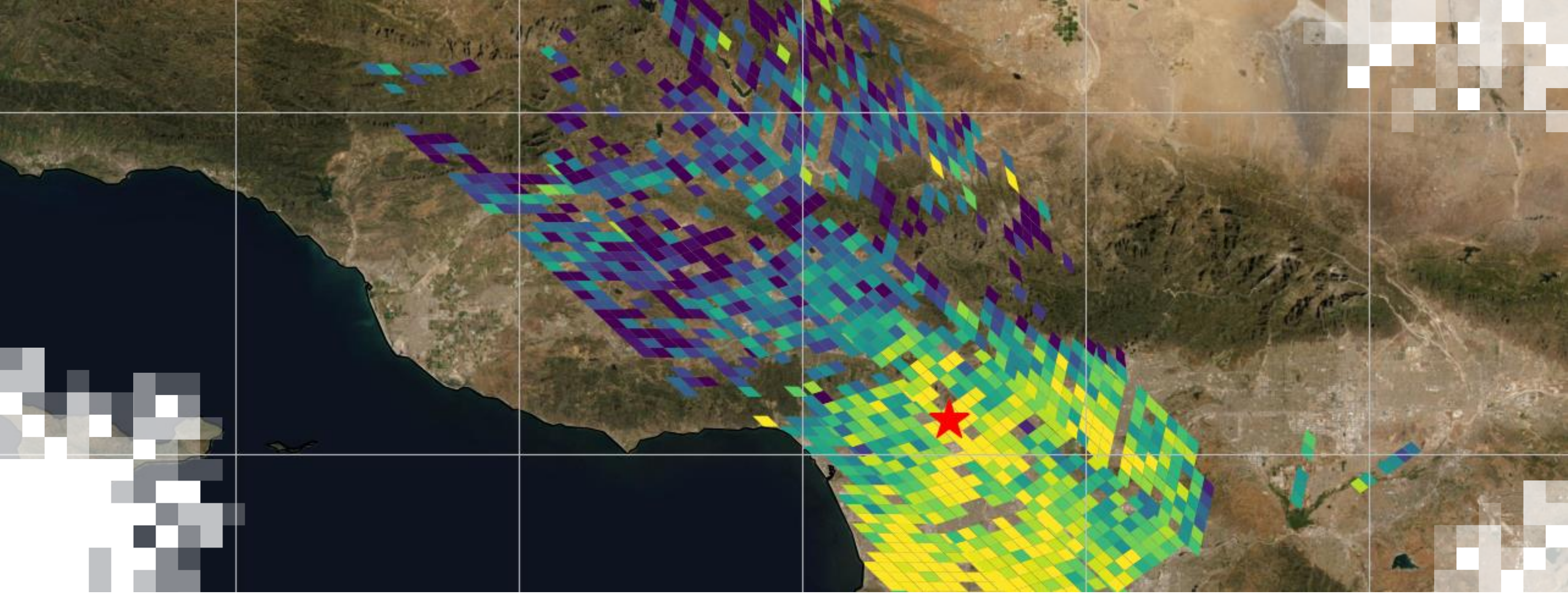


# Applications of Carbon Dioxide Measurements for Climate-Related Studies

## **Part 2: The Impact of Drought on $CO_2$**

# Agenda

**Session 1: XCO2 from OCO-2 and OCO-3: Mission Recap, and Data Characteristics and Limitations**

- 12:00 pm -2:00 pm U.S. East Coast Time (UTC-4:00)
- Tuesday July 9, 2024
- Invited Instructor: Vivienne Payne (JPL)

**Session 2: The Impact of Drought on CO2**

- 12:00 pm -2:00 pm U.S. East Coast Time (UTC-4:00)
- Wed. July 10, 2024
- Invited Instructors: Junjie Liu (JPL), Karen Yuen (JPL), David Moroni (JPL)

**Session 3: CO2 Measurements over a Large Urban Area**

- 12:00 pm -2:00 pm U.S. East Coast Time (UTC-4:00)
- Tuesday July 16, 2024
- Invited Instructors Abhishek Chatterjee (JPL), Karen Yuen (JPL), David Moroni (JPL)

**Homework due date: August 9, 2024**

**Certificate: will be given to participants that attend all the live sessions and complete the homework by the due date.**

# Part 2 – Trainers

**Junjie Liu**

OCO-2/3 Science Team Lead

JPL/NASA

**David Moroni**

OCO-2/3 Applied Science System Engineer

JPL/NASA

**Karen Yuen**

OCO-2/3 Applications Lead

JPL/NASA

# Part 2 Objectives

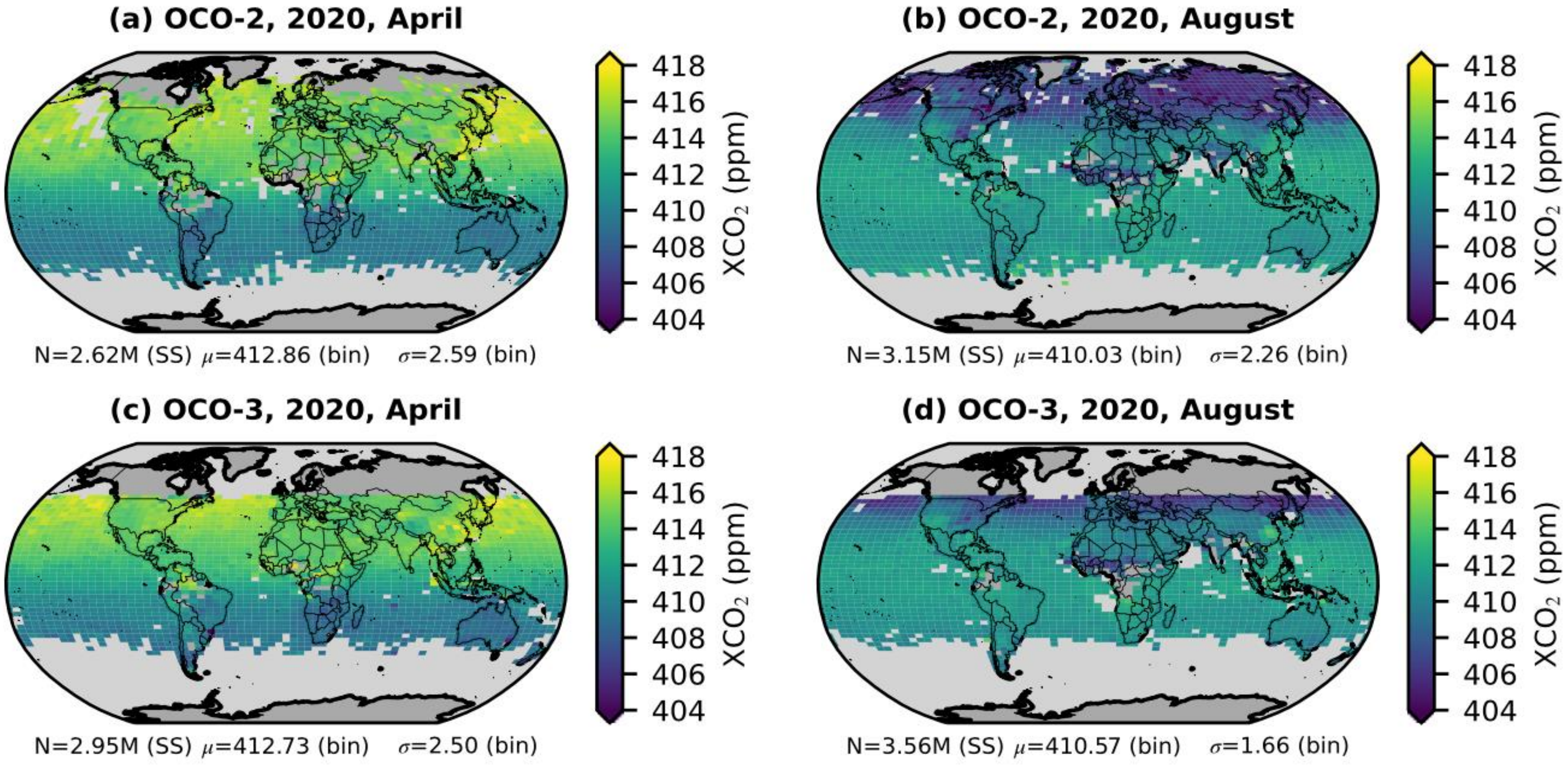
By the end of Part 2, participants will be able to:

- Identify El Niño event effects that can create regional drought conditions.
- Monitor global fluxes of atmospheric $CO_2$ concentrations to identify vulnerable areas.
- Use OCO-2 data to visualize the impacted areas and be able to do interpretation and comparison analysis.
- Identify the methods and processes to derive fluxes with atmospheric $CO_2$ measurements and interpret regional flux perturbations and country-scale fluxes and emissions.
- Follow steps to clone the ARSET Github repository and maintain the local code.

# How to Ask Questions

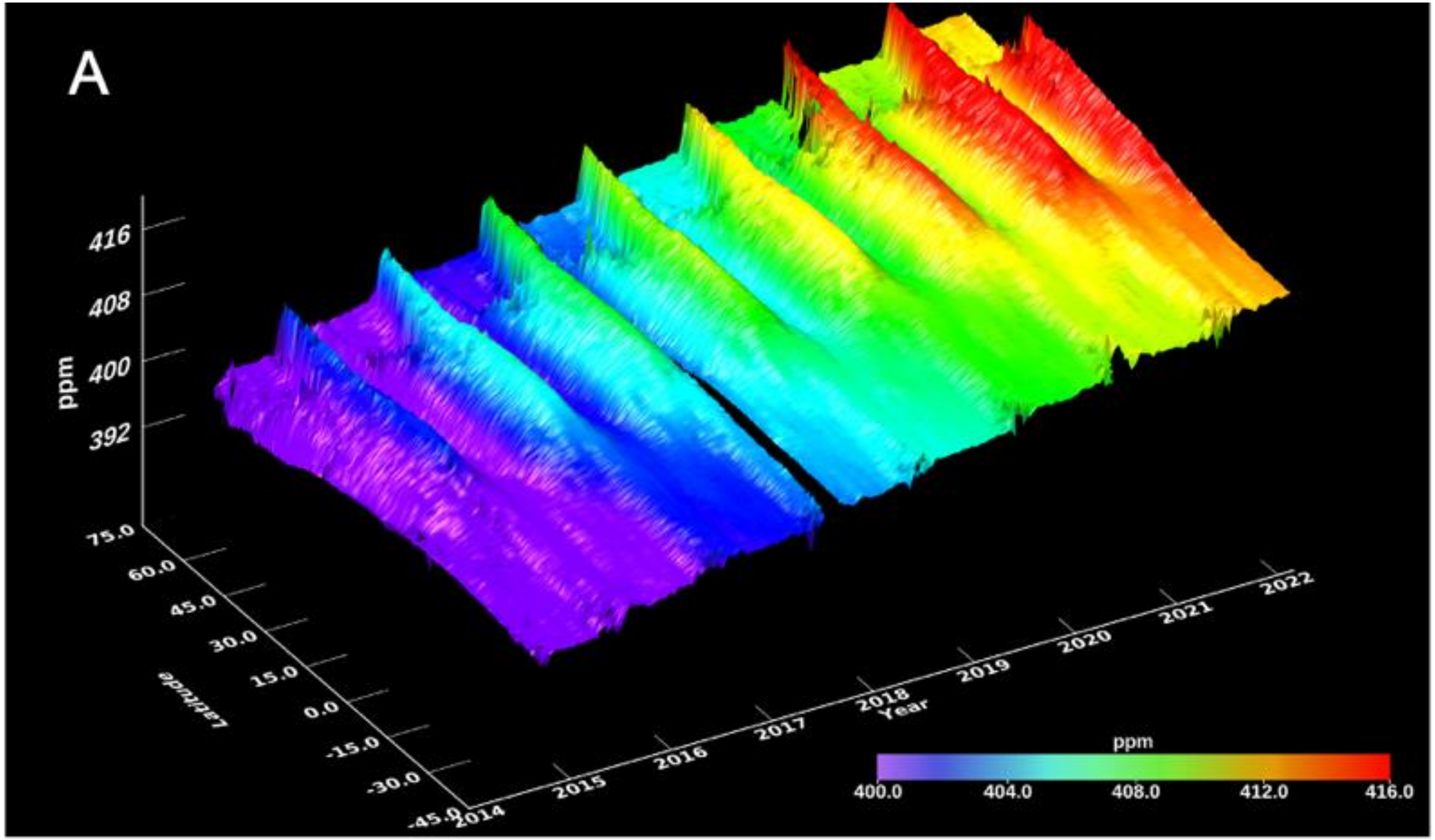
- Please write your questions in the Questions box and we will address them at the end of the webinar.
- Feel free to enter your questions as we go. We will try to answer all of the questions during the Q&A session after the webinar.
- The remainder of the questions will be answered in the Q&A document, which will be posted to the training website about a week after the training.

# $CO_2$ Seasonality Observed by OCO-2 and OCO-3



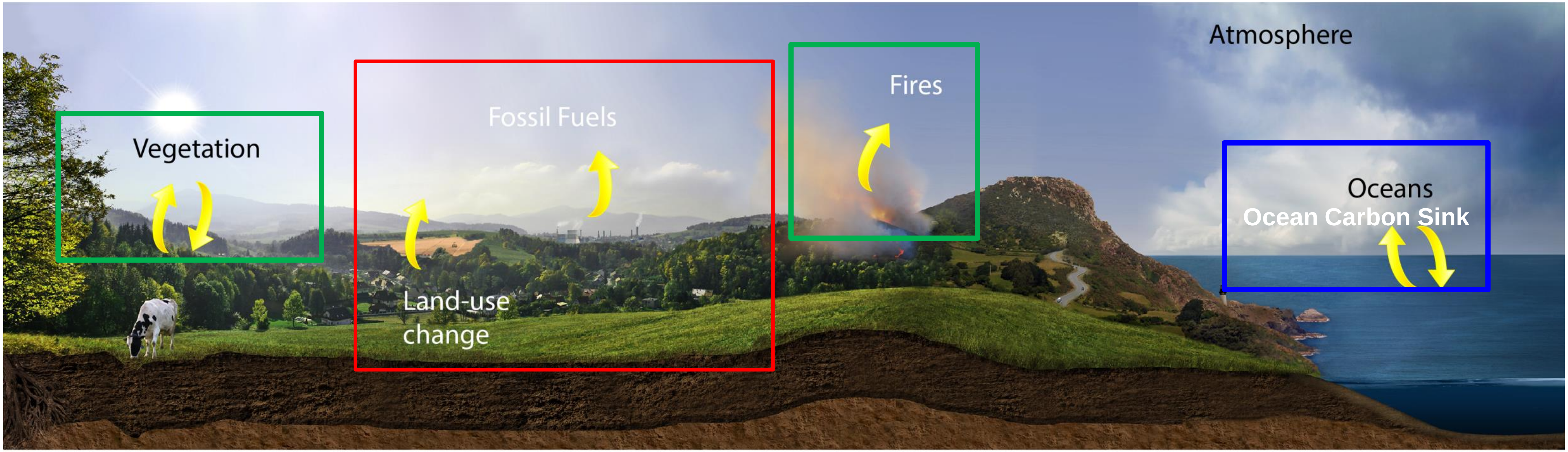

- Column $CO_2$ concentration in the Northern hemisphere is much higher in April than in August.
- $CO_2$ concentration is higher in the Northern Hemisphere than in the Southern Hemisphere in April, but lower in August.
- $CO_2$ concentration is higher over East Asia and the east and west coast of North America.

# The Relentless Rise of Atmospheric $CO_2$




- OCO-2 observes steady increase in atmospheric $CO_2$ concentration;
- The Northern Hemisphere has much larger seasonal cycles (i.e., peak to trough value in each year) than the Southern Hemisphere.
- On average, the atmospheric $CO_2$ concentration increases at about ~2.5ppm/year in recent years.

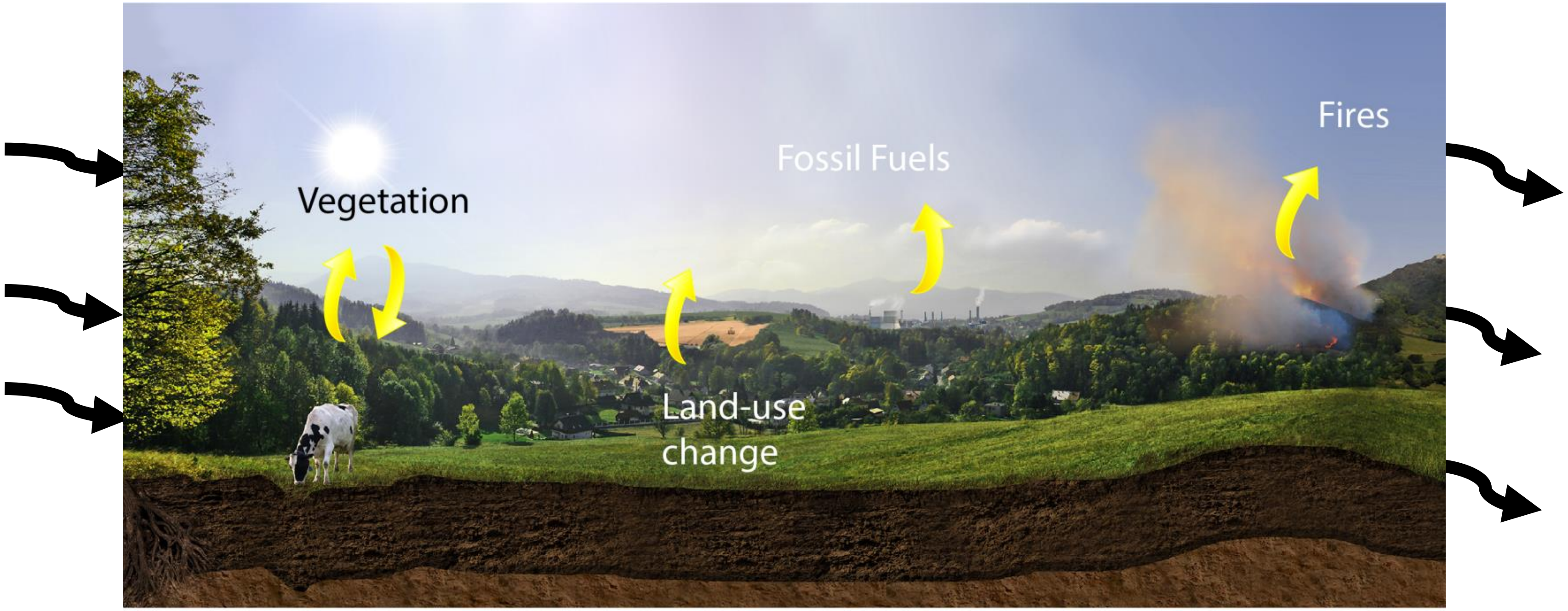
# The change in global mean atmospheric $CO_2$ concentration is a result of net carbon fluxes at the surface

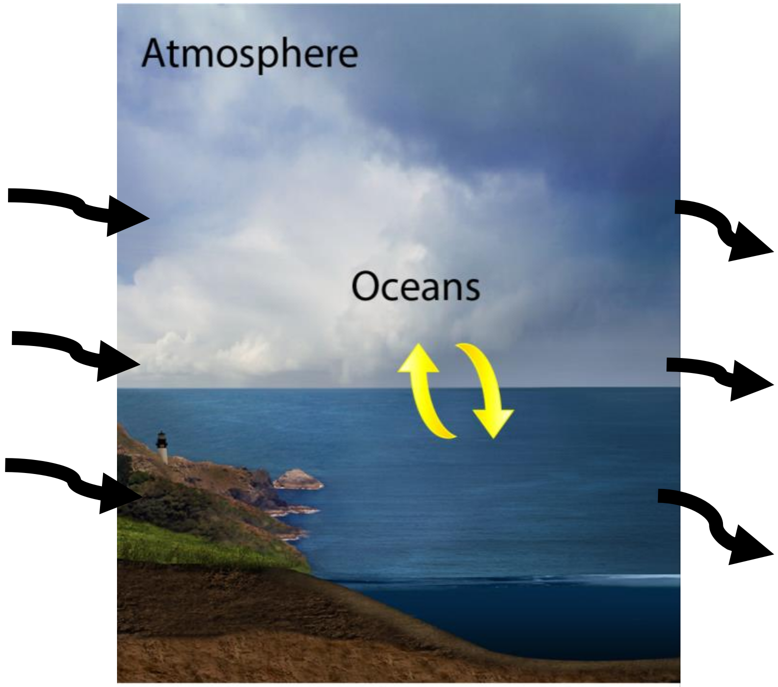



Credit: Jenny Mottar (NASA)

- Global: $\Delta C_{t \to t+1} = \int_t^{t+1} (anthropogenic\ (fossil\ fuel + land\ use) + net\ land + net\ ocean\ flux)$
- Net land carbon flux = carbon absorbed through photosynthesis - carbon released through respiration and fires.
- Net air-sea exchange = ocean ecosystem, $CO_2$ pressure differences between ocean surface and atmosphere.
- Annual global atmospheric $CO_2$ concentration changes = integrated surface carbon fluxes during the year

# Change in Regional/Local Atmospheric $CO_2$ concentration

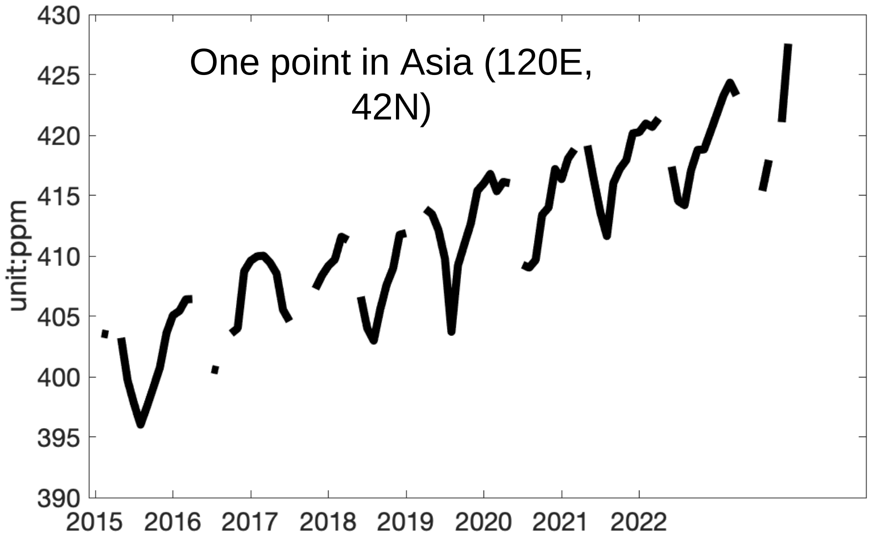


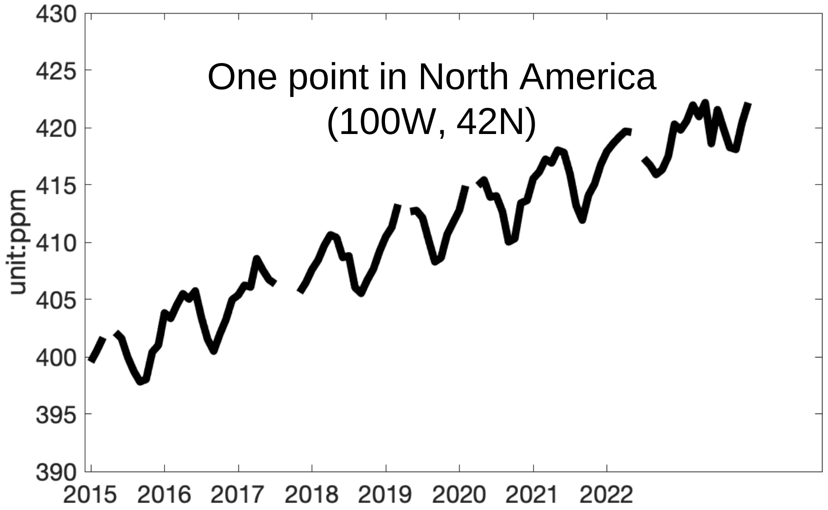



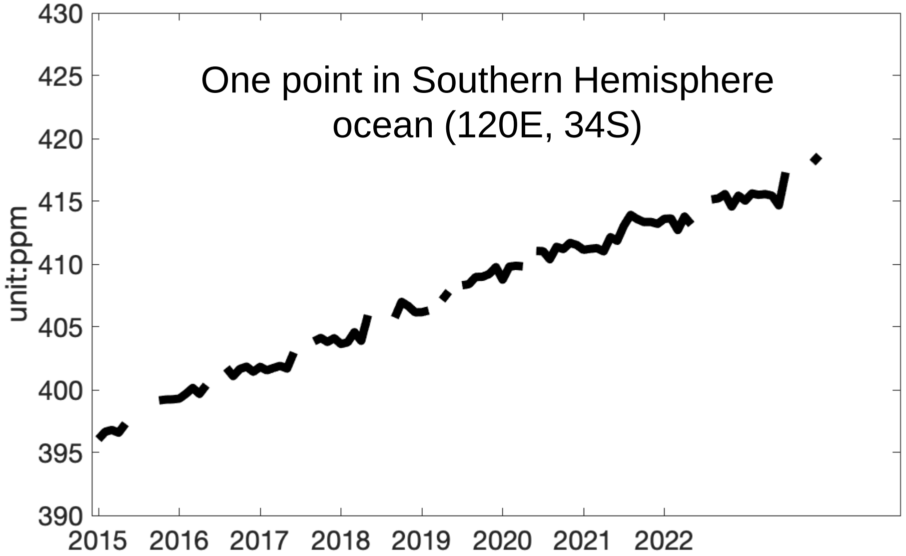

Credit: Jenny Mottar (NASA)

- Regional: $\Delta C_{t \rightarrow t+1}$= lateral transport + $\int_{t}^{t+1} (flux)_{local}$
- The change in atmospheric $CO_2$ concentration at any location is not only related to local surface carbon fluxes, but also atmospheric lateral transport.

# Observed OCO-2 $CO_2$ Column Concentration at Three Locations




- Regional: $\Delta C_{t \to t+1}$= lateral transport + $\int_t^{t+1} (flux)_{local}$
- The $CO_2$ concentration at all these three locations has a similar increasing trend.
- The increase in atmospheric $CO_2$ concentration is due to both the lateral transport and local surface carbon fluxes.
- The steady increase in atmospheric CO2 concentration at the ocean point in the left panel is attributed to fossil fuel emissions from other locations being transported to this point.

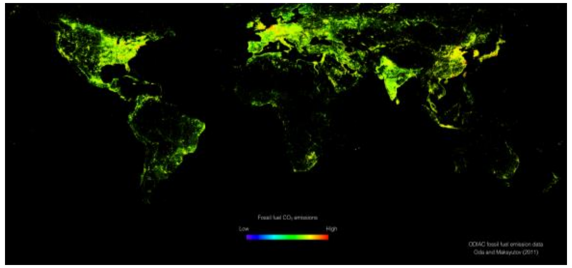
# Definitions of Fluxes and Concentration

- **Atmospheric $CO_2$**: expressed as parts by million by volume (ppmv or ppm)
  - 1ppm = one particle of $CO_2$ molecule per 1 million particles of dry air molecules (not including water vapor)
- **Carbon fluxes**: direction and rate of transfer of carbon between Earth's carbon pools, such as the oceans, atmosphere, land, and other living things
  - Unit: gC/m$^2$/day (carbon amount per area per time)
  - Other units: gigaton of carbon per year (GtC/year)= gC/ m$^2$/day x 365 x area x 1e-15

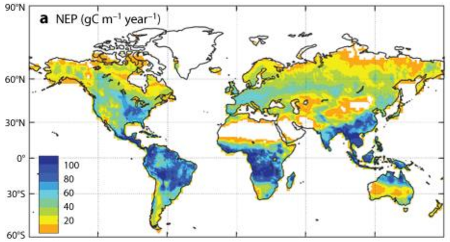
    Teragrams of carbon per year (TgC/year) = gC/ m$^2$/day x 365 x area x 1e-12

    Petagram of carbon is the same as gigaton of carbon.
- Connection between carbon fluxes and atmospheric $CO_2$ concentration
  - Convert from flux to mass unit and then to volume unit
  - The ratio between the number of CO2 molecules and the number of dry air molecules
  - amount of ppm=[(carbon flux) x (area) x (duration)]/12 /(the number of dry air molecules) *1e6
  - 1ppm ~= 2.14 GtC

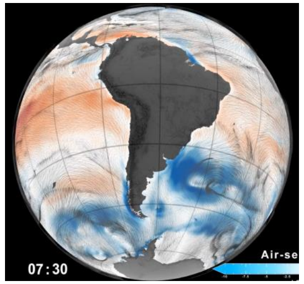
# Linking Surface Carbon Fluxes with Atmospheric $CO_2$ Concentration



Fossil fuel emissions



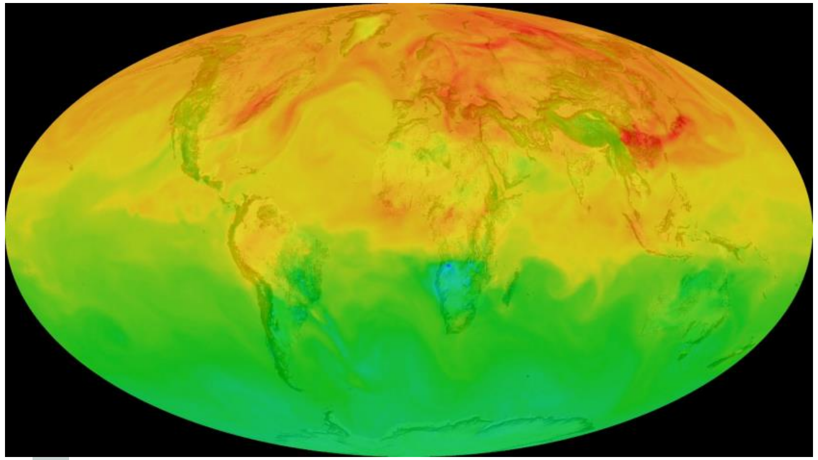

Net Land carbon Fluxes



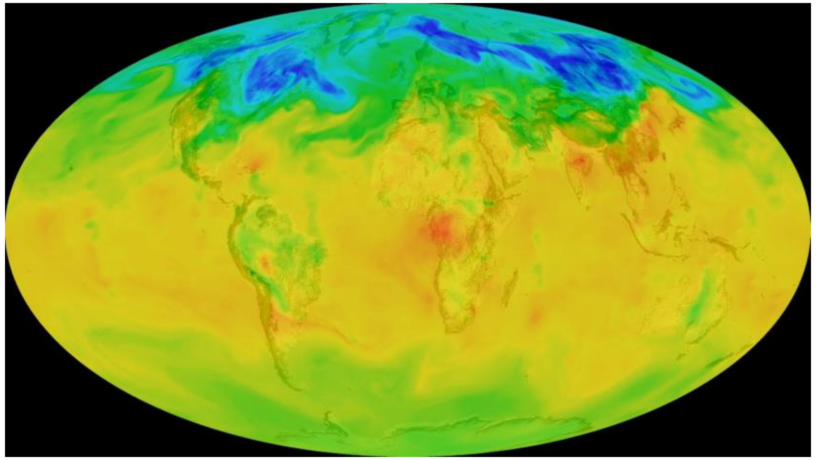

Net Air-Sea Exchange

Forward atmospheric transport model

Spring column CO2



Summer Column CO2

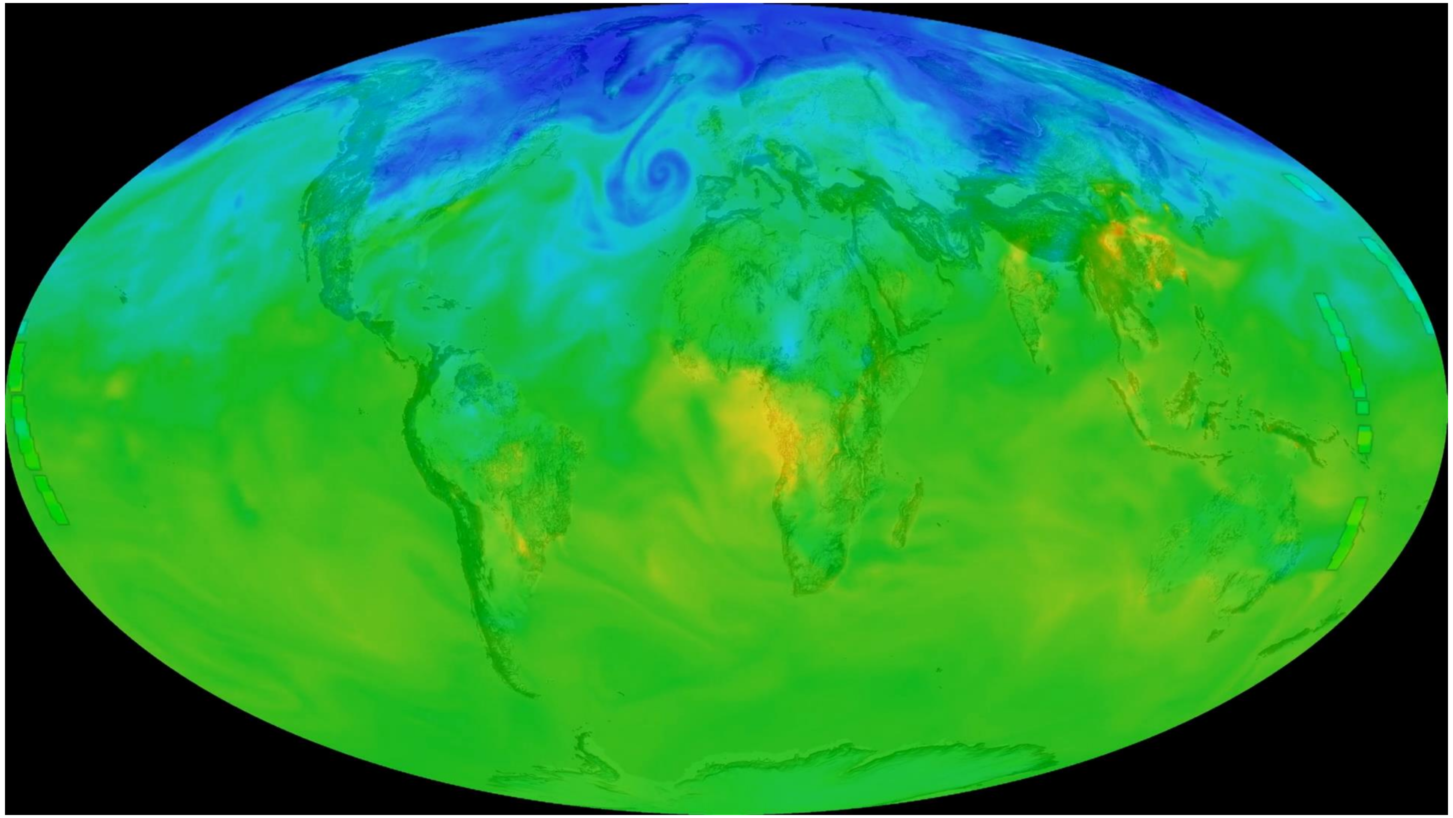


Warmer color: higher values; cooler color: lower values

https://svs.gsfc.nasa.gov/4519/

- Prescribing surface carbon fluxes and then running an atmospheric transport model, we can get the simulated spatial and temporal distributions of atmospheric $CO_2$ concentrations throughout the globe.
- The simulation by the atmospheric transport model is similar to the concept of an Earth digital twin.

# OCO-2 Samples a Snapshot of the Atmosphere

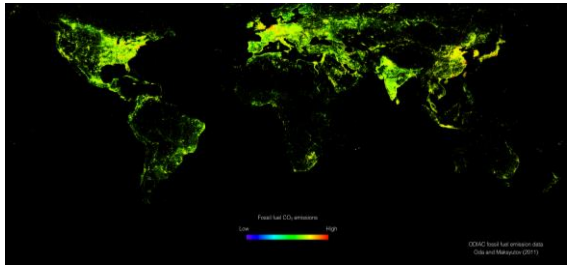


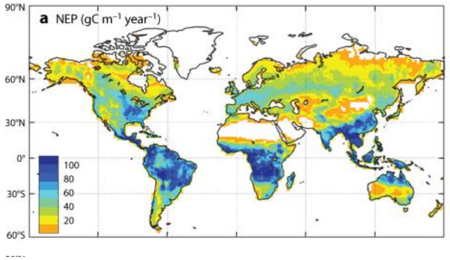
https://svs.gsfc.nasa.gov/4519/

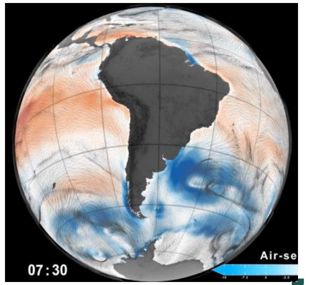
Warmer color: higher values; cooler color: lower values

- Each stripe on the globe represents one OCO-2 orbital track.
- OCO-2 only samples snapshots of atmospheric CO2 column in both space and time.
- Carbon released at the surface is transported throughout the globe by winds.
- The spatial patterns of atmospheric CO2 reflect both synoptic weather system and surface net carbon exchange.

# Atmospheric $CO_2$ Flux Inversion Process

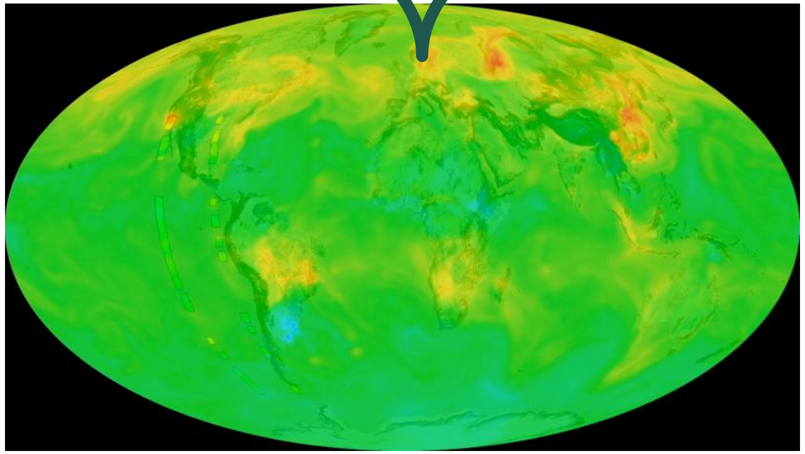




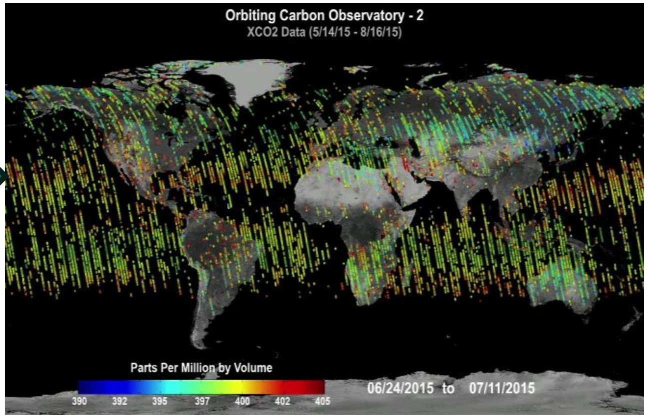




Adjusting the surface fluxes

Forward atmospheric transport by weather System



Comparing to Observations



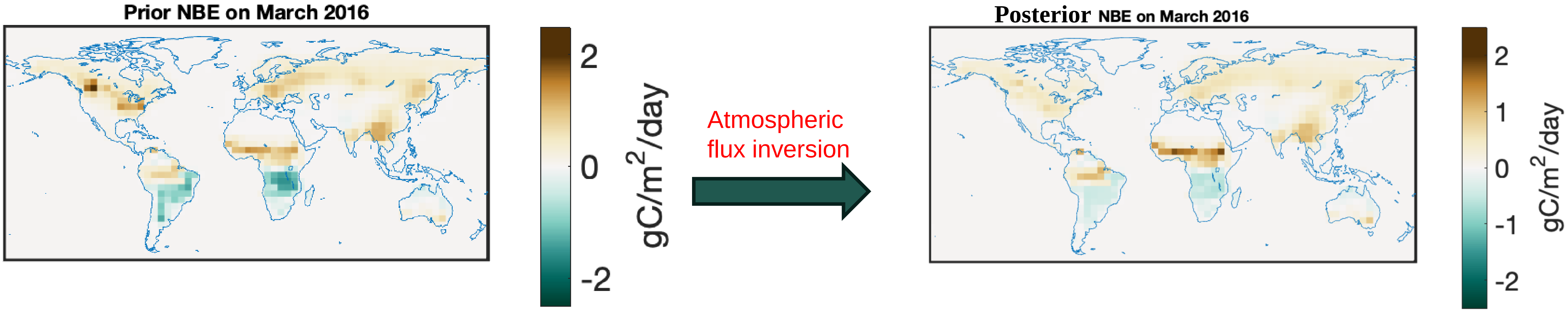

**Atmospheric CO2 Flux Inversion**

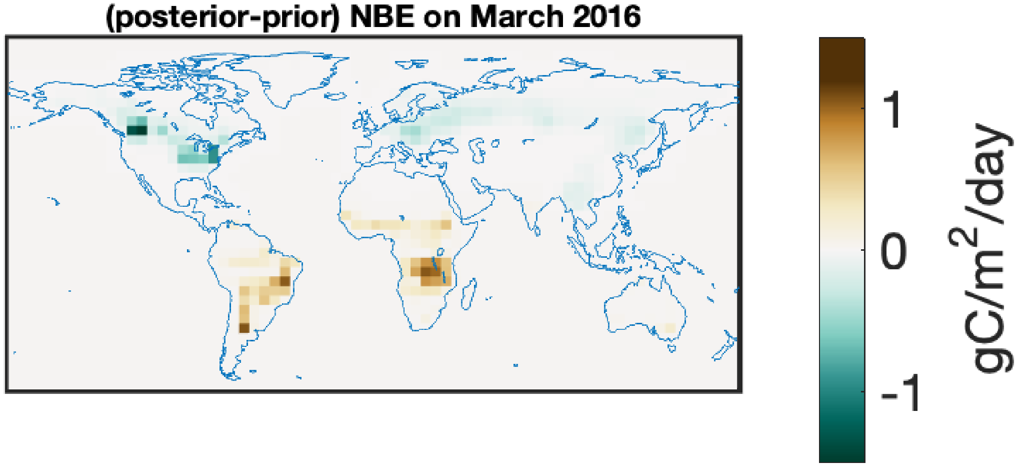
$$J(x) = (x - x^b)^T B^{-1} (x - x^b) + \sum_{i=1}^{n} (y - h(x))_i^T R^{-1} (y - h(x))$$

Measuring the sum of mismatch between observations (y) and model simulated values (h(x) and the differences between optimized fluxes (x) and prior fluxes ($x^b$)

Atmospheric inversion process optimizes surface carbon fluxes to best match the observations given the uncertainties in observations and the assumed prior carbon fluxes.

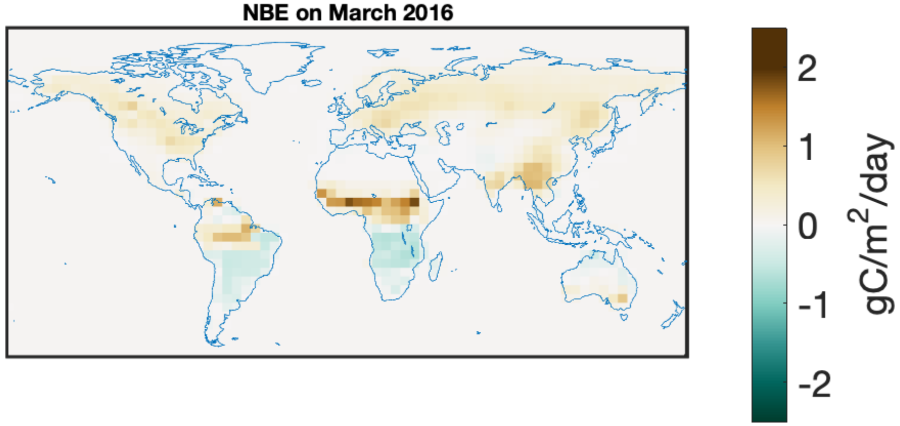
# The Prior Surface Carbon Fluxes are Adjusted to Best Match the Observations

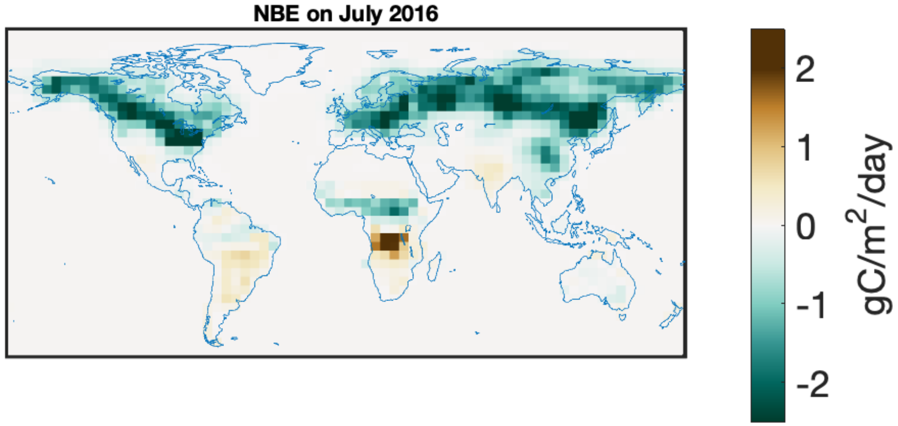


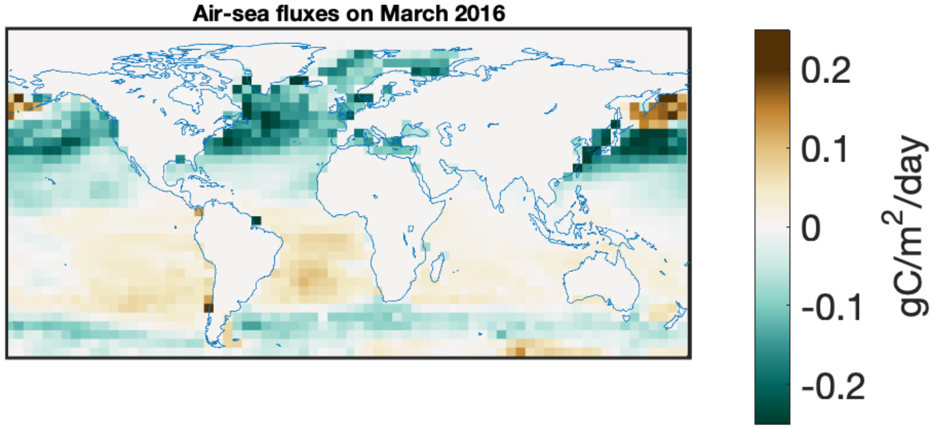



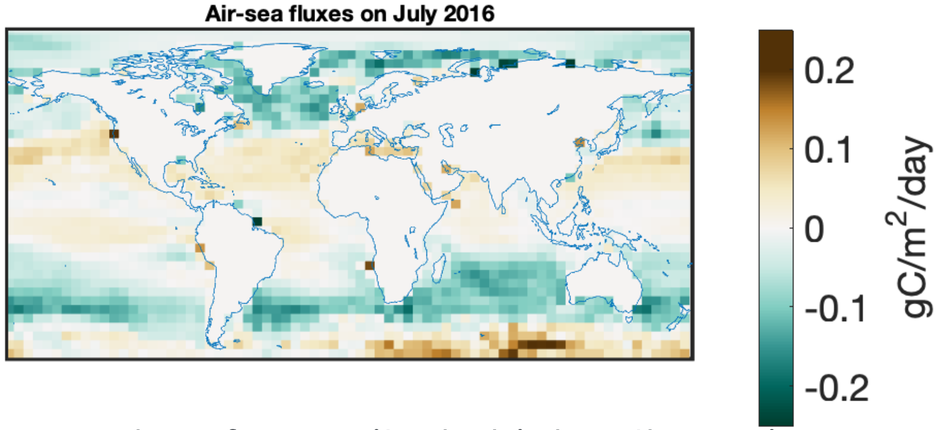

- NBE: net biosphere exchange that includes all land carbon fluxes except fossil fuel emissions. Positive: carbon is released to the atmosphere; Negative: carbon is absorbed from the atmosphere.
- The posterior $CO_2$ concentration based on posterior fluxes better matches the observations.
- The posterior flux shows larger carbon sources over the tropics and the Southern Hemisphere and weaker carbon sources over the northern high latitudes.

# Land Carbon Fluxes Have much Stronger Seasonality than Air-Sea Carbon Fluxes



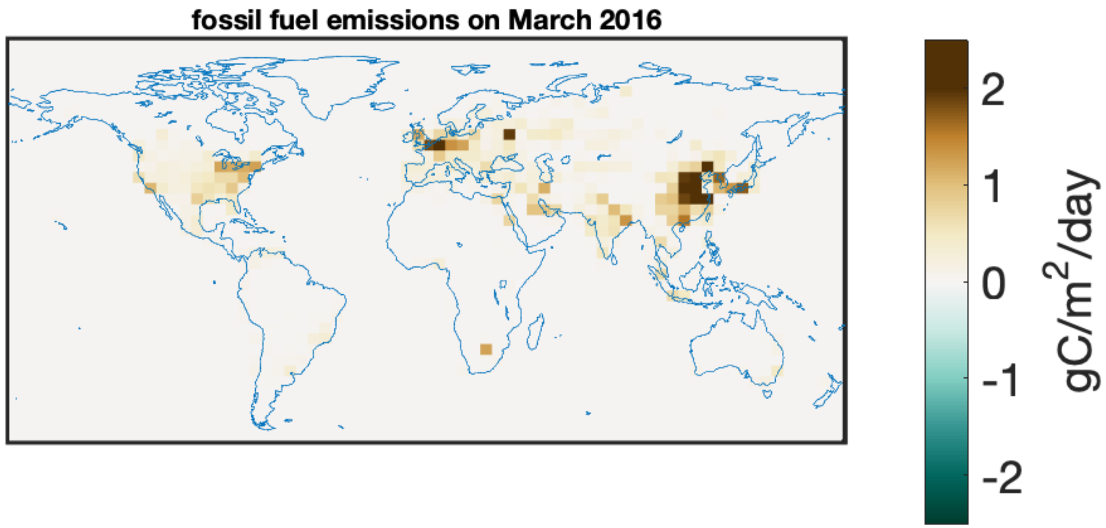



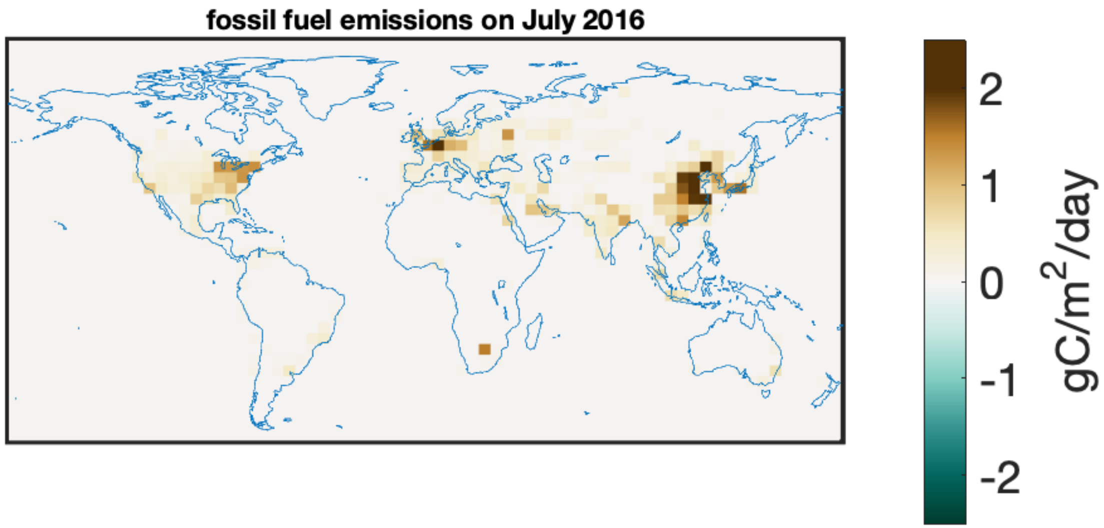




- The magnitude of land carbon fluxes is about an order of magnitude higher than air-sea carbon fluxes.
- The land carbon fluxes have much stronger seasonality than ocean carbon fluxes.
- The Northern Hemisphere land is a carbon source in winter and sink in summer, and the opposite is true for the Southern Hemisphere land.

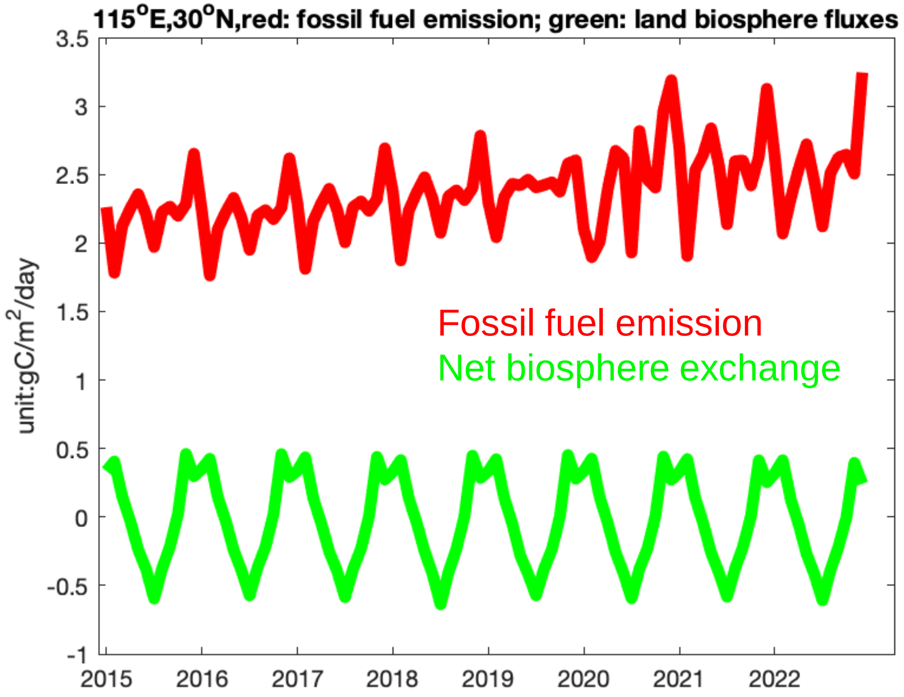
# Fossil Fuel Emission has a Weaker Seasonality than Land Carbon Fluxes

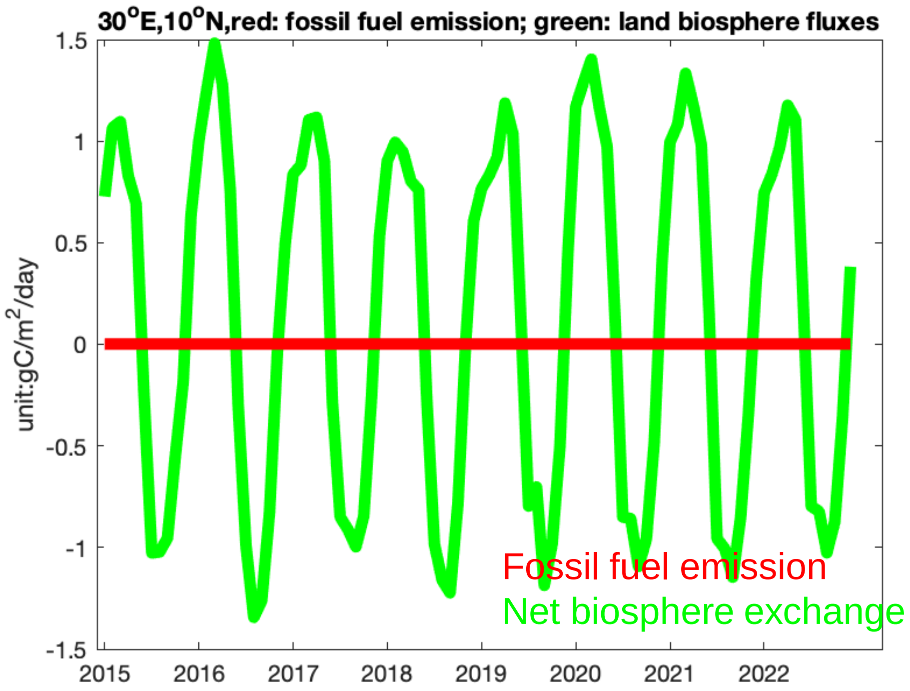



- Most of the fossil fuel emissions are concentrated over east Asia, North America, Europe, and India.
- Fossil fuel emissions have much weaker seasonality than land carbon fluxes.

# The Relative Magnitude of Net Biosphere Exchange and Fossil fuel Emissions Depends on Locations

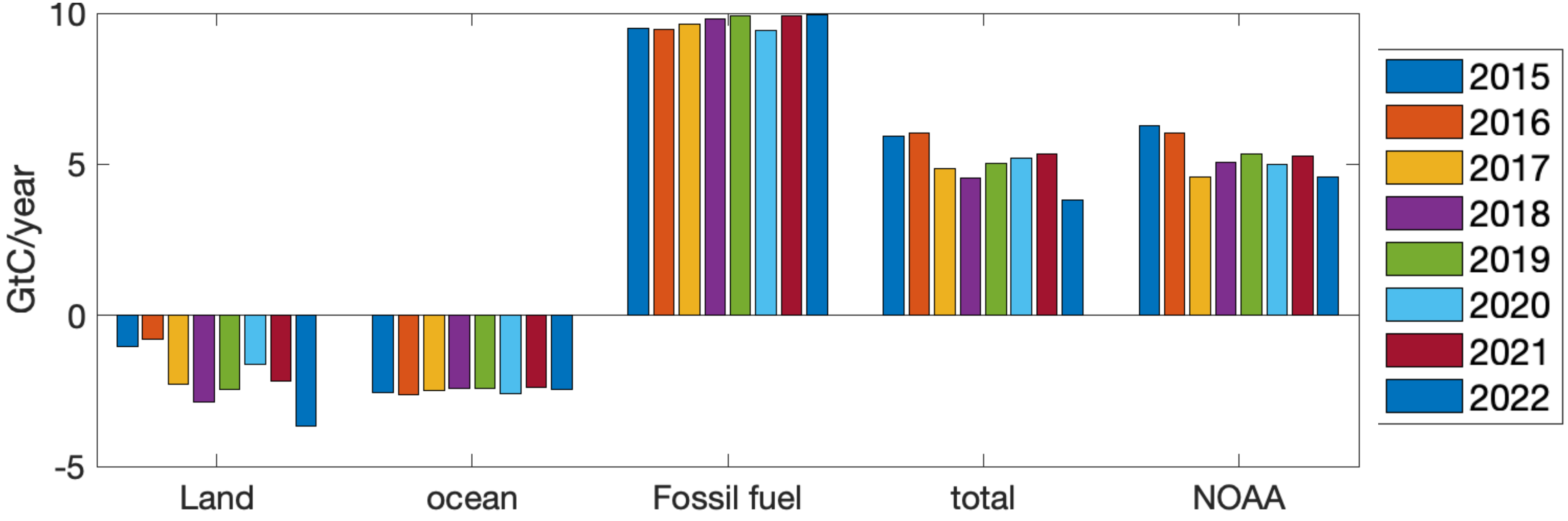



- Left panel: a grid point in China; Right panel: a grid point in North Africa.
- The annual mean fossil fuel emissions is much higher than land biosphere fluxes in China, while the fossil fuel emissions are negligible compared to land biosphere fluxes in Africa.
- You can make a similar plot for the locations and regions that you are interested.

# Larger year-to-year variabilities in net land carbon fluxes

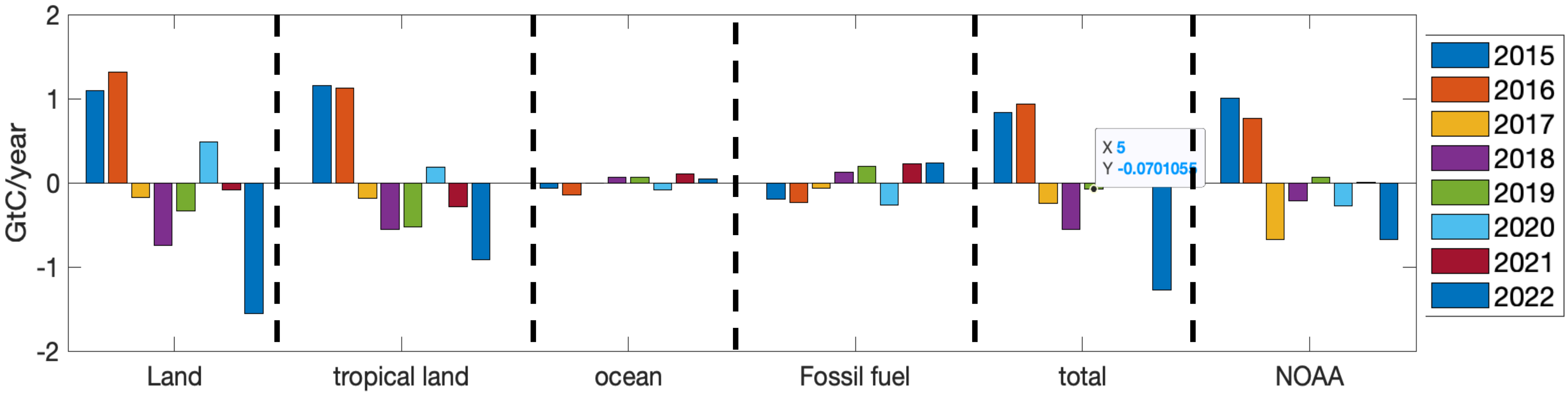
Annual total carbon fluxes over land, ocean, fossil fuel emissions, and total fluxes from 2015-2022




- Each color represents one specific year from 2015 to 2022.
- Negative numbers: carbon sinks; positive numbers: carbon sources.
- Land carbon fluxes have much larger year-to-year variability than ocean and fossil fuel emissions.
- The total carbon fluxes are the sum of land, ocean, and fossil fuel emissions, which represent the amount of carbon remaining in the atmosphere.
- The total carbon fluxes estimated from flux inversions agree with the CO2 growth rate observed by the NOAA Surface Observing Network.

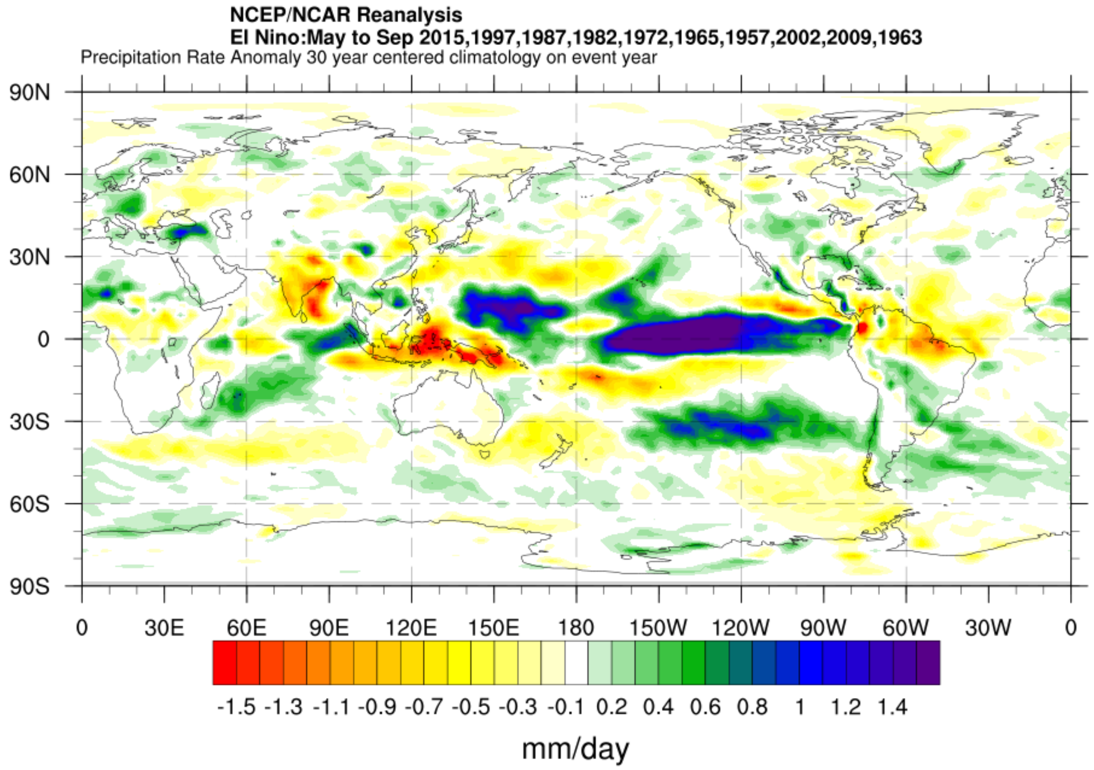
# Tropical Land Carbon Fluxes Dominate the Land Carbon Flux Year-to-year Variability

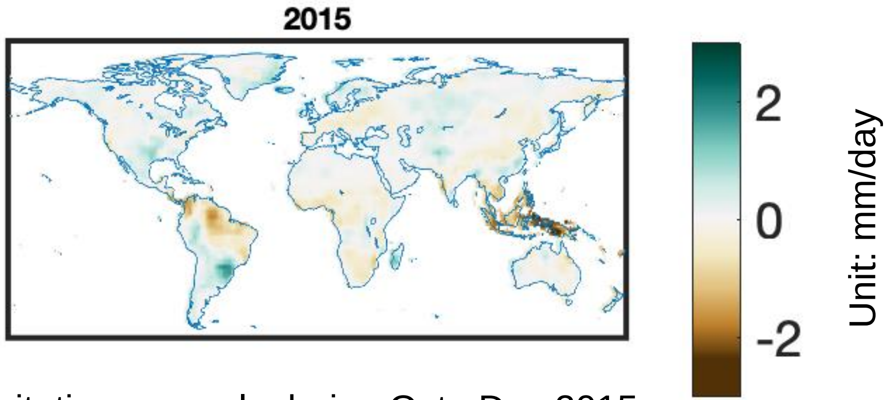
Annual carbon flux anomalies over land, tropical land, ocean, fossil fuel emissions, total fluxes, and NOAA observed CO2 from 2015 to 2022



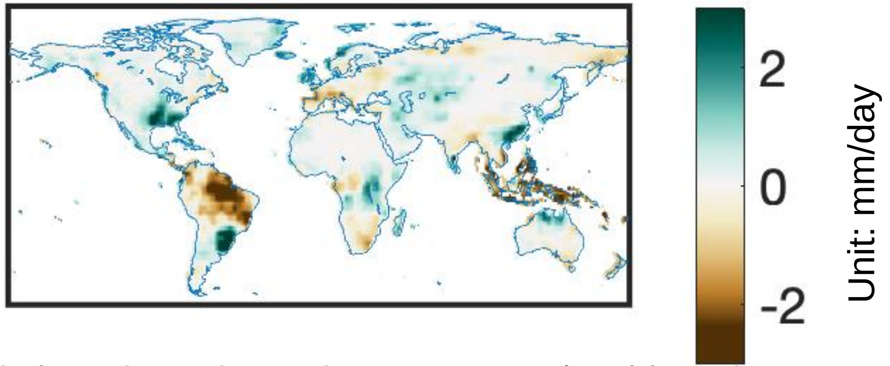

- The color bar represents 2015 to 2022 from the left to the right.
- Annual carbon flux anomalies = annual carbon fluxes – mean carbon fluxes between 2015-2022.
- 2015 and 2016 have much weaker net land carbon sink, reflected in the Figure as positive land carbon flux anomalies, which primarily come from the tropical land.
- Tropical land is defined as the land area between 25S and 25 N.
- Both ocean and fossil fuel emissions have very weak year to year variability.

# Drought Over Tropical Land During 2015-2016 El Niño



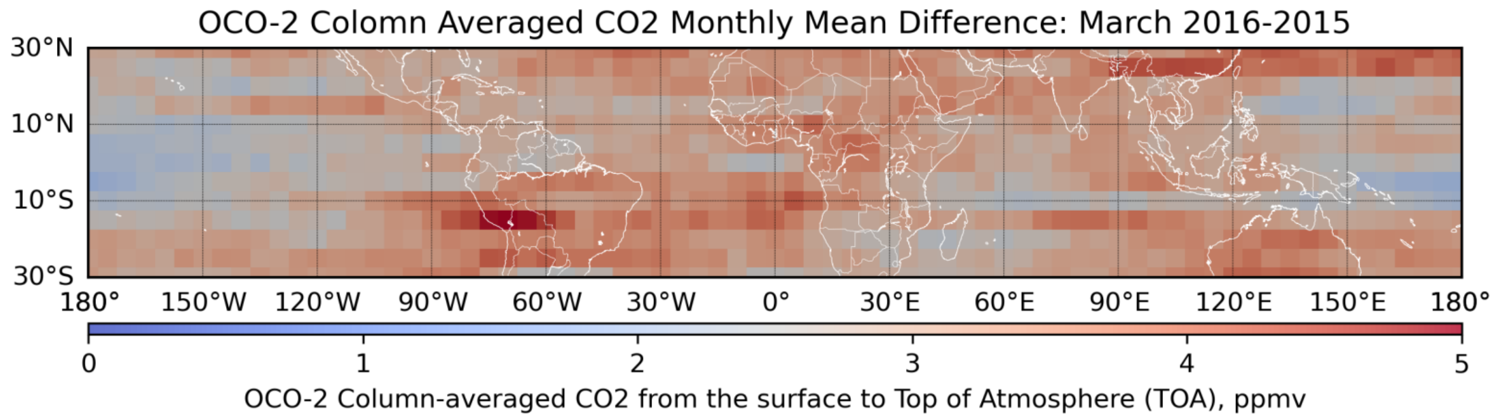

Precipitation anomaly during Oct –Dec 2015



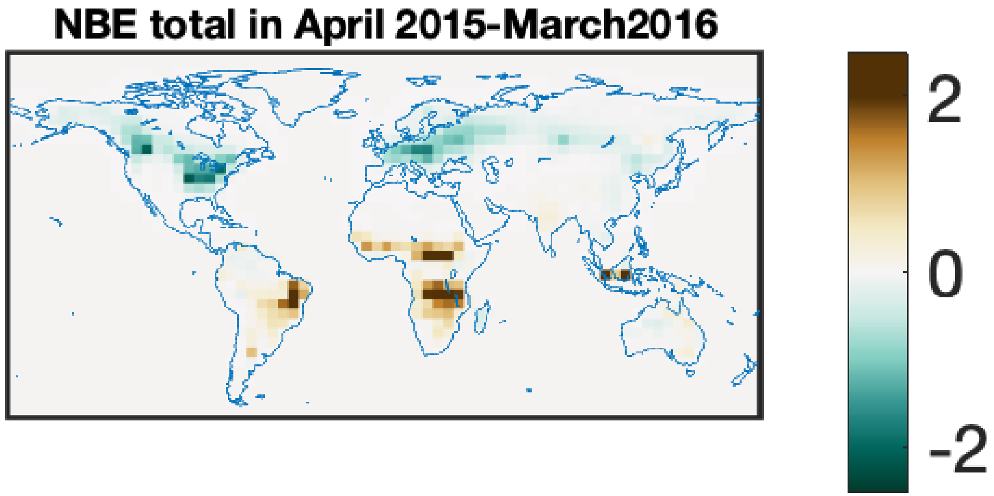

- El Niño years cause changes in circulation patterns, which lead to drought over tropical land, especially over tropical South America and tropical Asia.
- In 2015, tropical South America and tropical Asia experienced severe drought, especially during Oct-Dec. 2015.
- Climatology mean is defined from 2015 to 2023.

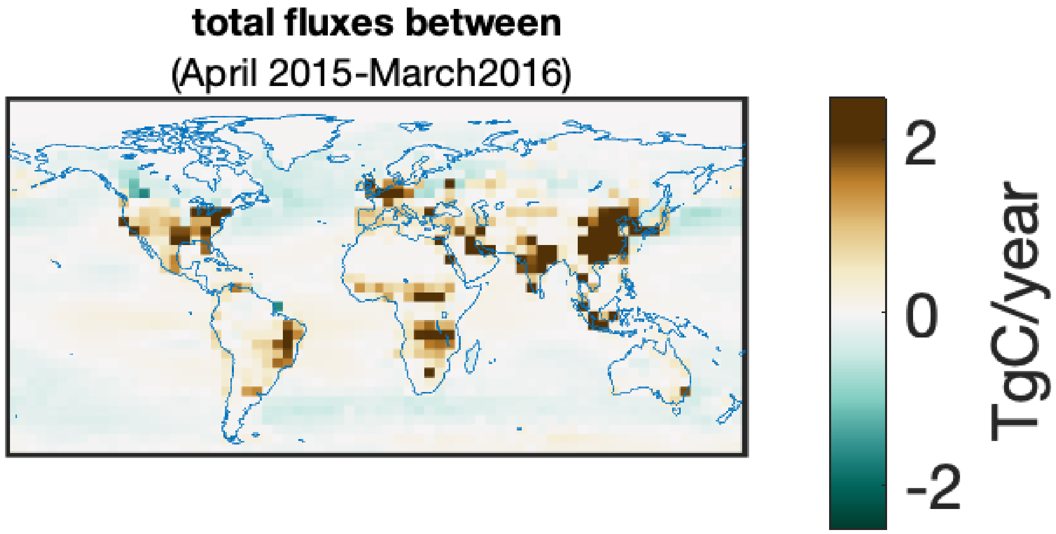
Data source: GPCP precipitation

# Drought Signal in both Atmospheric CO2 Concentration and Surface CO2 fluxes

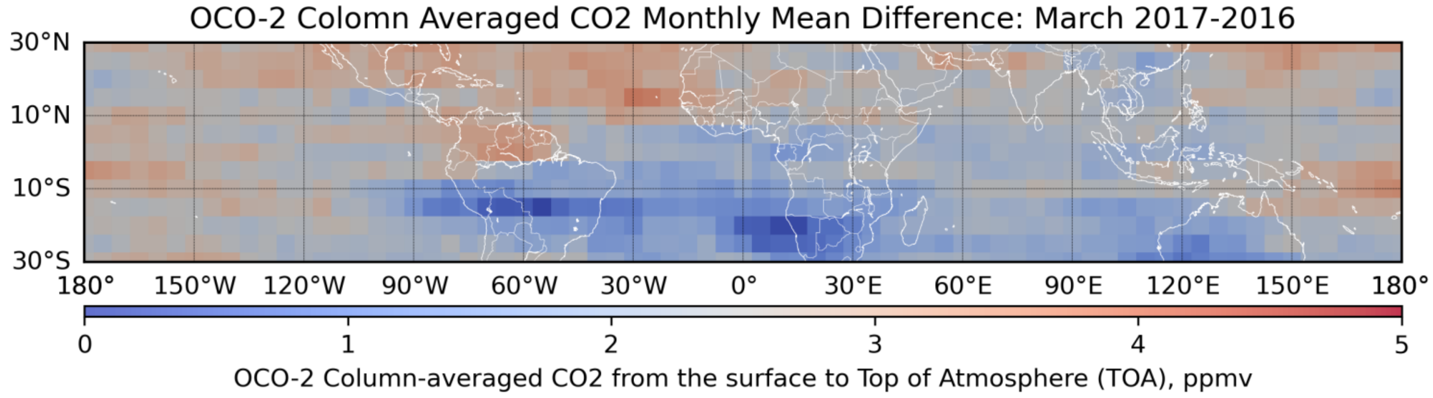


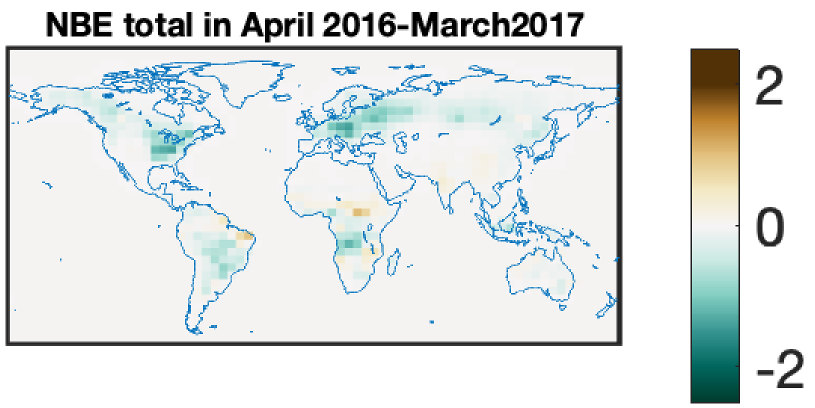

- March 2016 and March 2015 CO2 concentration difference = lateral transport + $\int_{April\ 2015}^{March\ 2016}(flux)_{local}$
- Much larger CO2 increase (>4ppm) over the tropics that corresponds to net carbon sources over the tropical land.
- Lateral transport carries fossil fuel signal to the tropics.

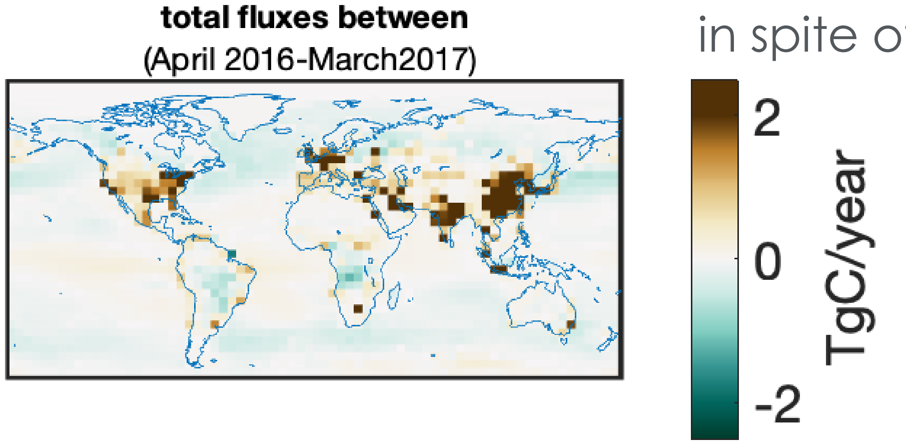


# Annual CO2 increase becomes Weaker with the Ending of El Nino

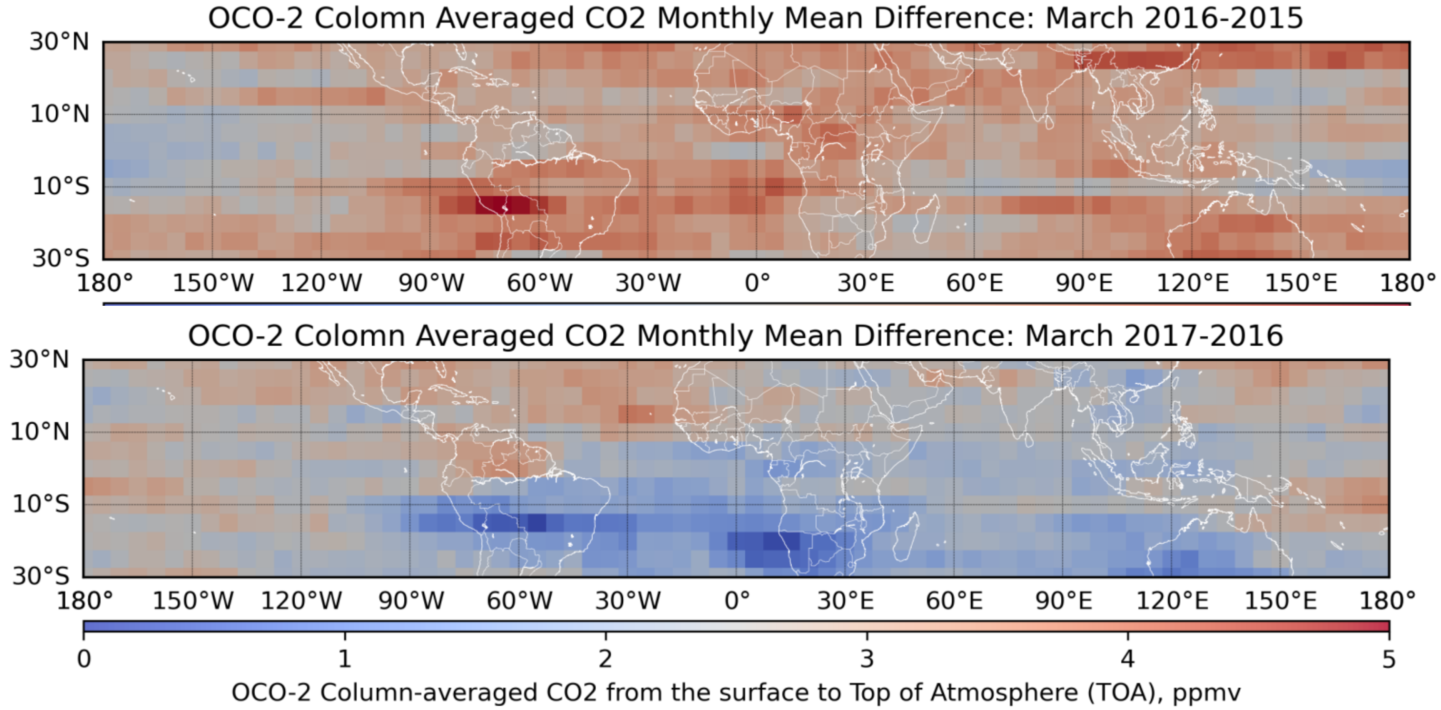


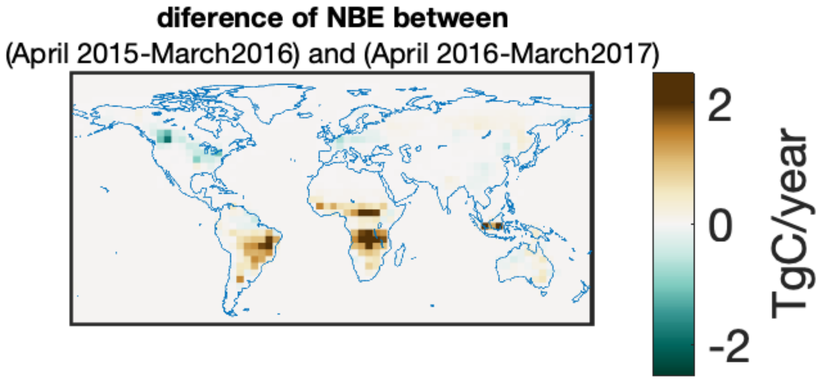



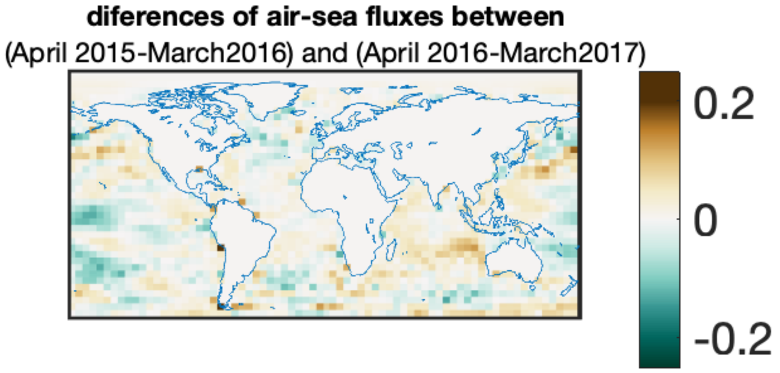

- March 2017 and March 2016 CO2 concentration difference = lateral transport + $\int_{April\ 2016}^{March\ 2017}(flux)_{local}$
- Much weaker CO2 increase (<2 ppm) over the tropics, which corresponds to carbon sinks over the tropical land.
- Lateral transport carries the fossil fuel signal to the tropics, causing atmospheric CO2 concentration to continue increasing from 2016 to 2017 in spite of the local carbon sink.

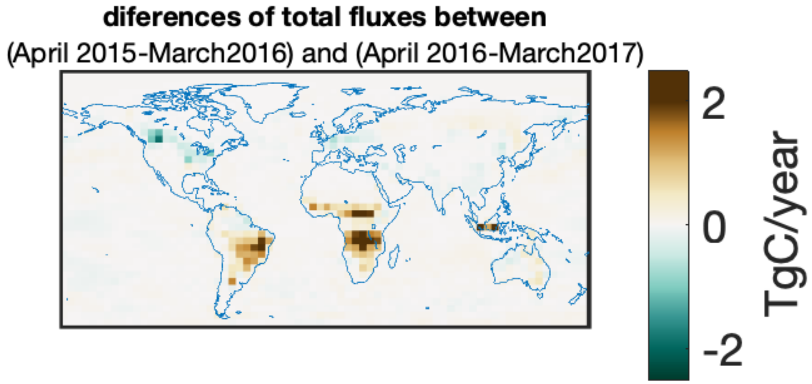
# Difference Between 2015/2016 El Nino and the Year Afterward




- Much larger CO2 increase over the tropics during El Nino than the year afterwards.
- Correspondingly, the tropical land is a much larger carbon source during EL Nino than the year afterwards.



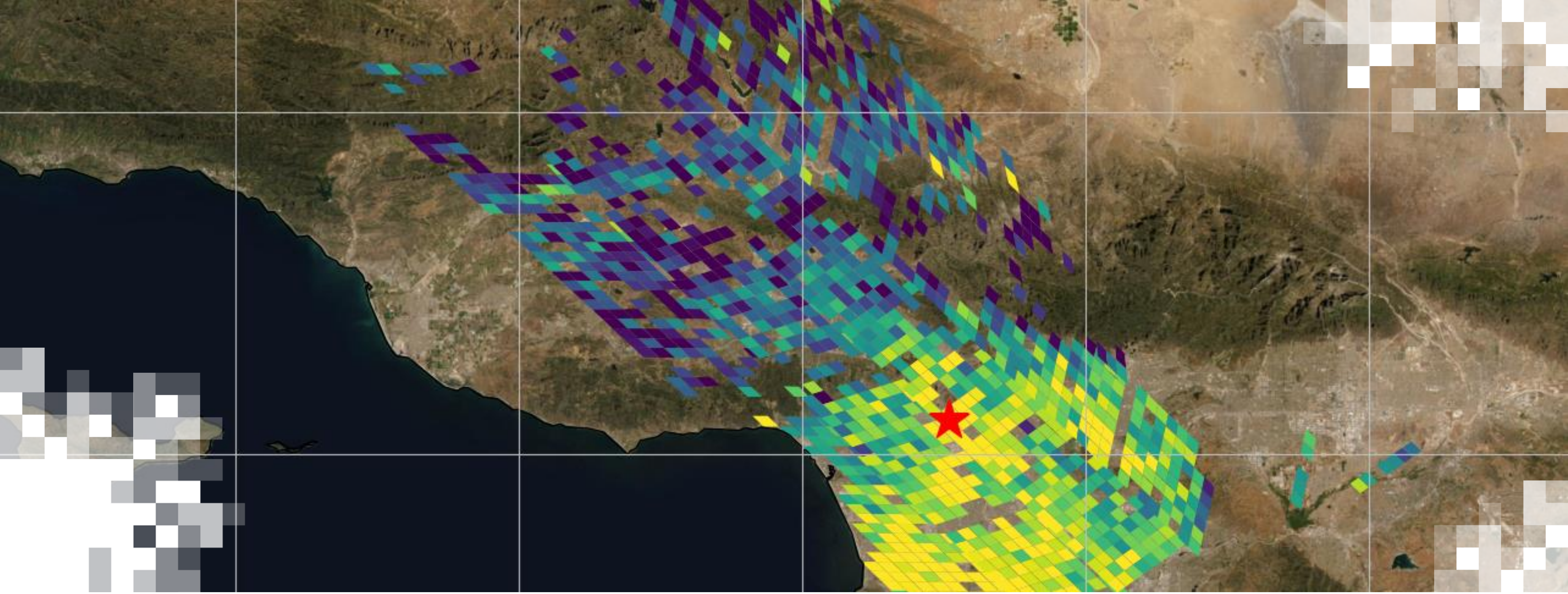



# Summary

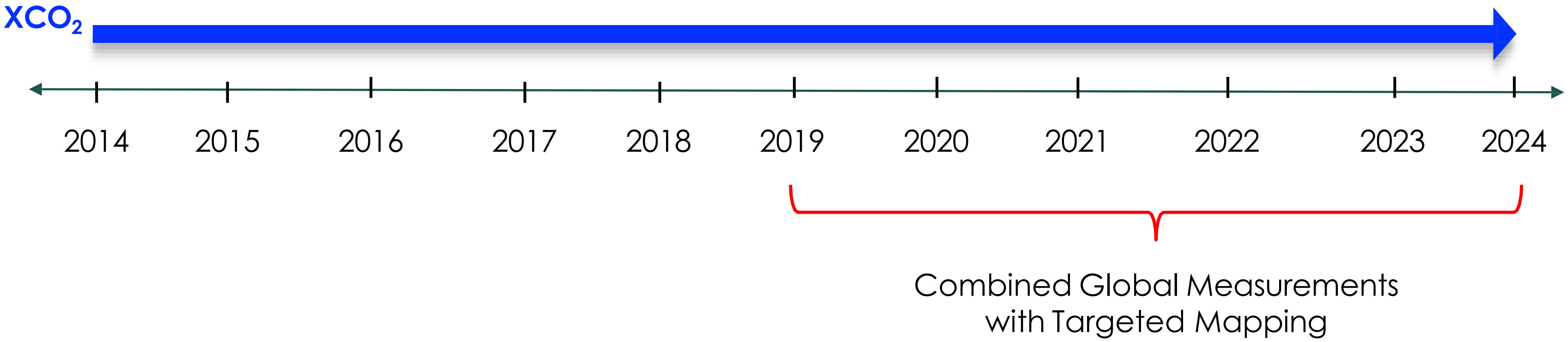
- Interpretation of column CO2 concentration
- Global carbon cycle processes
- The link between surface carbon fluxes and atmospheric CO2 concentration
- Units for both fluxes and concentration and the conversions between the two
- Atmospheric CO2 flux inversion process
- Interpretation of surface carbon fluxes
- The impact of El Nino on atmospheric CO2 concentration and surface carbon fluxes
- References

- https://carbon2018.globalchange.gov/chapter/1/
- Liu *et al.* Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño. *Science* 358, eaam5690 (2017). DOI: 10.1126/science.aam5690
- Parazoo, N., et al. (2024). Antecedent conditions mitigate carbon loss during flash drought events. *Geophysical Research Letters*, 51, e2024GL108310. https://doi.org/10.1029/2024GL108310
- Jiang, X., Li, K.-F., Liang, M.-C., & Yung, Y. L. (2021). Impact of Amazonian fires on atmospheric $CO_2$. *Geophysical Research Letters*, 48, e2020GL091875. https://doi.org/10.1029/2020GL091875



# Getting Started with OCO Data

# Timeline of Available XCO2 Data



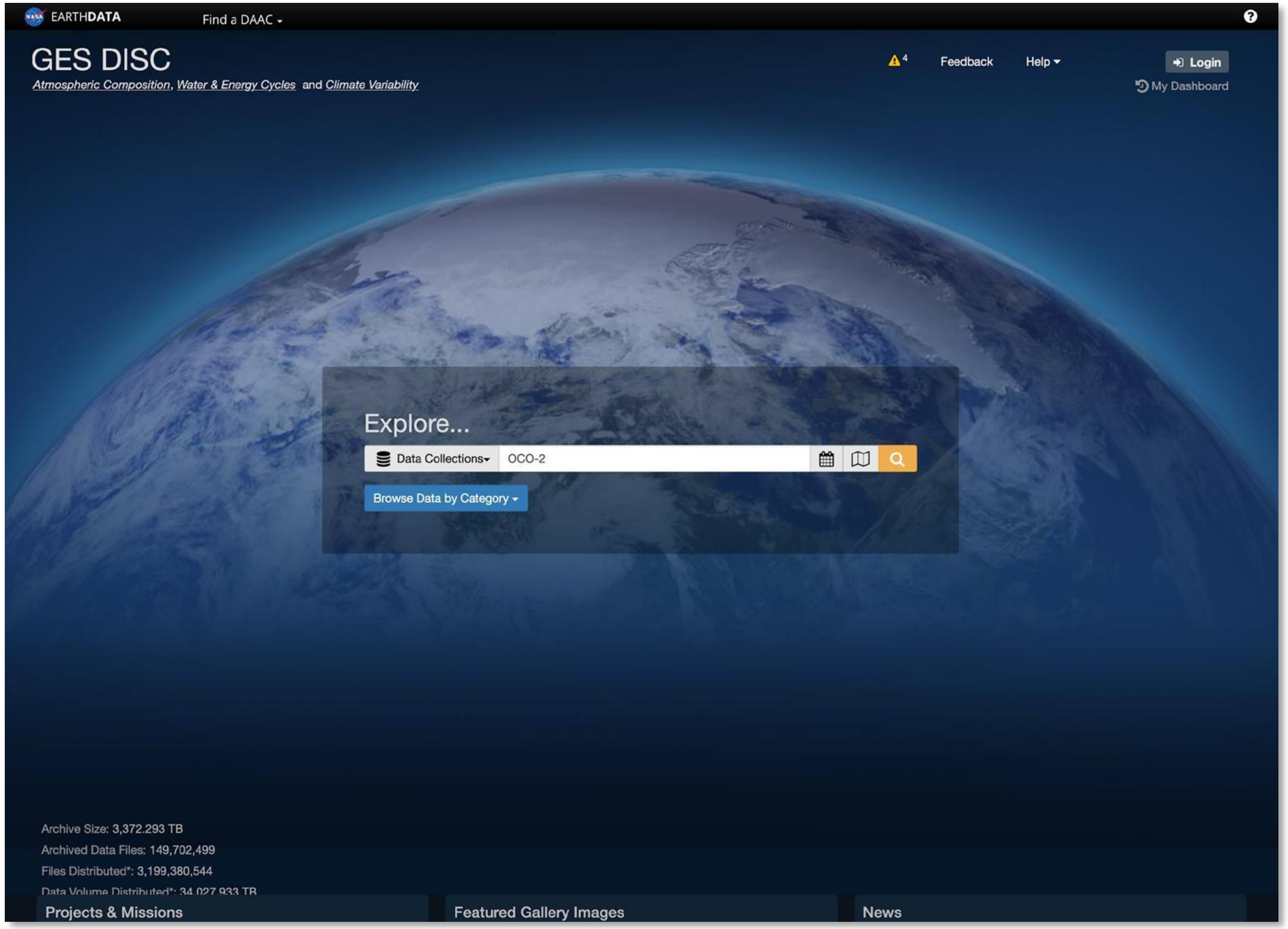
# All OCO-2 and OCO-3 are available through NASA's Goddard Earth Science Data and Information Service Center (GES DISC)

OCO-2 and OCO-3 data are stored at the GES DISC!

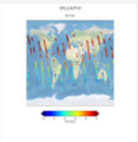
Be sure to register for a profile. It's free!

You can browse and look without a login, but you will need one to download data files.

You can always find the data or data collections by entering "OCO-2" or "OCO-3" in the search bar.



# Same Name, Updated Version, and Now Cloud Accessible

| Dataset | Source | Version | Time Res. | Spatial Res. | Process Level | Begin Date | End Date |
|---|---|---|---|---|---|---|---|
|  Hover OCO-2 Level 2 bias-corrected XCO2 and other select fields from the full-physics retrieval aggregated as daily files, Retrospective processing V11.1r (**OCO2**_L2_Lite_FP 11.1r) Get Data | OCO-2 OCO-2 | 11.1r | 16 days | 2.25 km x 1.29 km | 2 | 2014-09-06 | 2024-04-01 |

## OCO-2 Lite$XCO_2$ File Naming Convention:

oco2_LtCO2_[AcquisitionDate]_{ShortBuildID]_[ProductionDateTime][Source].nc4

oco2_LtCO2_240104_B11100Ar_240229181720s.nc4

Note: Latest version of OCO-2 Data is Version 11.

# OCO-2/OCO-3 are Compliant with Open Science at NASA

The mission data are freely available. Please help support the missions and the continued availability of the data by citing its use!

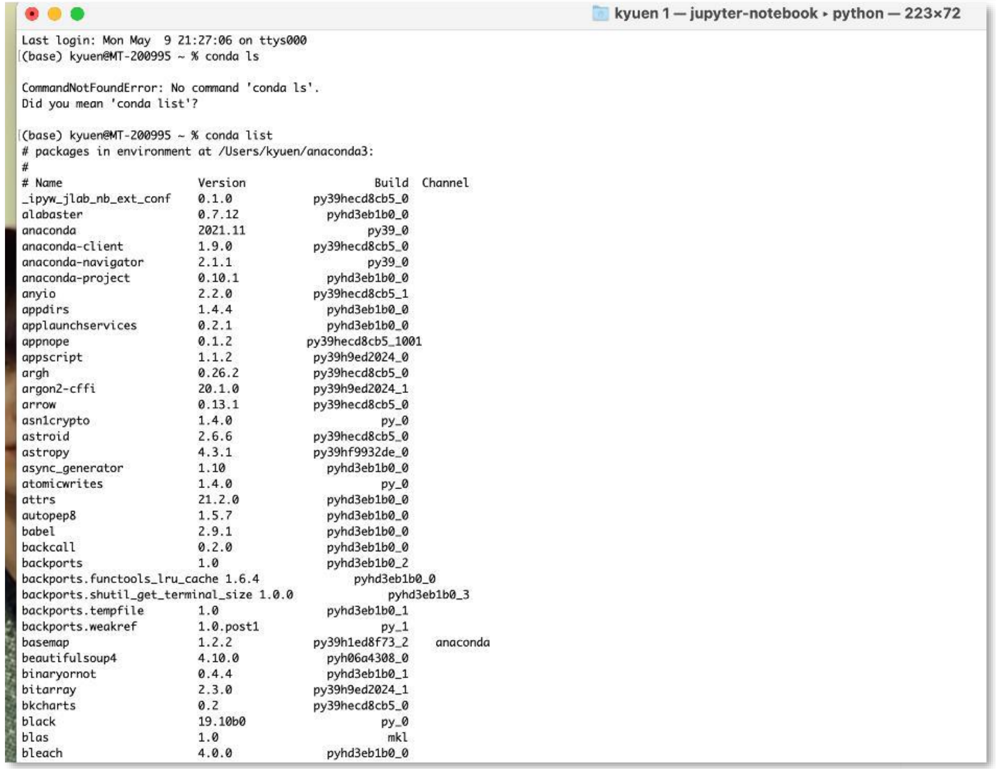
**To cite the data in publications:**
OCO-2/OCO-3 Science Team, Vivienne Payne, Abhishek Chatterjee (2022), OCO-2 Level 2 bias-corrected XCO2 and other select fields from the full-physics retrieval aggregated as daily files, Retrospective processing V11.1r, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: **[*Data Access Date*]**, 10.5067/8E4VLCK16O6Q

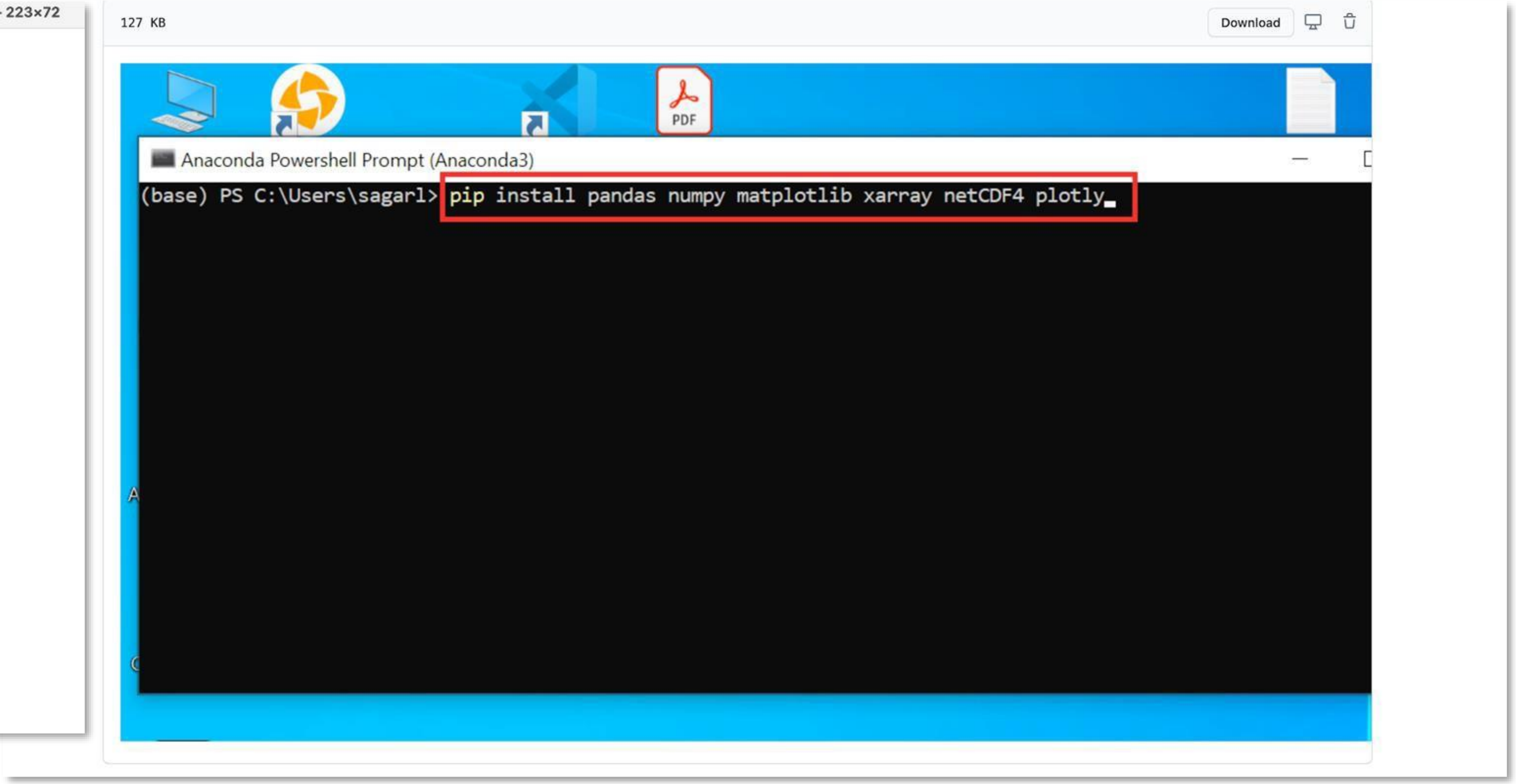
# Jupyter Notebook Portion

- Before following along, you will need to download some software packages for this portion of the training.
- We will be working in Python 3, and Python and Jupyter notebook are packaged within Conda. Please follow the install directions listed for your operating system (Windows, Mac OS, Linux). https://docs.conda.io/projects/conda/en/latest/user-guide/install/index.html
- The libraries that you will need to use and import in the code below should be included in Conda.
- Please remember which directory you download your files, and we recommend creating a folder for the data.
- **Jupyter Notebook Installation Guide (if you would prefer to just load this without Conda)**
- From this list of websites, you can follow instructions to setup Jupyter Notebook:
  - https://jupyter.org/install
  - https://www.geeksforgeeks.org/how-to-install-jupyter-notebook-in-windows/
  - https://test-jupyter.readthedocs.io/en/latest/install.html

# Next Step

The libraries you need should be installed with Conda. To verify, open a terminal and type Conda List. Scroll to check that what you need is there. If not, do pip install.



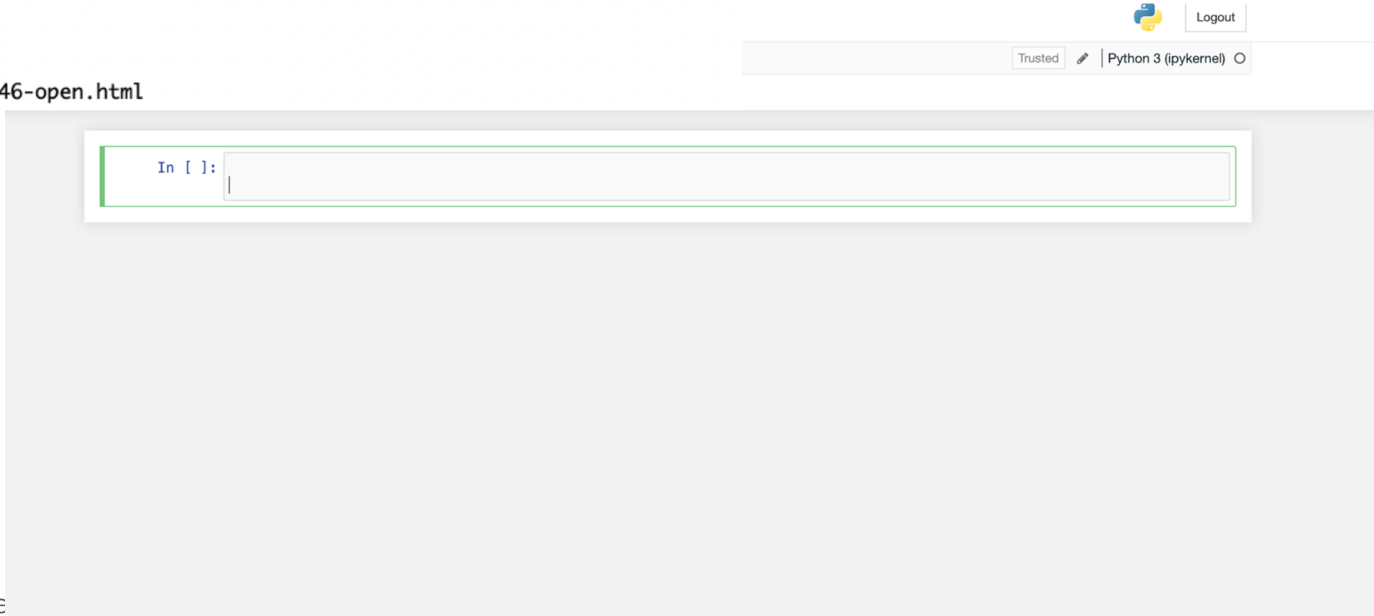



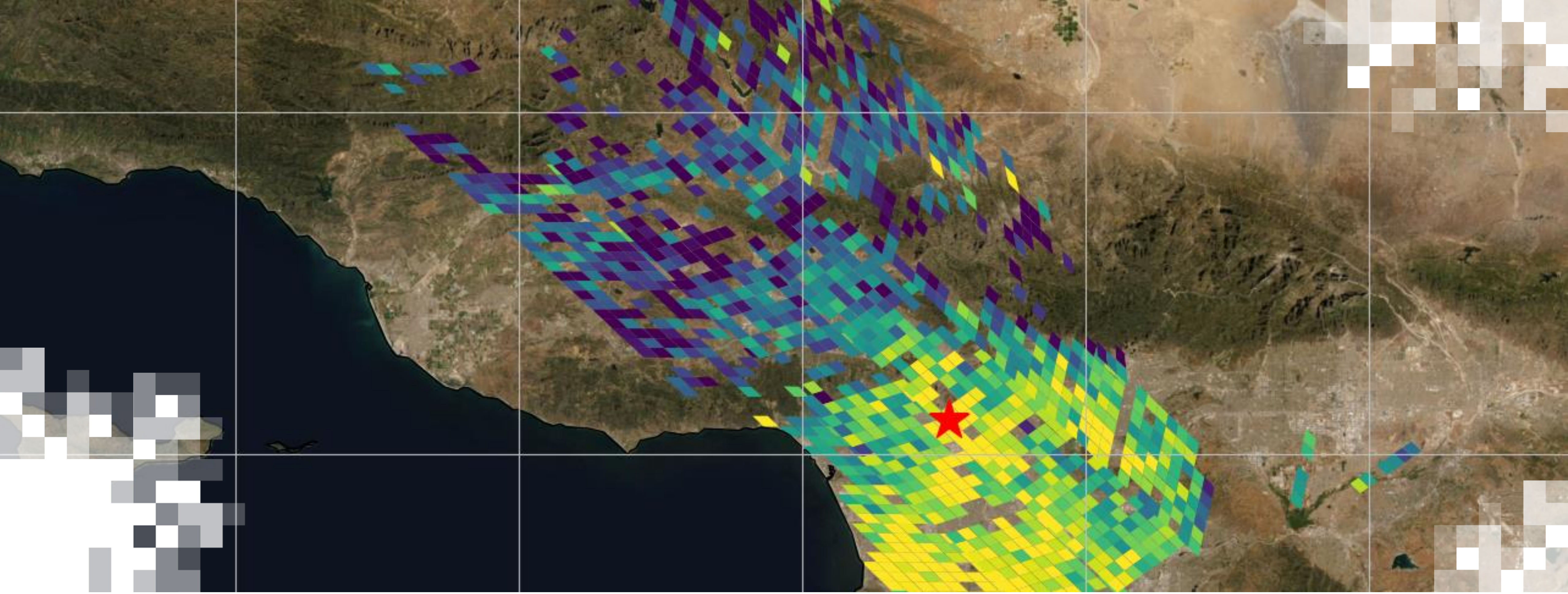
# Final Step

To open Jupyter notebook, simply type Jupyter notebook in the terminal prompt and it will open up a new notebook in your chosen browser.

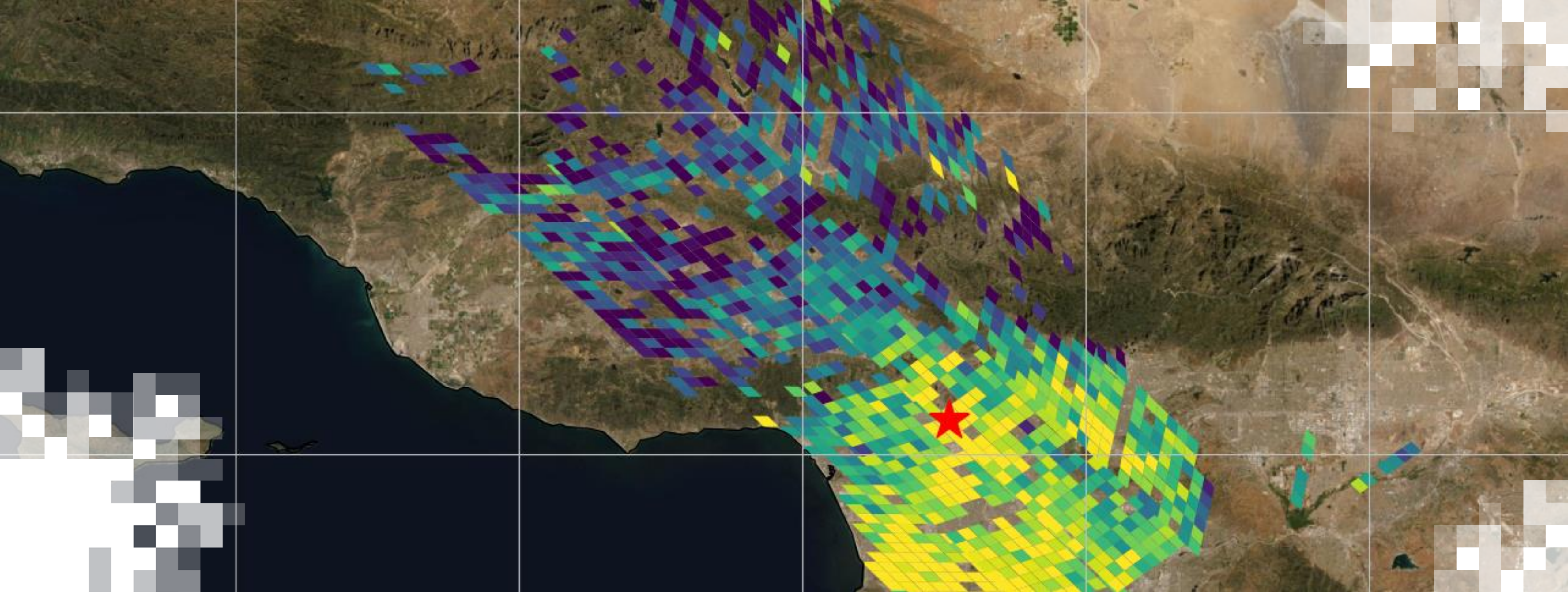
```
Last login: Mon May  9 21:29:44 on ttys001
(base) kyuen@MT-200995 ~ % jupyter notebook
[I 2022-05-12 19:39:01.808 LabApp] JupyterLab extension loaded from /Users/kyuen/anaconda3/lib/python3.9/site-packages/jupyterlab
[I 2022-05-12 19:39:01.808 LabApp] JupyterLab application directory is /Users/kyuen/anaconda3/share/jupyter/lab
[I 19:39:01.813 NotebookApp] The port 8888 is already in use, trying another port.
[I 19:39:01.813 NotebookApp] The port 8889 is already in use, trying another port.
[I 19:39:01.814 NotebookApp] Serving notebooks from local directory: /Users/kyuen 1
[I 19:39:01.814 NotebookApp] Jupyter Notebook 6.4.5 is running at:
[I 19:39:01.814 NotebookApp] http://localhost:8890/?token=8d904a1bab00dd06d19f4c44d22cae9bd1cc91121be9e98b
[I 19:39:01.814 NotebookApp]  or http://127.0.0.1:8890/?token=8d904a1bab00dd06d19f4c44d22cae9bd1cc91121be9e98b
[I 19:39:01.814 NotebookApp] Use Control-C to stop this server and shut down all kernels (twice to skip confirmation).
[C 19:39:01.818 NotebookApp]

    To access the notebook, open this file in a browser:
        file:///Users/kyuen%201/Library/Jupyter/runtime/nbserver-29346-open.html
```





# Jupyter Notebook Demonstration



Part 2:
**Summary**

# Summary

- Interpret column $CO_2$ spatial and temporal distributions.
- The factors that contribute to the change in local and global atmospheric $CO_2$ concentration
- The units of atmospheric $CO_2$ concentration and surface carbon fluxes
- The link between surface carbon fluxes and atmospheric $CO_2$ concentration
- Atmospheric $CO_2$ flux inversion process
- Interpret spatial and temporal distributions of surface carbon fluxes
- Interpret drought signals in both OCO-2 $CO_2$ concentration and inferred fluxes

- Data sources:
  - $CO_2$ concentration
    - OCO-2 V11
  - Carbon Fluxes
    - CMS-Flux posterior NBE
    - CMS-Flux posterior air-sea fluxes
    - Fossil fuel emissions
    - CMS-Flux NBE prior fluxes
  - Other data source
    - OCO-2 MIP Fluxes
    - US GHG Center country carbon stock change

- References:

# References


- Crisp, D.,  et al. 10, 59–81, https://doi.org/10.5194/amt-10-59-2017, 2017.
- Liu, J. et al 2017 Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Nino Science **358** eaam5690
- Liu, J., et al. Carbon Monitoring System Flux Net Biosphere Exchange 2020 (CMS-Flux NBE 2020), Earth Syst. Sci. Data, 13, 299–330, https://doi.org/10.5194/essd-13-299-2021, 2021.
- A. Chatterjee *et al.* Influence of El Niño on atmospheric $CO_2$ over the tropical Pacific Ocean: Findings from NASA’s OCO-2 mission.*Science***358**,eaam5776(2017).DOI:10.1126/science.aam5

# Contact

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- Webinar Webpage:
  - https://appliedsciences.nasa.gov/get-involved/training/english/arset-aplicaciones-de-mediciones-de-dioxido-de-carbono-para-estudios
- ARSET Webpage:
- https://appliedsciences.nasa.gov/arset
- Twitter: @NASAARSET

# 3rd Session

**CO2 Measurements over a Large Urban Area**

- Recognize the importance and challenges of measuring carbon dioxide over metropolitan areas.
- Identify important aspects of space-based $CO_2$ measurements over urban areas.
- Access, subset, and download multi-year OCO-3 SAM data using a provided Jupyter notebook.
- Visualize OCO-3 SAM data over urban areas and perform an interpretative and comparative analysis.

# Thank You!