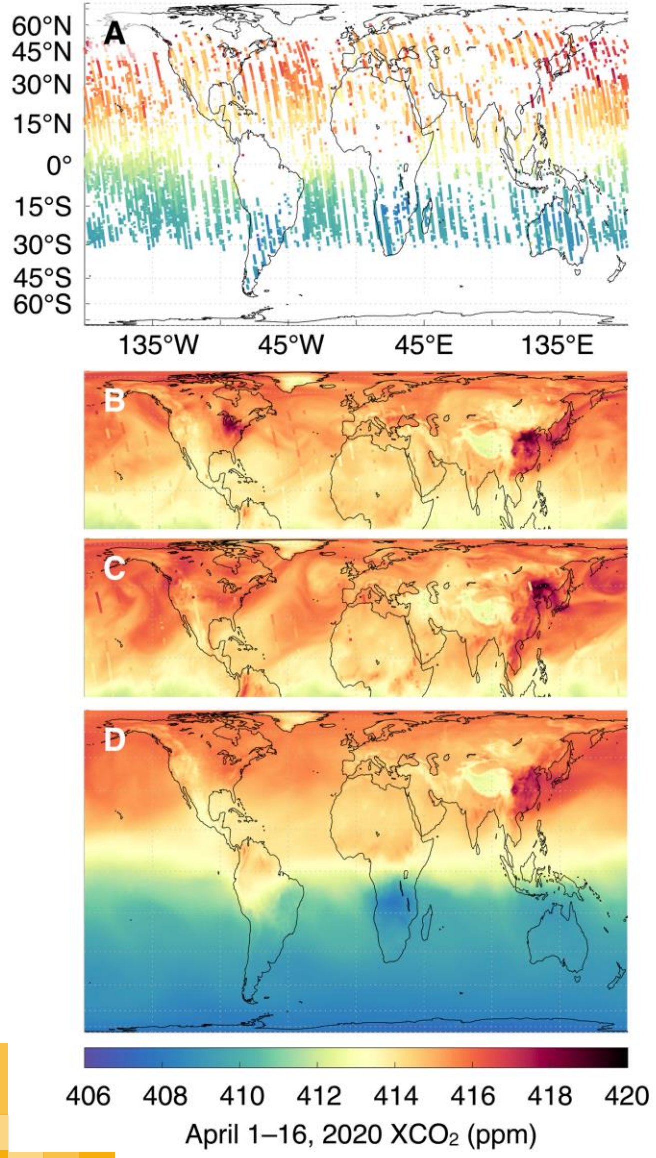
Carbon Cycle Response to Anthropogenic Perturbations

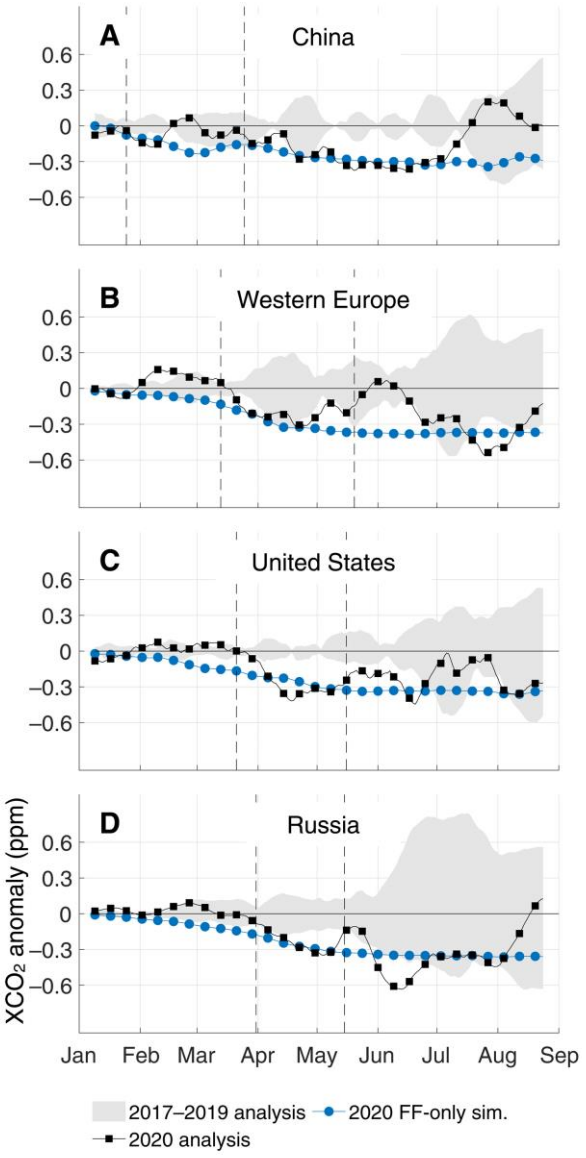
COVID-19 Induced Reductions in Human Emissions Activity

- The COVID-19 pandemic and resulting limitations on travel and other economic sectors by countries around the globe drastically decreased air pollution and greenhouse gas emissions within just a few weeks.
- Emissions estimates for 2020 based on economic activity data suggested that, compared to 2019 emissions, daily global emissions decreased by as much as 15–20% in April 2020.
- Metrics for change in human activity at different scales show that the strongest impact of COVID-19 lockdowns were in the transportation sections, and that these impacts varied substantially from country to country.
- See Laughner et al. (2021).



Regional Reductions in CO_2 Concentrations Detected from Space





- Gap-filled 50-km XCO_2 fields (daily and monthly), which is produced by assimilating bias-corrected OCO-2 data into the GEOS Constituent Data Assimilation System (CoDAS).
- Starting in February 2020 and continuing through May 2020, column CO_2 over many of the world's largest emitting regions was 0.14 to 0.62 parts per million less than expected in a pandemic-free scenario, consistent with reductions of 3 - 13% in annual global emissions.
- Anomaly and concentration maps available on trilateral (NASA/ESA/JAXA) Earth Data Dashboard –

  https://eodashboard.org/covid-19
- See Weir et al. (2021).

The Full COVID-19 and Carbon Cycle Story is Highly Nuanced

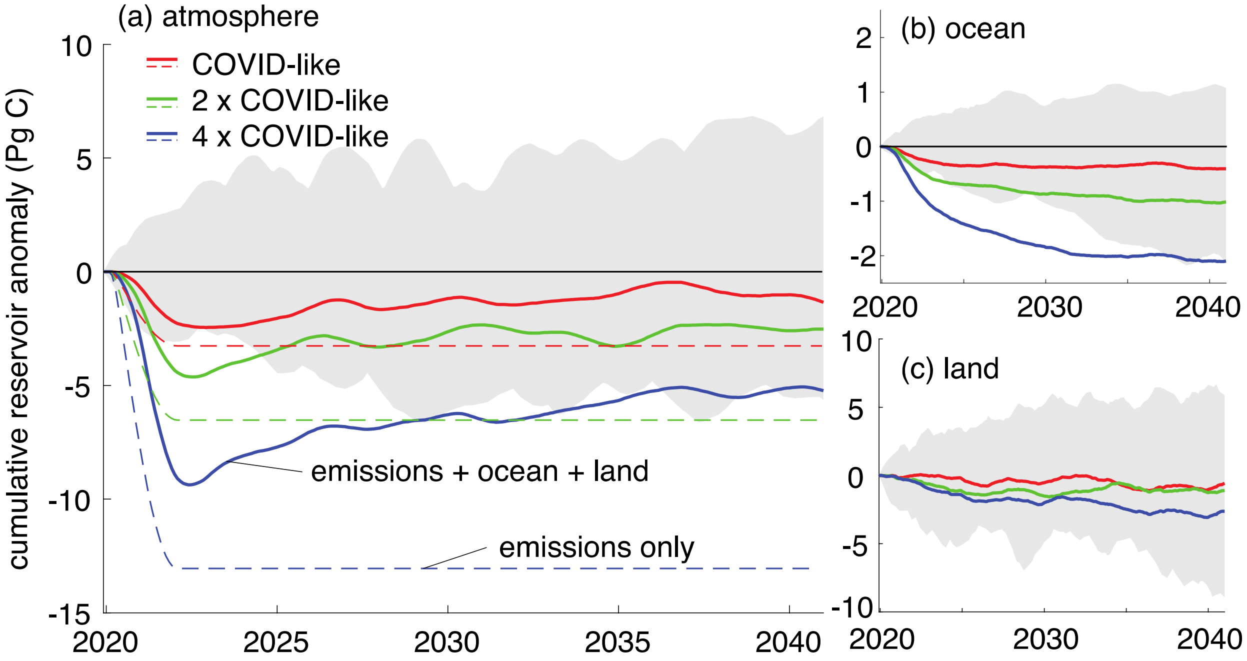
- Satellite monitored changes in early 2020 XCO_2 due to the COVID-19 pandemic were small (0.14–0.62 ppm), negative, and consistent with country-level activity data.

  - The US, Europe, and East Asia saw the most noticeable reductions.

  - However, at global and annual scales, we can't distinguish the signal from natural CO_2 variability.

- Ocean and land compartments had reduced uptake in 2020.

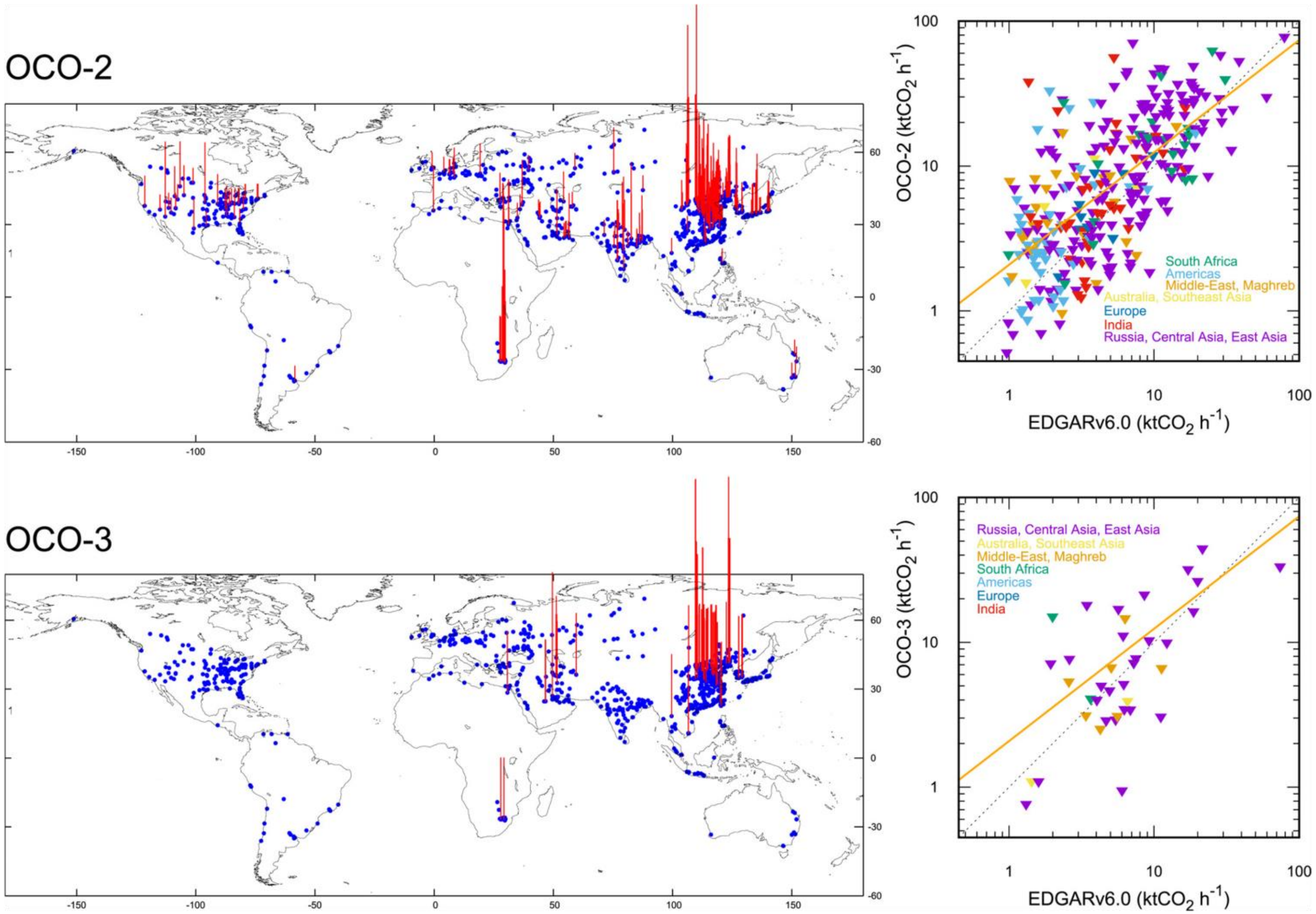
  - The COVID-like emissions reduction signal in the atmospheric carbon reservoir may have been detectable above the noise of internal variability for at least 2-3 consecutive years, if not for the slowing ocean and land carbon sink.



Response of the 3 Major Carbon Reservoirs and their Recovery Post-Pandemic

See Lovenduski et al. (2021)

CO_2 Emitters from Large Point Sources can be Seen from Space

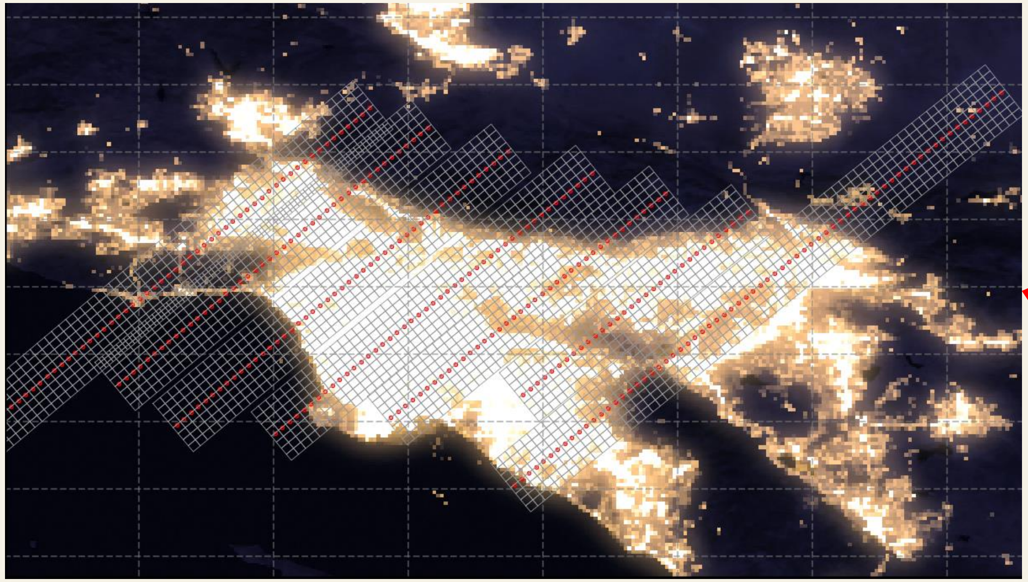


See Chevallier et al. (2022)

- OCO-2 and OCO-3 observes emission plumes from large point sources - in the wake of the Paris Climate Agreement, there is an increasing need to monitor emissions from fossil fuel combustion around the world.
- Blue dots represent global locations, where emissions exceed 1.0 $ktCO_2\ h^{-1}$. Red impulses on these maps illustrate the number of times when retrieved emissions are attributed to these cells for OCO-2 (top) and OCO-3 (bottom).
- OCO-2 and OCO-3 explain a large part of the variability seen in a global emission inventory (EDGAR).

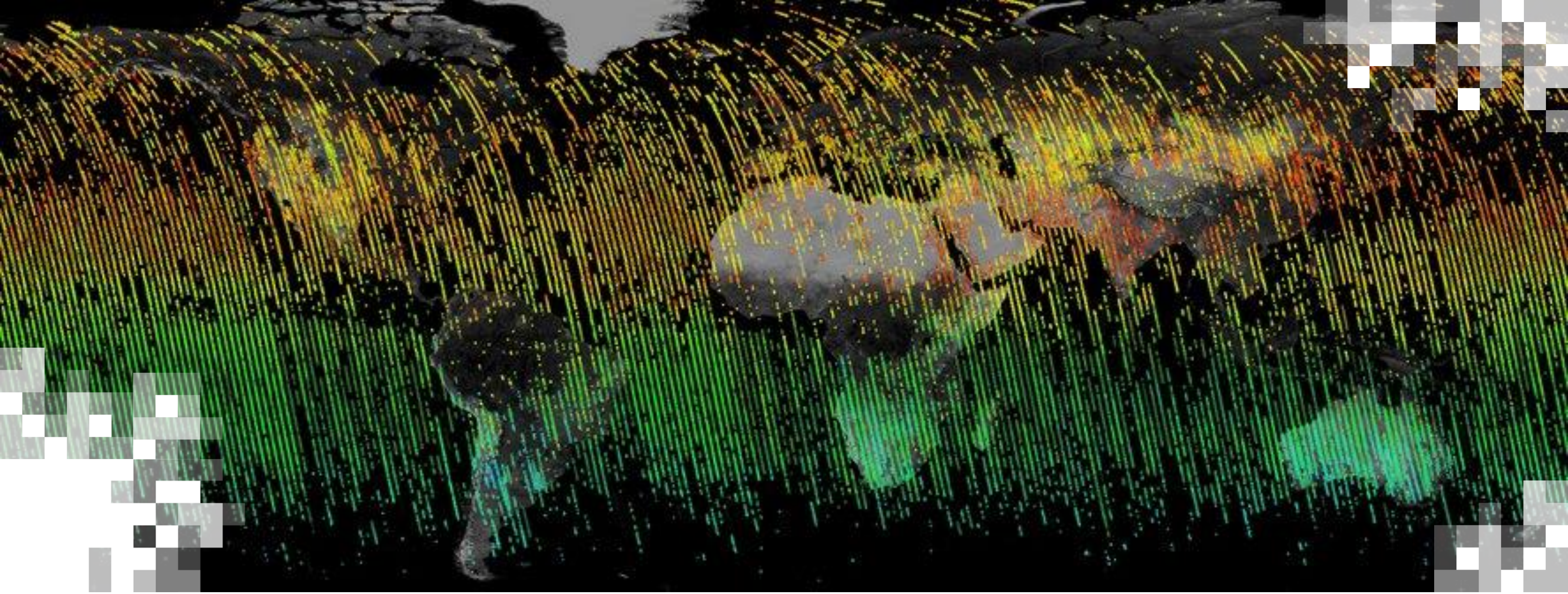
Other Urban and Local Emission Studies

- Next Training – Session 4 (June 2) - **Understanding Urban Carbon Emissions with Space-Based Carbon Dioxide Observations**



OCO-3 SAM Mode Coverage Over the Los Angeles Megacity

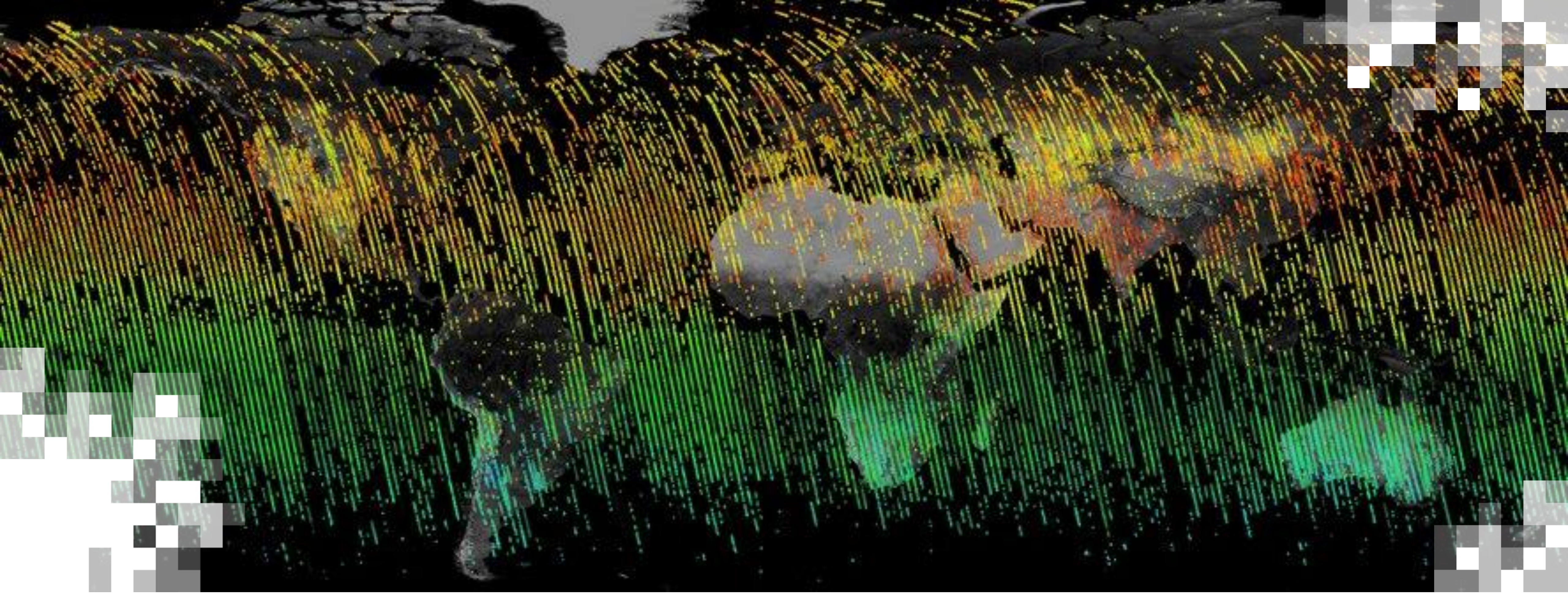
Credit: NASA Earth Observatory/NOAA NGDC



Summary

Wrap-Up: What have we learned?

- CO_2 monitoring from space is becoming an increasingly important and relevant capability in support of climate studies and to inform policy decisions.
  - However, native Level 2 XCO_2 data often have missing soundings.
  - The scientific community uses Level 3 (gap-filled XCO_2 product) and Level 4 (information about emissions and removals of CO_2) for the majority of global and regional studies.
- CO_2 flux estimates derived from XCO_2 are used to constrain net biosphere exchange (NBE) and net carbon exchange (NCE) between the land and ocean surfaces & the atmosphere.
  - These estimates are providing valuable information to the UNFCCC Global Stocktake process.
- XCO_2 data also provides unique insights into global and regional carbon cycle processes and how those respond to various forcings, natural (climate patterns) and anthropogenic perturbations (emission changes).
  - 2015 - 2016 El Niño and the COVID-19 pandemic are classic case studies that demonstrate how we can use XCO_2 data to advance our geophysical understanding of carbon cycle science.



References & Data Repositories

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Data Repositories

- Level 2 XCO_2 Data –
  OCO-2 – https://disc.gsfc.nasa.gov/datasets/OCO2_L2_Lite_FP_10r/summary?keywords=OCO2%20L2
  OCO-3 - https://disc.gsfc.nasa.gov/datasets/OCO3_L2_Lite_FP_10.4r/summary?keywords=OCO3%20L2
- Level 3 Gap-Filled Estimates of Atmospheric CO_2 Concentrations –
  Daily Data Product – https://disc.gsfc.nasa.gov/datasets/OCO2_GEOS_L3CO2_DAY_10r/summary?keywords=OCO2%20GEOS%20L3
  Monthly Data Product - https://disc.gsfc.nasa.gov/datasets/OCO2_GEOS_L3CO2_MONTH_10r/summary?keywords=OCO2%20GEOS%20L3
- Level 4 Carbon Flux Estimates Derived from an Ensemble of Inversion Models - https://gml.noaa.gov/ccgg/OCO2_v10mip/index.php

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- Training Webpage:
  - https://appliedsciences.nasa.gov/join-mission/training/english/arset-measuring-atmospheric-carbon-dioxide-space-support-climate

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Thank You!