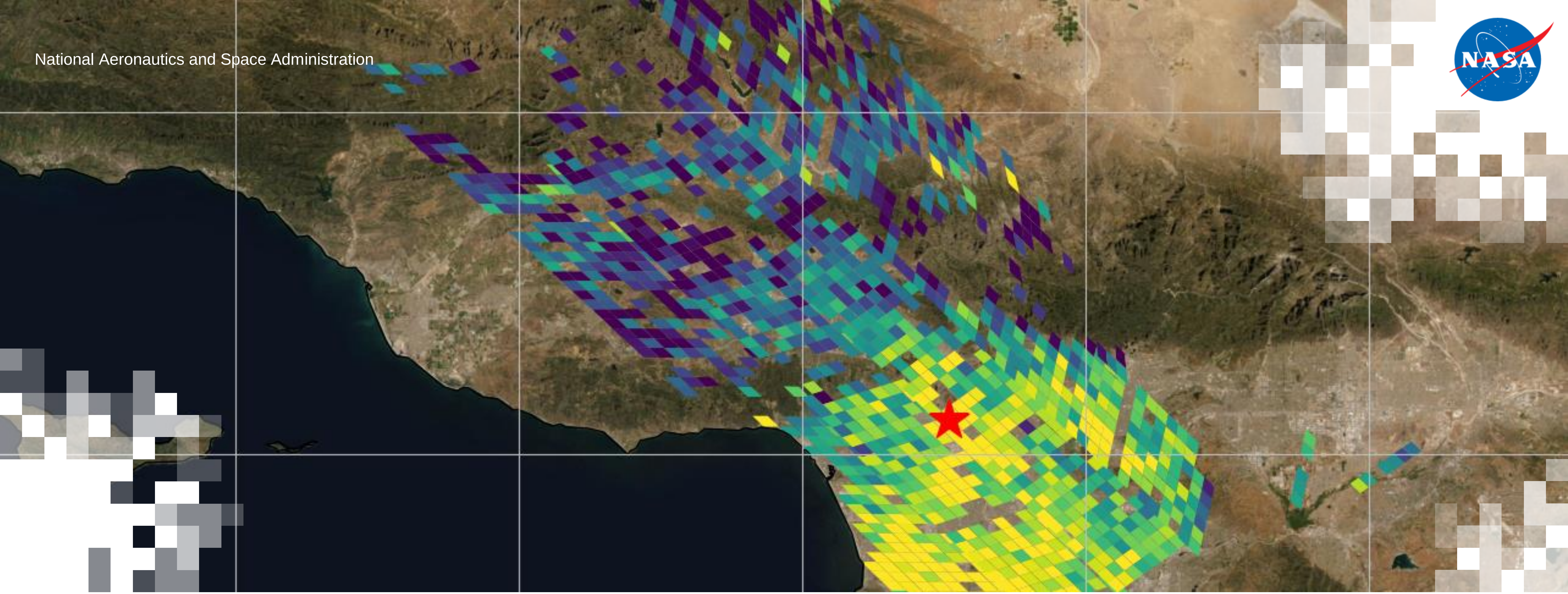
National Aeronautics and Space Administration



Applications of Carbon Dioxide Measurements for Climate-Related Studies

Part 1: XCO_2 from OCO-2 and OCO-3: Mission Recap and Data Characteristics and Limitations

Dr. Vivienne Payne (NASA JPL), Project Scientist, OCO-2 Mission

July 9, 2024

Training Objectives

By the end of this training attendees will be able to:

- Identify the characteristics and limitations of the NASA Orbiting Carbon Observatory, OCO-2 and OCO-3 XCO2 measurements.
- Access and download data through the Distributed Active Archive Center (GES DISC), and open and visualize XCO2 data from OCO-2/OCO-3 in GES DISC Earthdata.
- Interpret XCO2 data from OCO-2/OCO-3 for global, regional, and local scales.
- Assess the level of confidence to place in XCO2 measurements using the quality flags incorporated into each dataset.
- Analyze OCO-2 data for assessing the impacts of an El Nino event on Level 2 CO2 concentrations and Level-4 fluxes over tropical regions.
- Analyze OCO-3 data for assessing the variations in Level-2 CO2 concentrations over a metropolitan area.

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.

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 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.

Prerequisite

ARSET - Measuring Atmospheric Carbon Dioxide from Space in Support of Climate Related Studies

Review of Prior Knowledge

1. Spaceborne measurements of atmospheric carbon dioxide (CO_2) are becoming an increasingly important and relevant capability in support of climate studies and to inform policy decisions.
2. NASA’s OCO-2 and OCO-3 missions are dedicated to providing this critical measurement, and also provide measurements of solar-induced chlorophyll fluorescence (SIF).
3. Measurements of atmospheric CO_2 can be used in conjunction with models to infer CO_2 fluxes.
4. CO_2 flux estimates derived from OCO-2/3 data are used to constrain net biosphere exchange (NBE) and net carbon exchange (NCE) between the land and ocean surfaces and the atmosphere.
5. OCO-2/3 data also help constrain emissions from hotspots, such as urban areas, megacities, and power plants.

Part 1 Objectives

By the end of Part 1, participants will be able to:

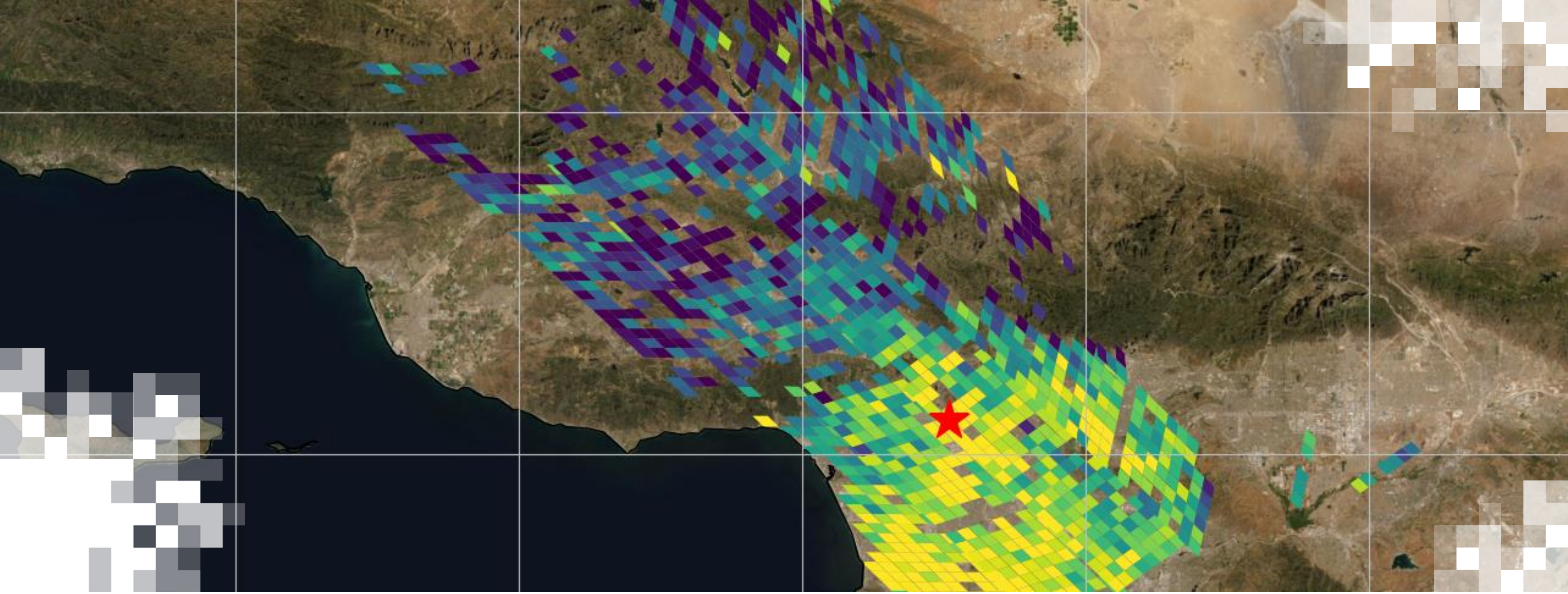
- Identify the characteristics and limitations of XCO_2 measurements from OCO-2/OCO-3.
- Explore application areas where XCO_2 is useful.
- Identify where to access and how to use the quality flags in a dataset for assessment of the measurement.
- Interpret data and address considerations for using CO_2 in different application areas.

Part 1 – Trainer

Dr. Vivienne Payne

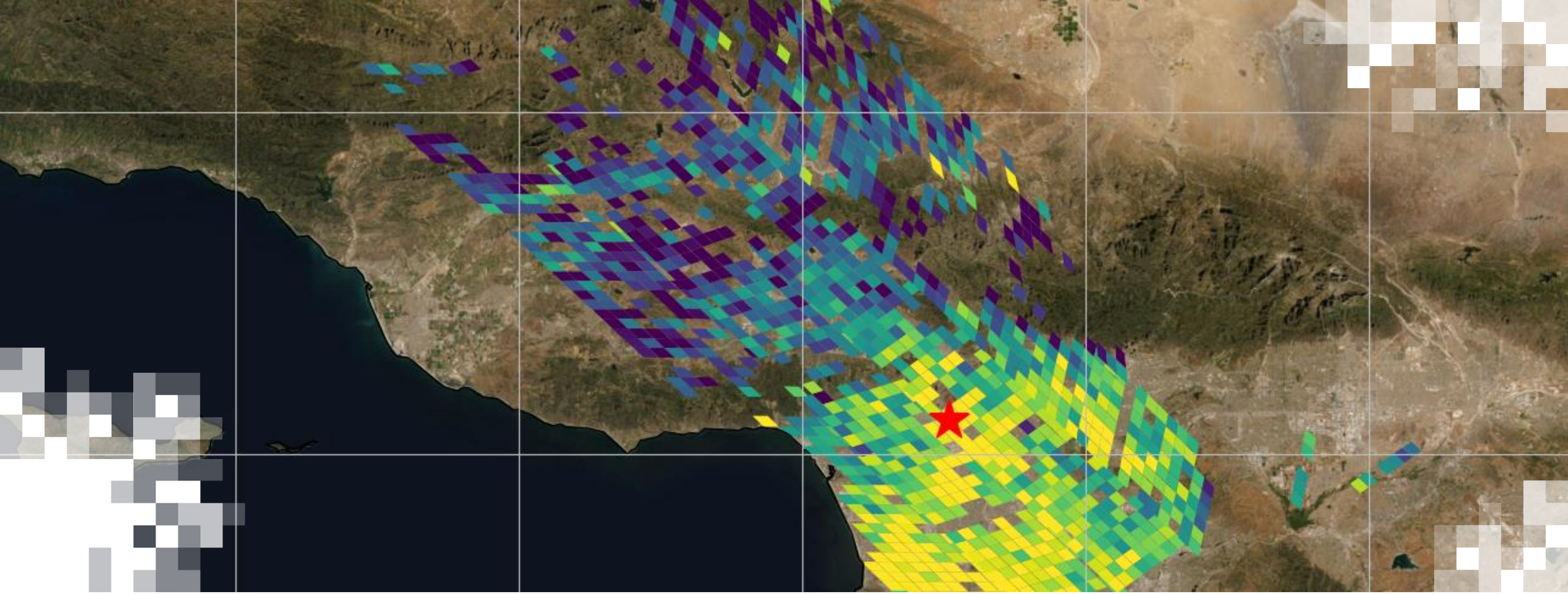
Project Scientist, OCO-2 Mission

NASA JPL



Part 1:

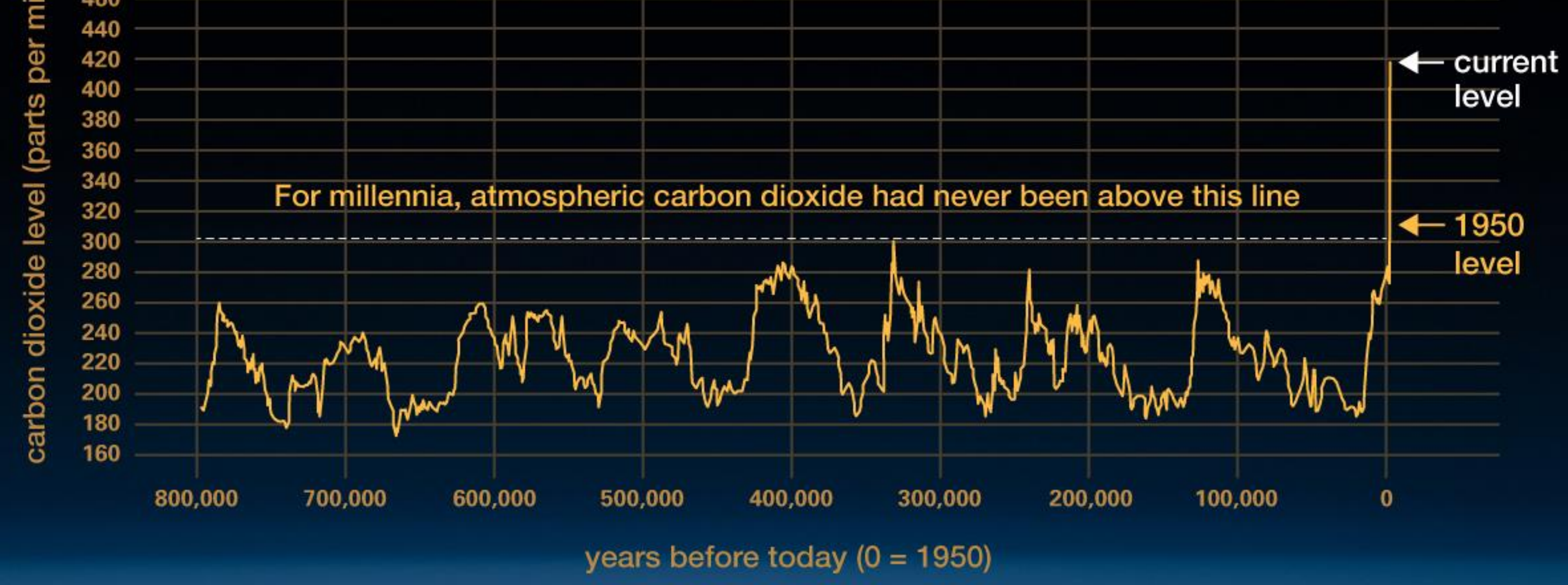
XCO_2 from OCO-2 and OCO-3:
Mission Recap and Data Characteristics and Limitations



Missions Recap: The Orbiting Carbon Observatory Missions

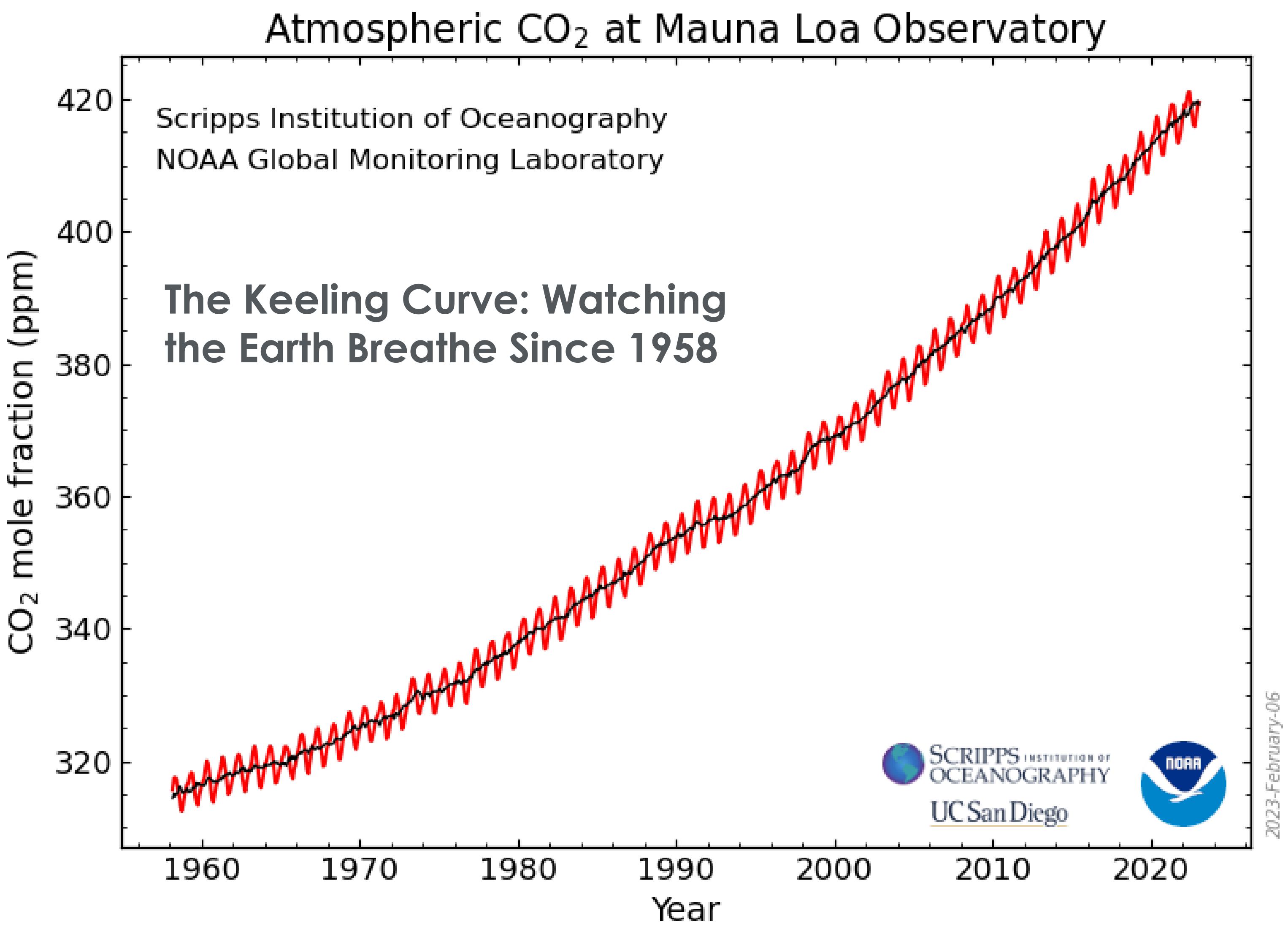
Increases in CO_2 result in warmer temperatures on Earth.

- CO_2 ≅ 2/3 heating from human-produced greenhouse gases
- Ice cores provide a record of atmospheric CO_2 for 800,000 years.
- Atmospheric CO_2 is increasing at an unprecedented rate.



Ground-Based Measurements of Atmospheric CO_2

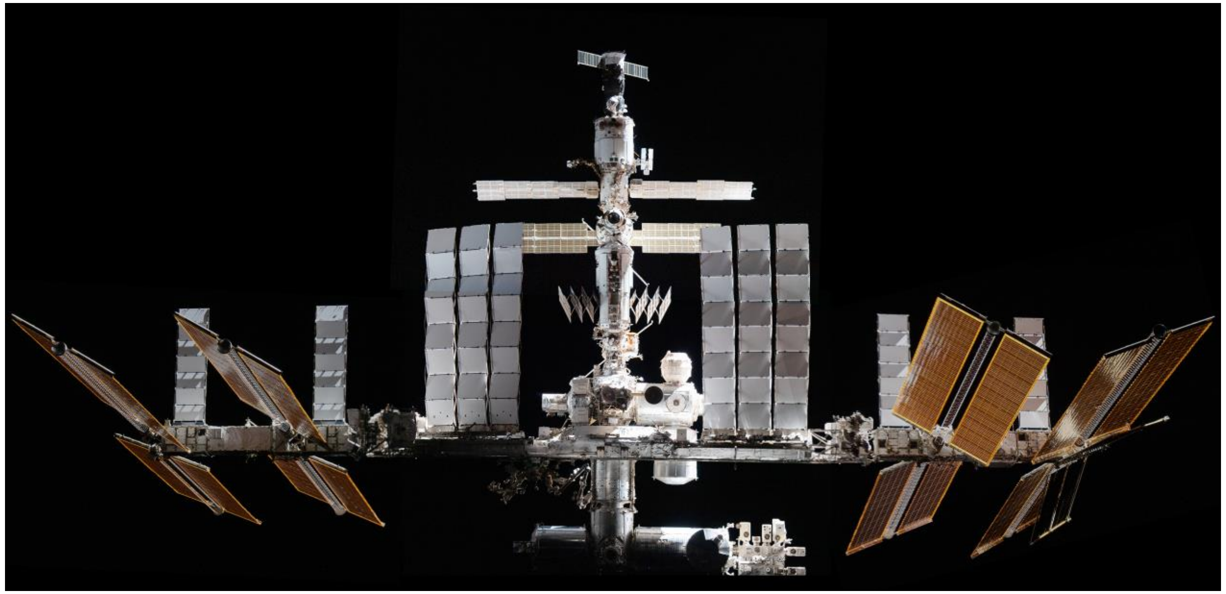
- Decades of measurements
- Measurements are sparse….



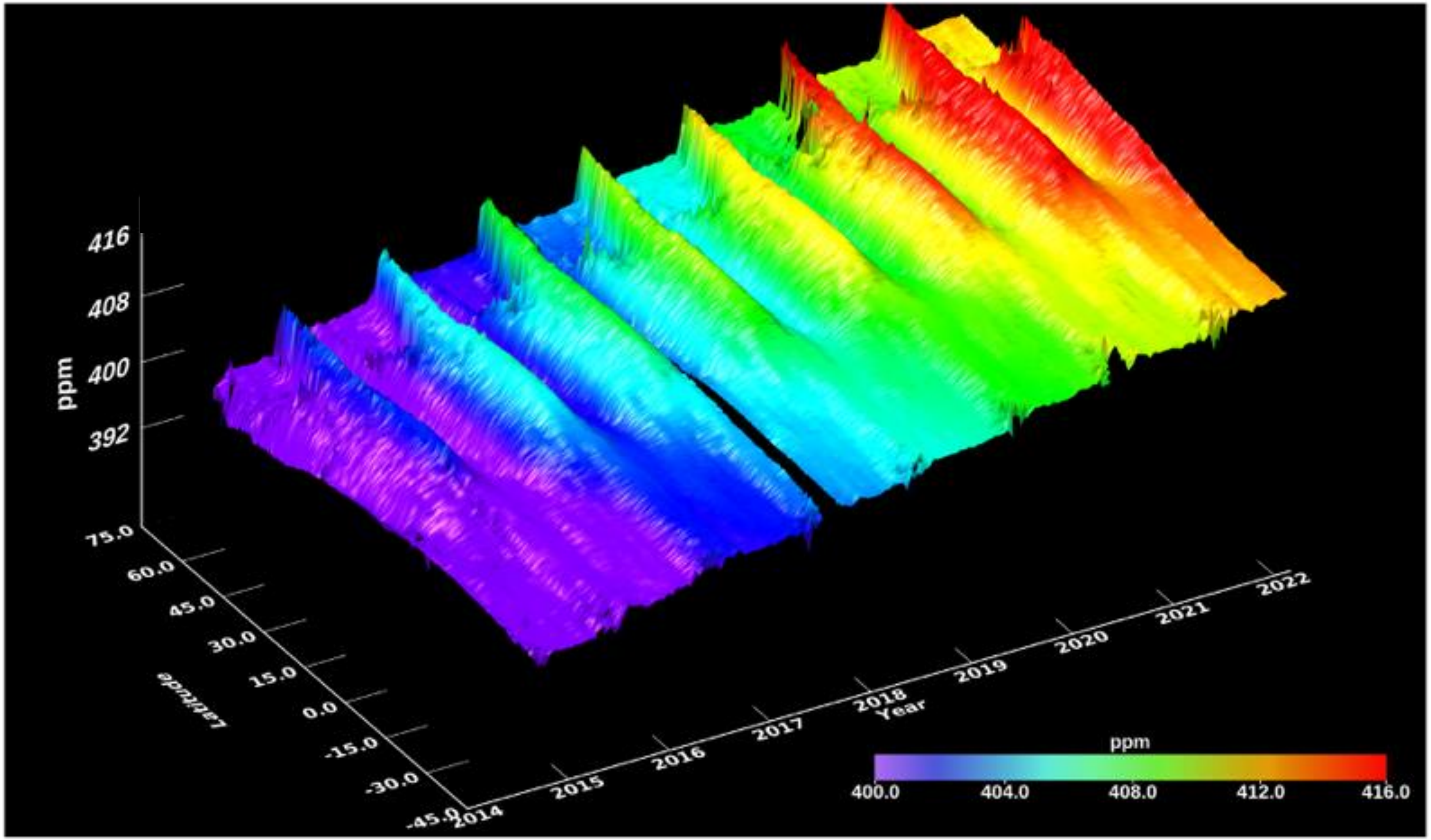
Dedicated NASA Satellite Missions for Studying CO_2

- Orbiting Carbon Observatory-2 (OCO-2)
  - Launched July 2, 2014
  - Sun-synchronous polar orbit (A-Train)
  - Measures both column average CO_2 (XCO_2) and solar-induced chlorophyll fluorescence (SIF)

- Orbiting Carbon Observatory-3 (OCO-3)
  - Launched May 4, 2019
  - ISS (JEM-EF Port 3), ± 52° inclined orbit
  - Measures both column average CO_2 (XCO_2) and solar-induced chlorophyll fluorescence (SIF)



OCO-2 Measures the Relentless Rise of CO_2 in the Atmosphere



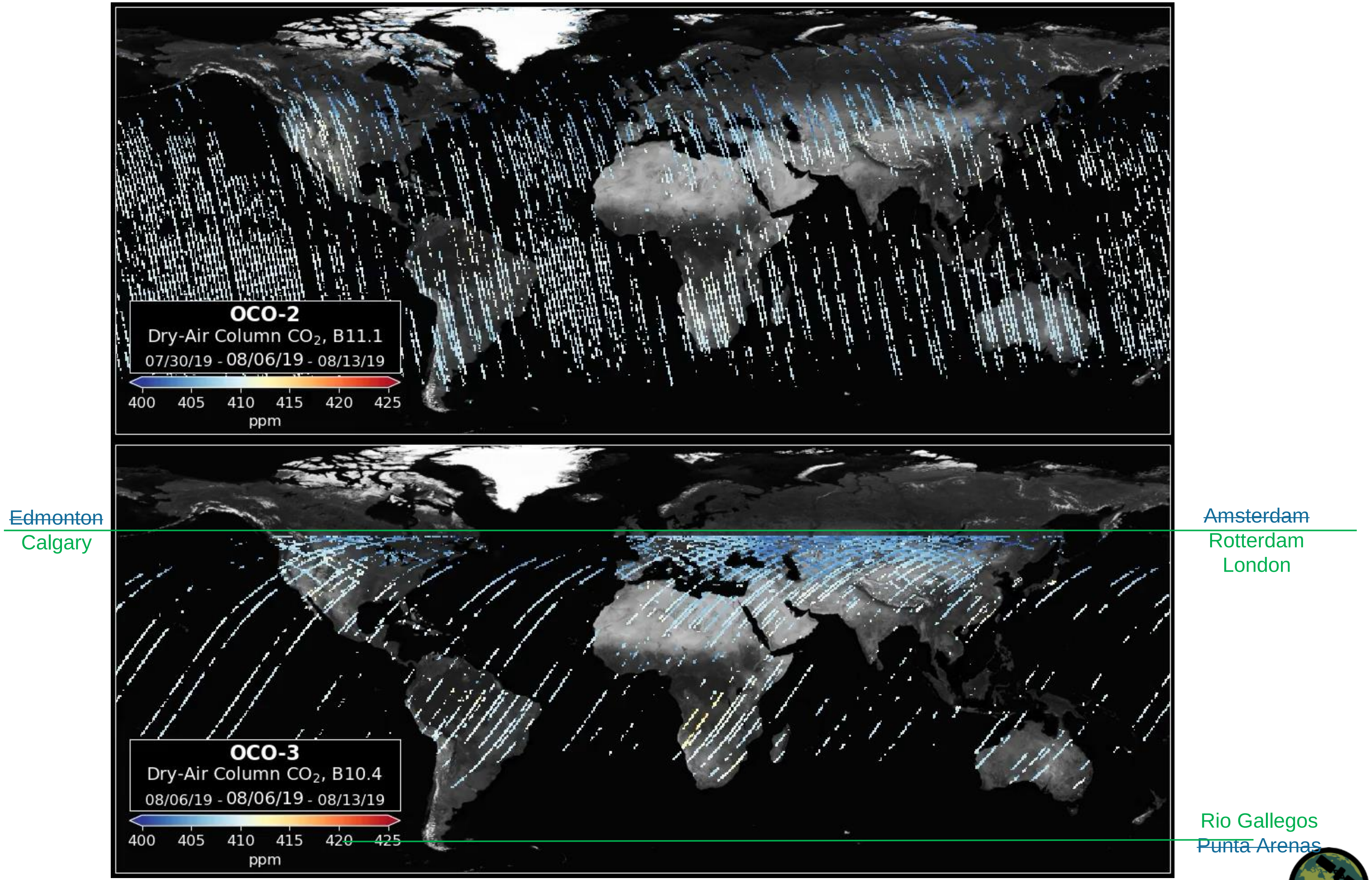
OCO-2 and OCO-3 Complementary Coverage and Sampling

OCO-2

- "Pole-to-pole" coverage, depending on season;
- Fixed 1330h equator crossing time (and local overpass time)
- 16-day repeat cycle

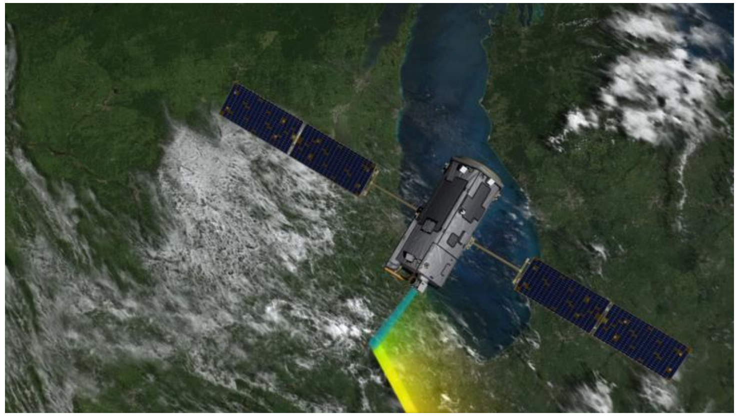
OCO-3

- Coverage limited to ±52° latitude, changing with season;
- Observations span all times of day



What are the Different Observing Modes for OCO-2?

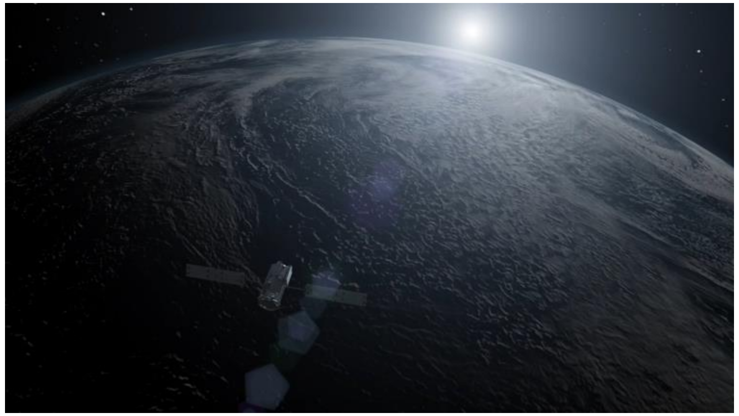
Nadir Mode



In Nadir Mode, the spacecraft looks straight down.

- Highest spatial resolution
- Does not provide adequate signal-to-noise ratio over dark ocean surfaces.

Glint Mode



In Glint Mode, the spacecraft points the instrument toward the bright "glint" spot, where solar radiation is reflected from the surface.

- At high latitudes, up to 100x signal at high altitudes Nadir measurements.
- Significantly improves the signal-to-noise ratio over the dark ocean.

Target Mode

In Target Mode, the Observatory locks its view onto a specific surface location and retains that view while flying overhead.

- Comparisons with ground-based measurements helps identify and correct systematic and random errors in the OCO-2 XCO_2 data products.

Videos by John Howard/JPL

OCO-3 has an additional, unique observing mode.

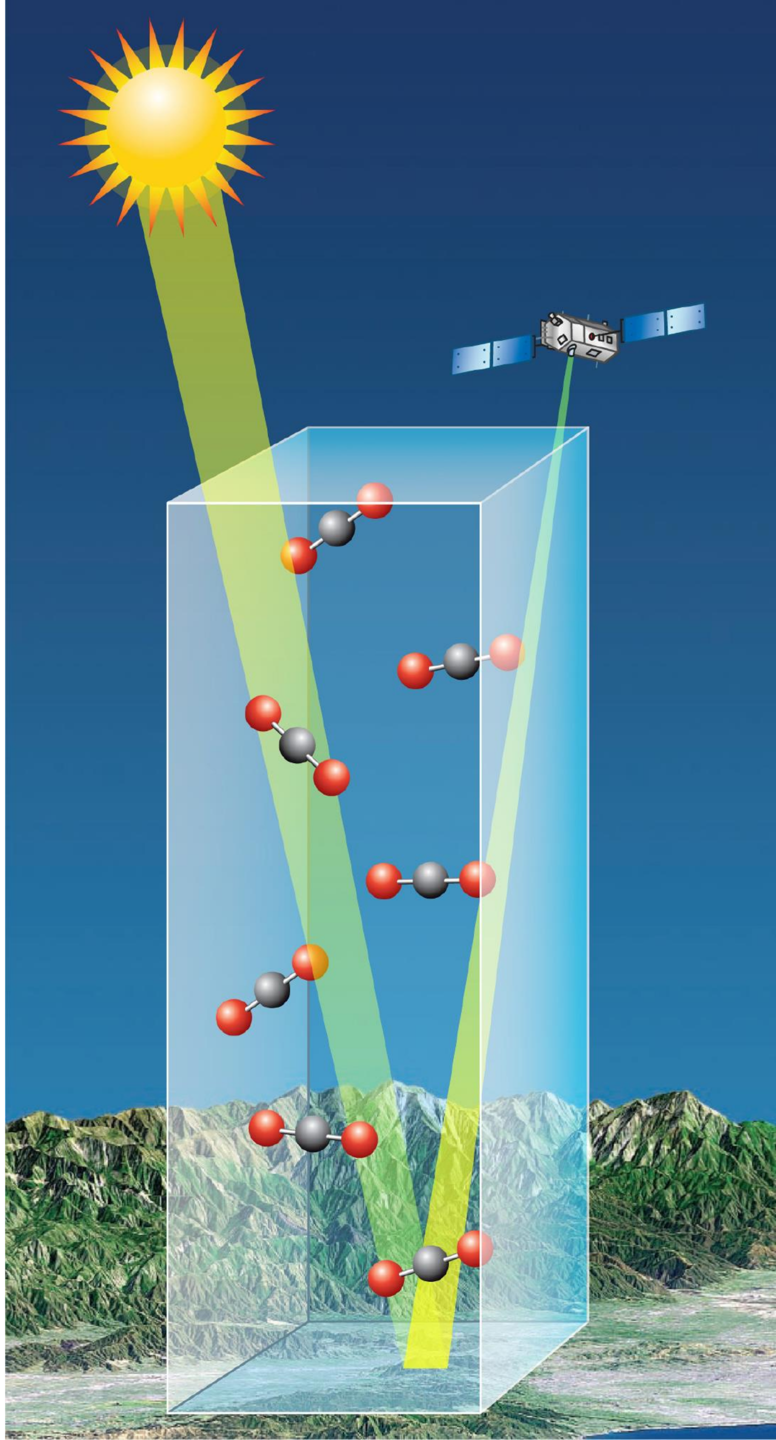
Snapshot Area Mapping (SAM) Observation Mode:

- Focuses on localized emissions from human activities (megacities, power plants, landfills) by taking “map-like” measurements
- Collects data over an ~80 km × 80 km area in 2 minutes
- Complements the near-global nadir & glint measurements from routine operations

Video: Animation showing SAM operation mode over a point source; in this example, we see XCO_2 measurements over the Bełchatów power plant (Poland) from three ISS overpasses.

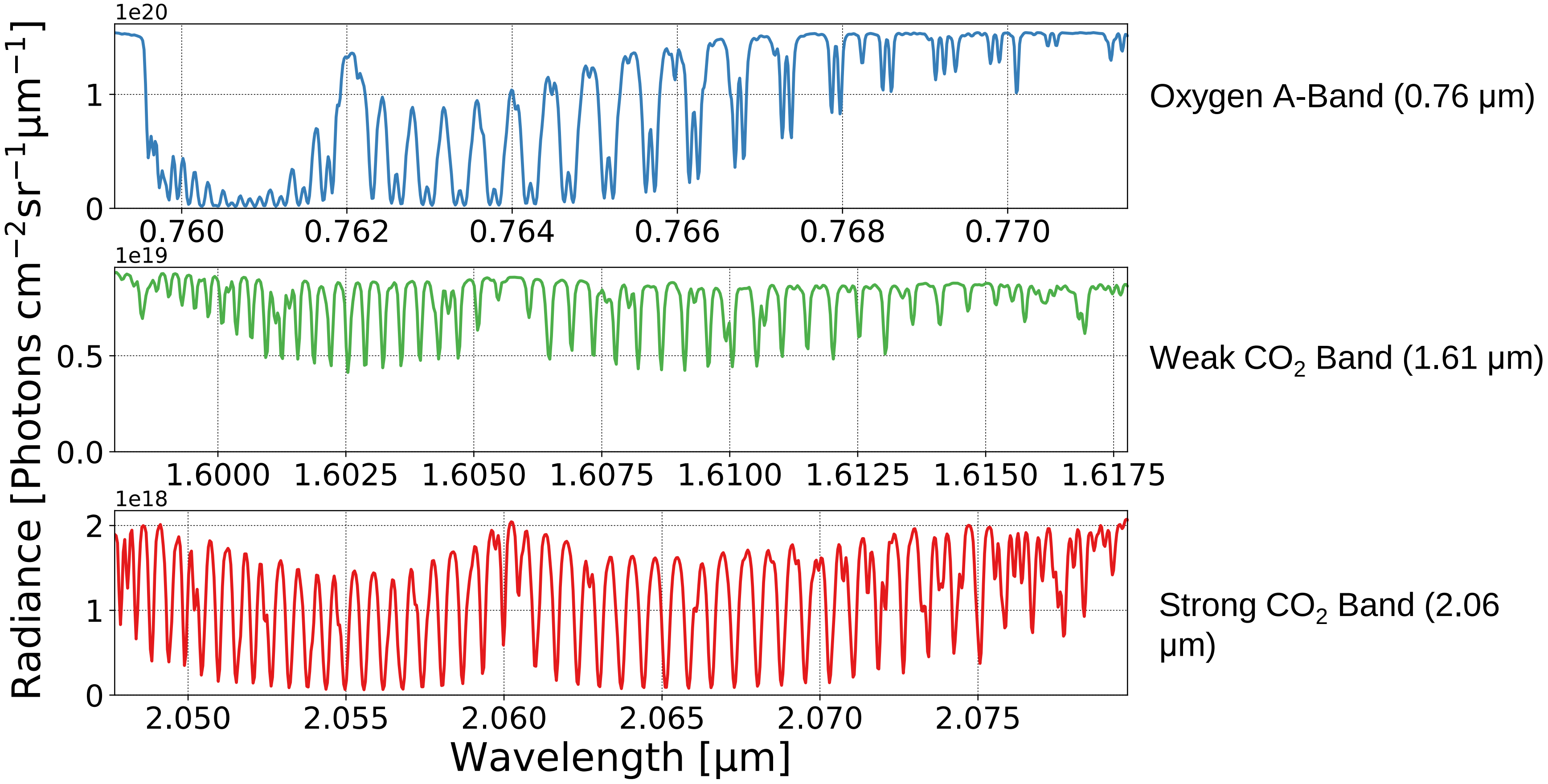
What is the XCO_2 measurement?

- **XCO_2** is the column average Volume Mixing Ratio (VMR) of carbon dioxide in the atmosphere.
- **Column Average VMR:** Average amount of gas in a vertical column above a given location.

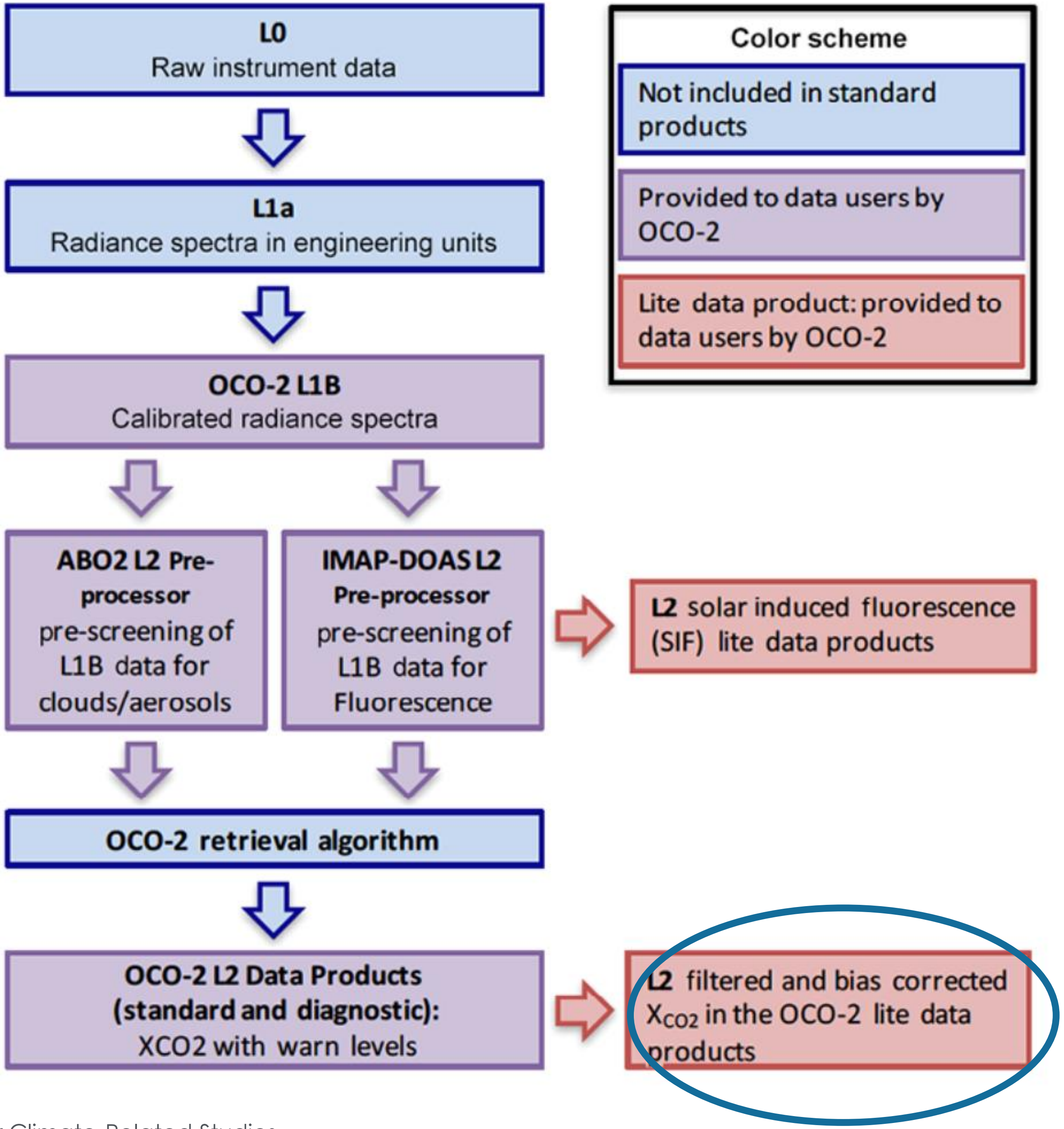


How is XCO_2 Measured?

- The OCO-2 and OCO-3 spectrometers detect the molecular "fingerprints".
- The absorption levels in the spectra tell us how many molecules were in the region where the instrument measured.



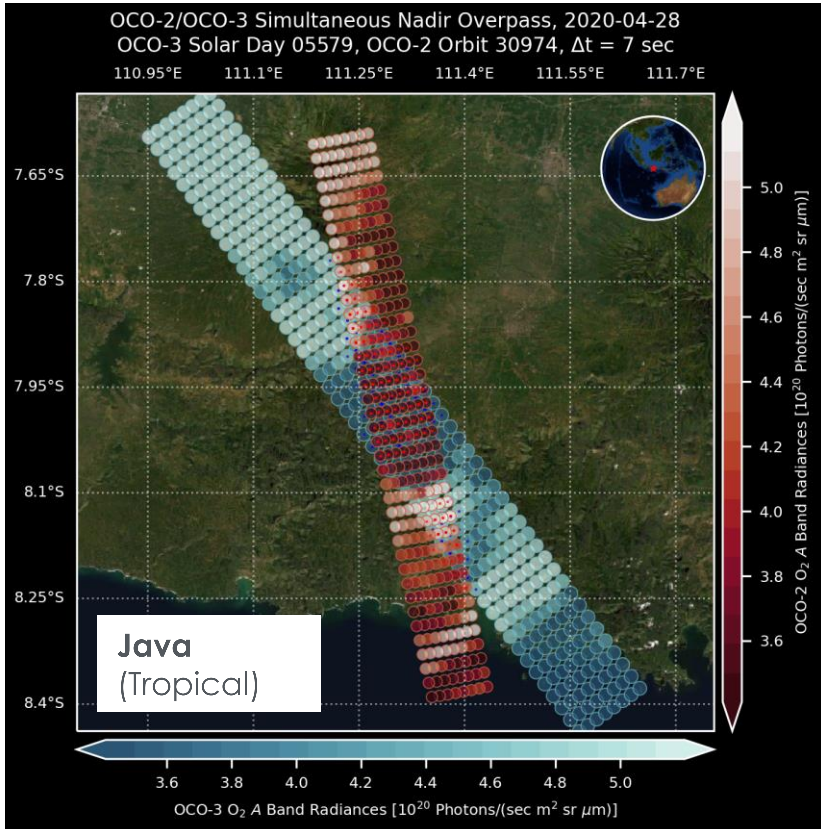
XCO_2 Data Processing

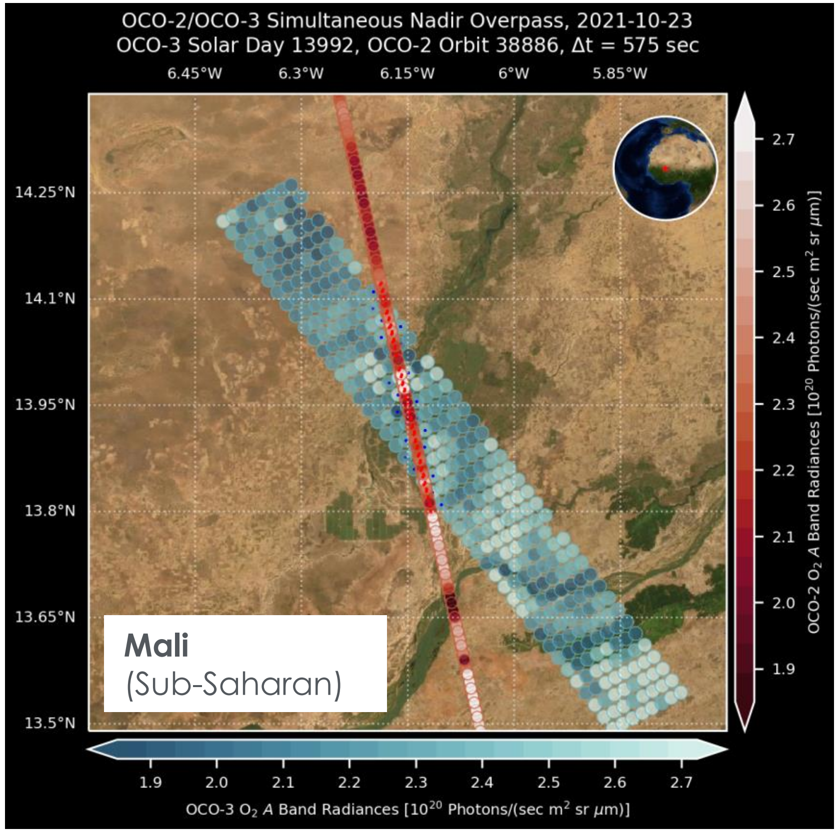


Flowchart from
Eldering et al. (2017)

Measurement Characteristics: Swath Width

Examples of A-Band Radiances for OCO-2 and OCO-3 Simultaneous Nadir Overpasses (within 7 seconds)





Figures: Thomas Kurosu

- **OCO-2 Swath Width:**
  - Changes throughout the orbit
  - OCO-3 swath width is more uniform due to pointing capability

Measurement Characteristics: Daily Sampling

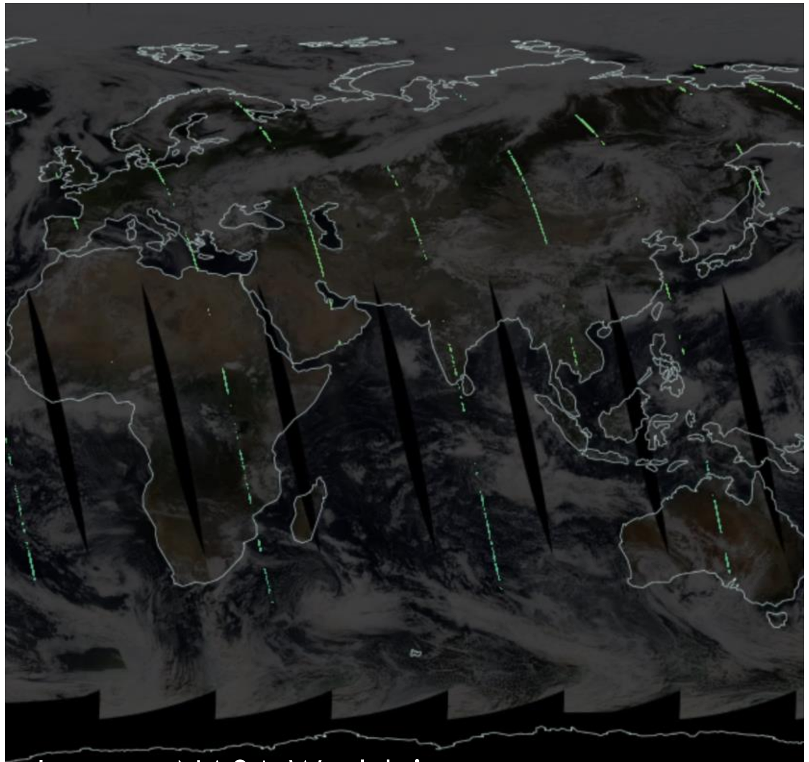


Image: NASA Worldview

- **OCO-2** orbits the Earth 14.5 times a day, gathering data over sunlit, cloud-free regions. This image shows the locations of successful XCO_2 measurements over Africa, Eurasia, and Australia for a single day (31st May 2021).

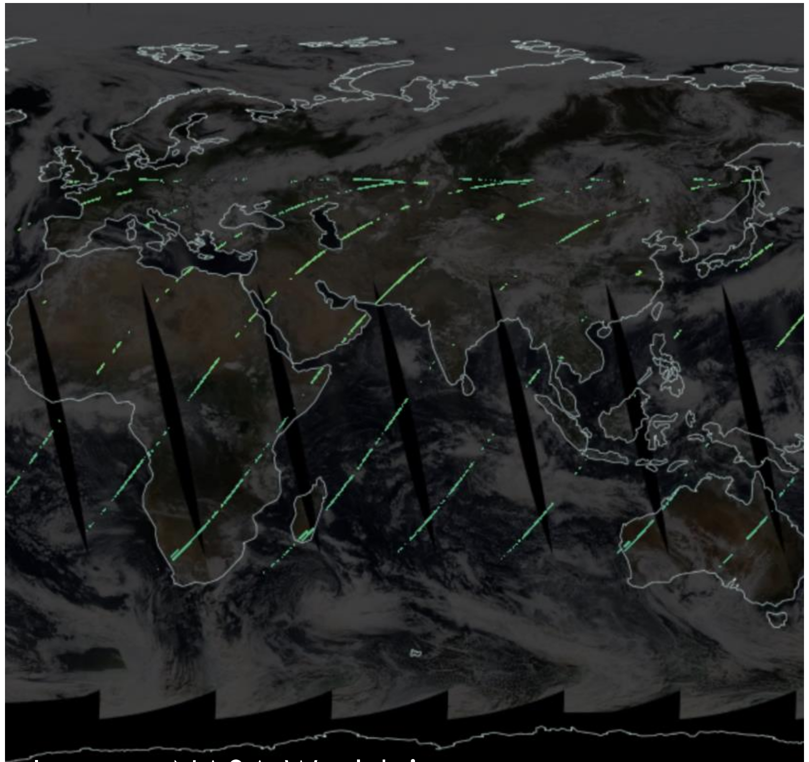
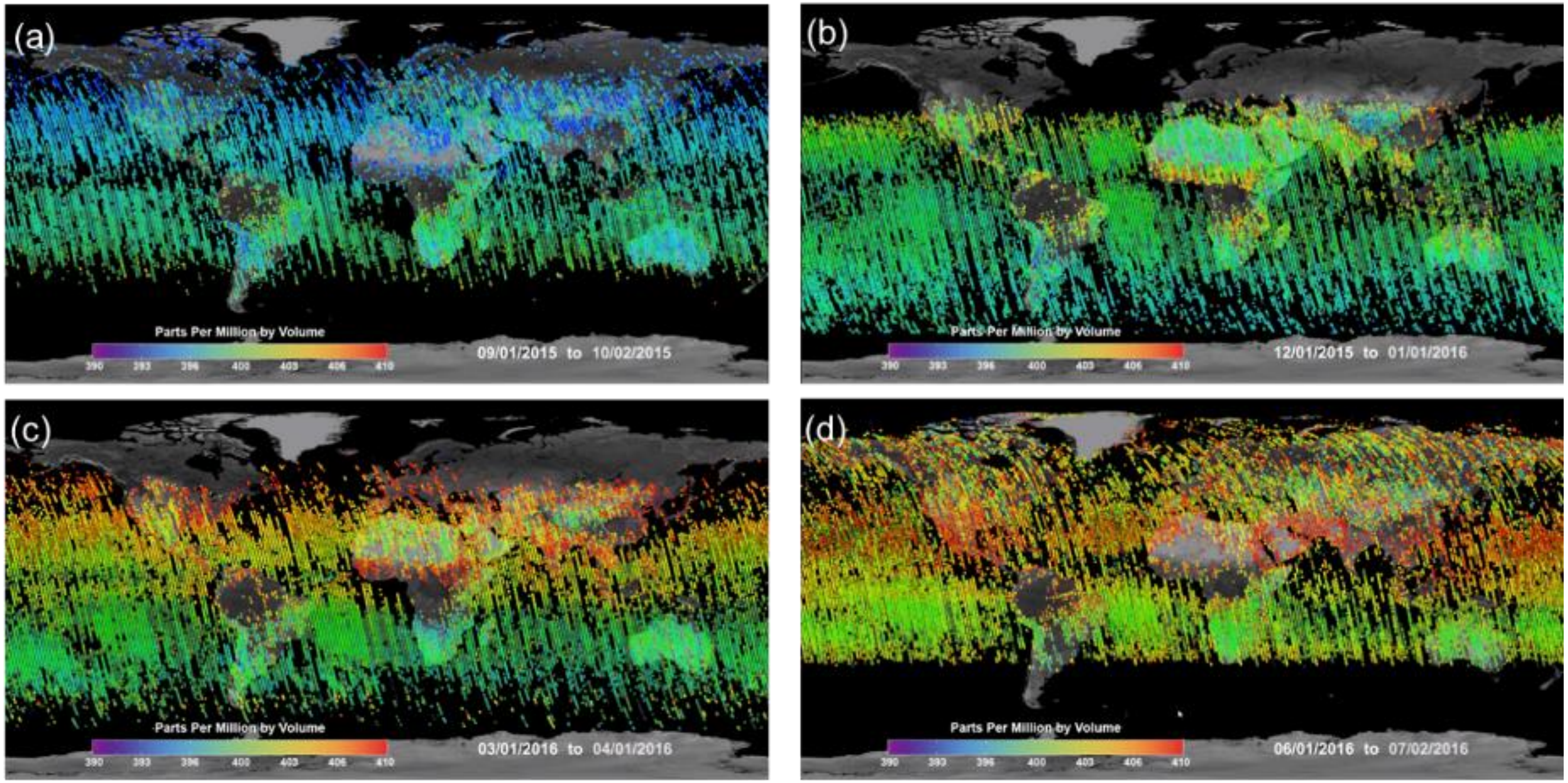


Image: NASA Worldview

- **OCO-3** also samples cloud-free, sunlit regions, with orbital sampling that follows the track of the ISS. This image shows the locations of successful XCO_2 measurements for the same area and day.

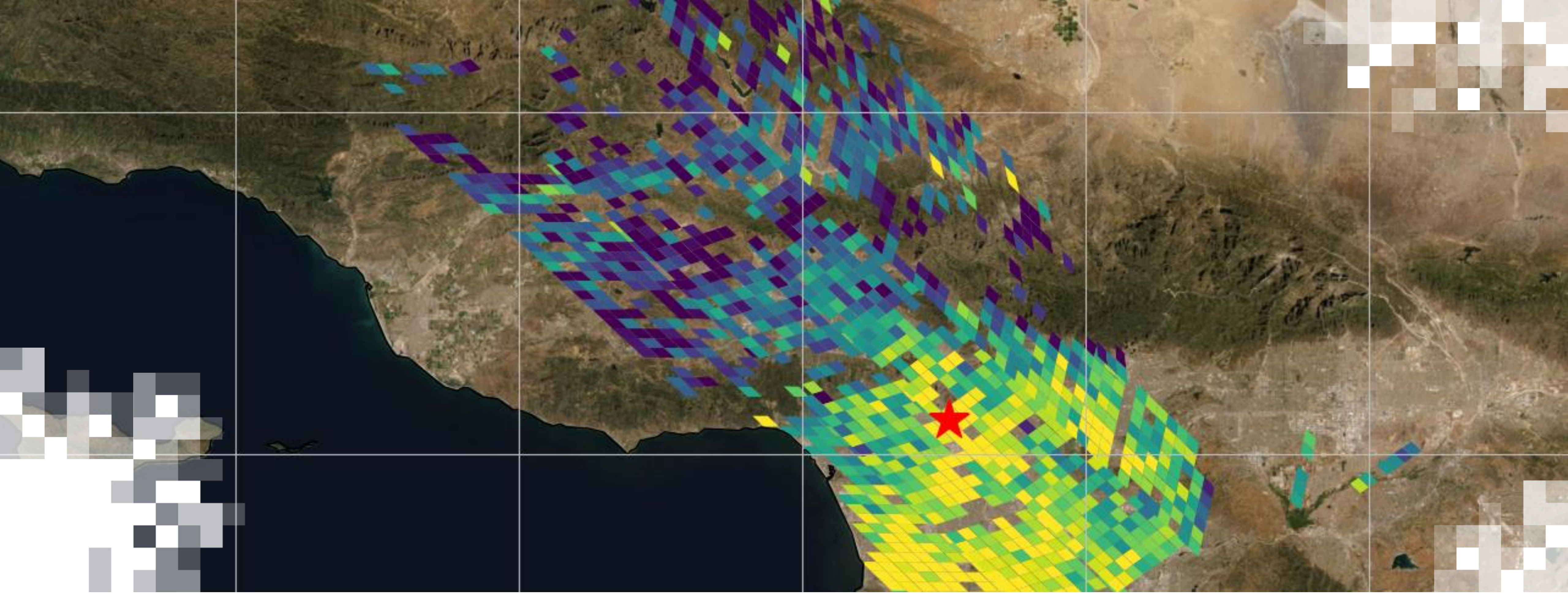
What are the limitations of the measurement?



Maps of XCO_2 along OCO-2 orbit tracks for (a) September 2015, (b) December 2015, (c) March 2016, and (d) June 2016, illustrating the XCO_2 variations and latitude coverage as a function of season. The footprint size is exaggerated for visibility. The color bars all extend from 390 to 410 ppm. Persistent clouds and the availability of sunlight limits the latitude coverage in the winter hemisphere.

Factors Affecting the Quality of the Measurement:

- Clouds
- Optically-Thick Aerosols
- Uneven Terrain (Mountains)
- High Solar Zenith Angles

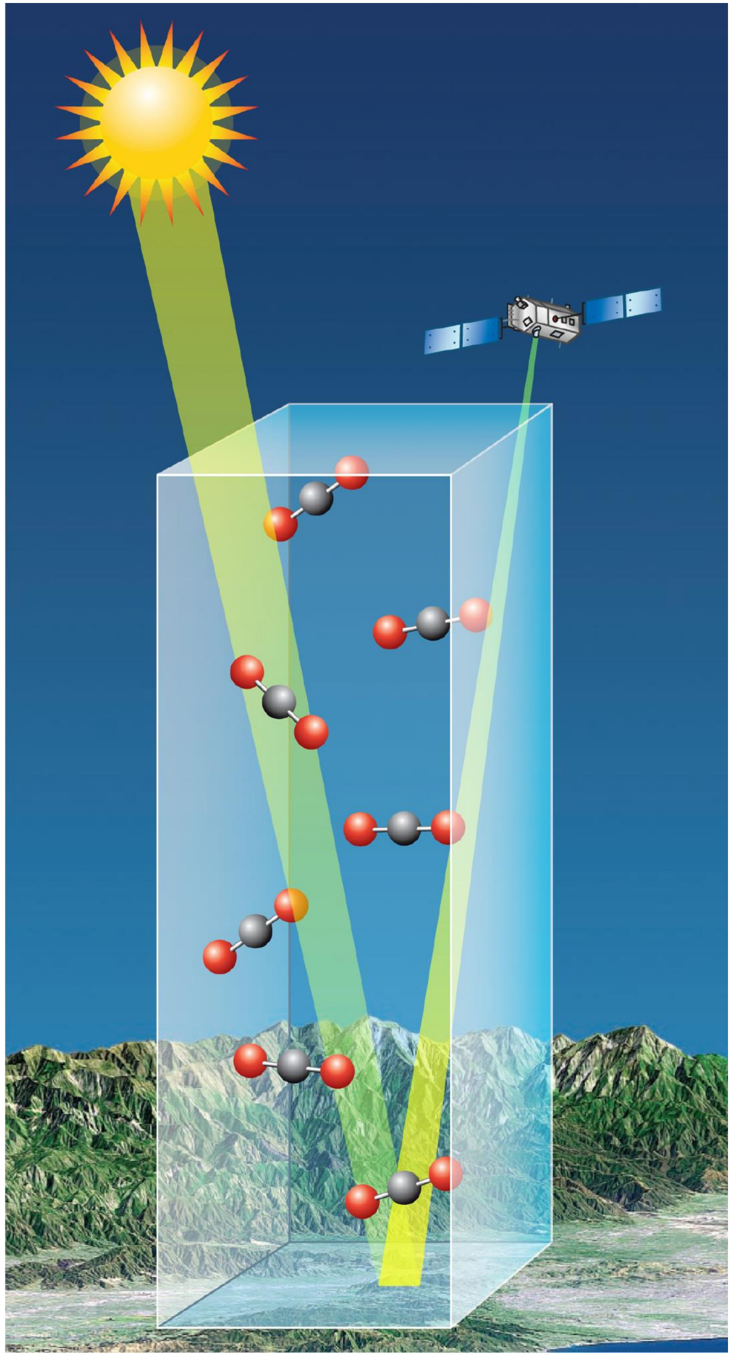


Quality Flags

What is "Truth"?

- The XCO_2 in the OCO-2/OCO-3 data product is the column average volume mixing ratio. This is a measure of the amount of carbon dioxide in the atmospheric column as a whole.

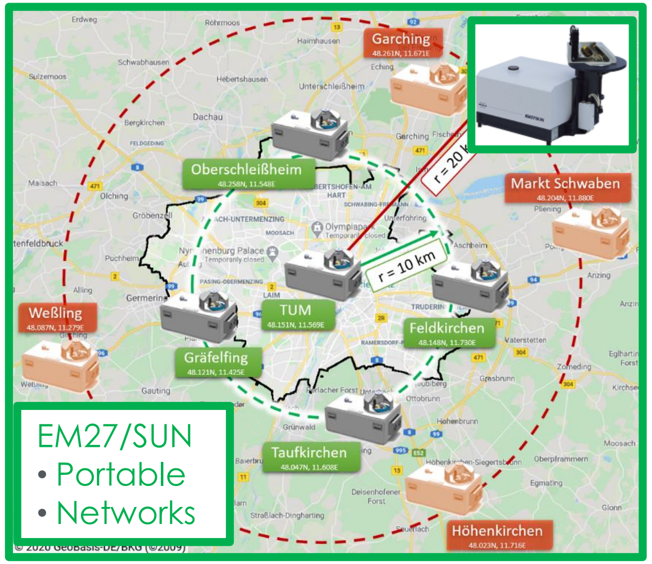
- This is **not directly comparable** to a measurement at a single point, such as an in situ measurement at a surface site, or at a single point in the atmosphere.

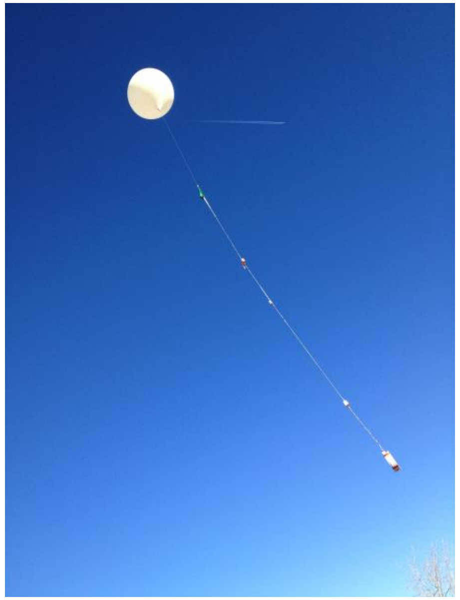


How are the OCO-2/3 XCO_2 measurements validated?

Image Credit: TCCON

Image Credit: TCCON





https://gml.noaa.gov/ccgg/aircore/

https://gml.noaa.gov/ccgg/aircraft/

The Total Carbon Column Observing Network (TCCON)

A Network of Ground-Based Fourier Transform Spectrometers…

- Recording direct solar spectra in the near-infrared spectral region.
- Retrieving accurate and precise column-averaged abundance of CO_2.
- An essential validation resource for OCO-2, OCO-3, the Greenhouse Gases Observing Satellites GOSAT and GOSAT-2, the Sentinel-5P instrument TROPOMI, TanSat, and other missions.

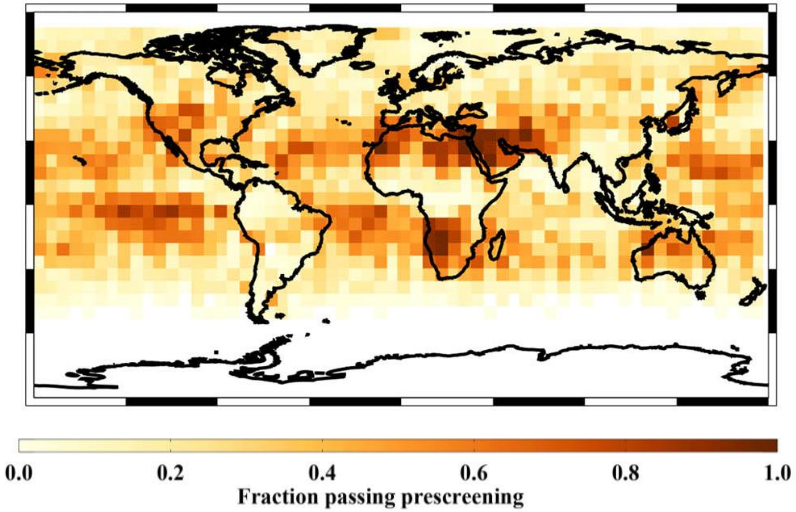
For the latest TCCON information, please visit the TCCON Wiki at https://tccon-wiki.caltech.edu.

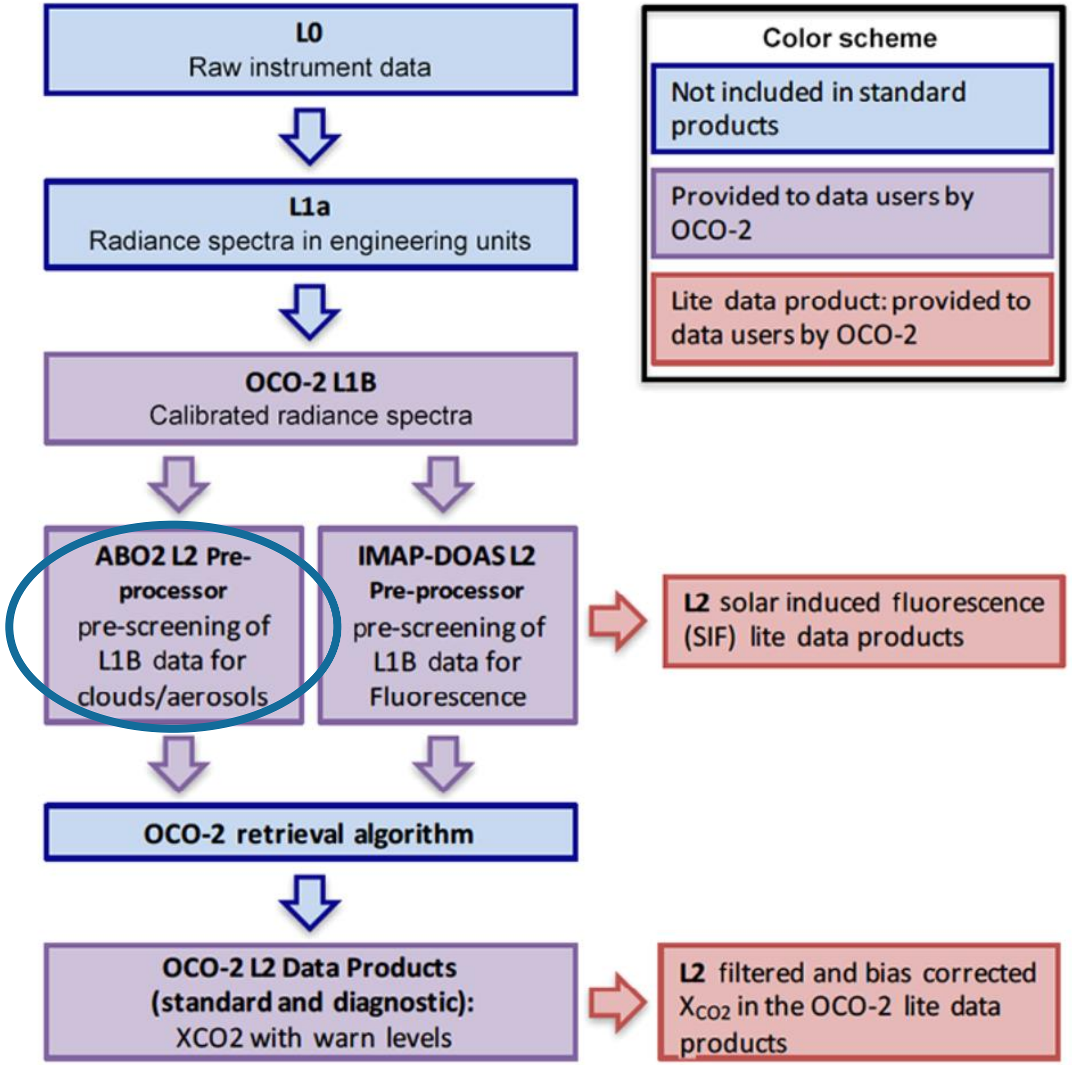
TCCON
total carbon column observing network

Pre-Screening of the Data

- L1B radiance spectra are pre-screened to check for obvious cloud or aerosol contamination.
- Measurements that pass the pre-screening are processed through to Level 2.
- The fraction of data that pass the prescreening step varies according to location and season.

This figure shows the fraction of OCO-2 glint mode soundings in 6° by 6° lat/lon boxes that pass prescreening for the month of June 2016. Figure from O'Dell et al. (2018).





Further Filtering with the Quality Flag

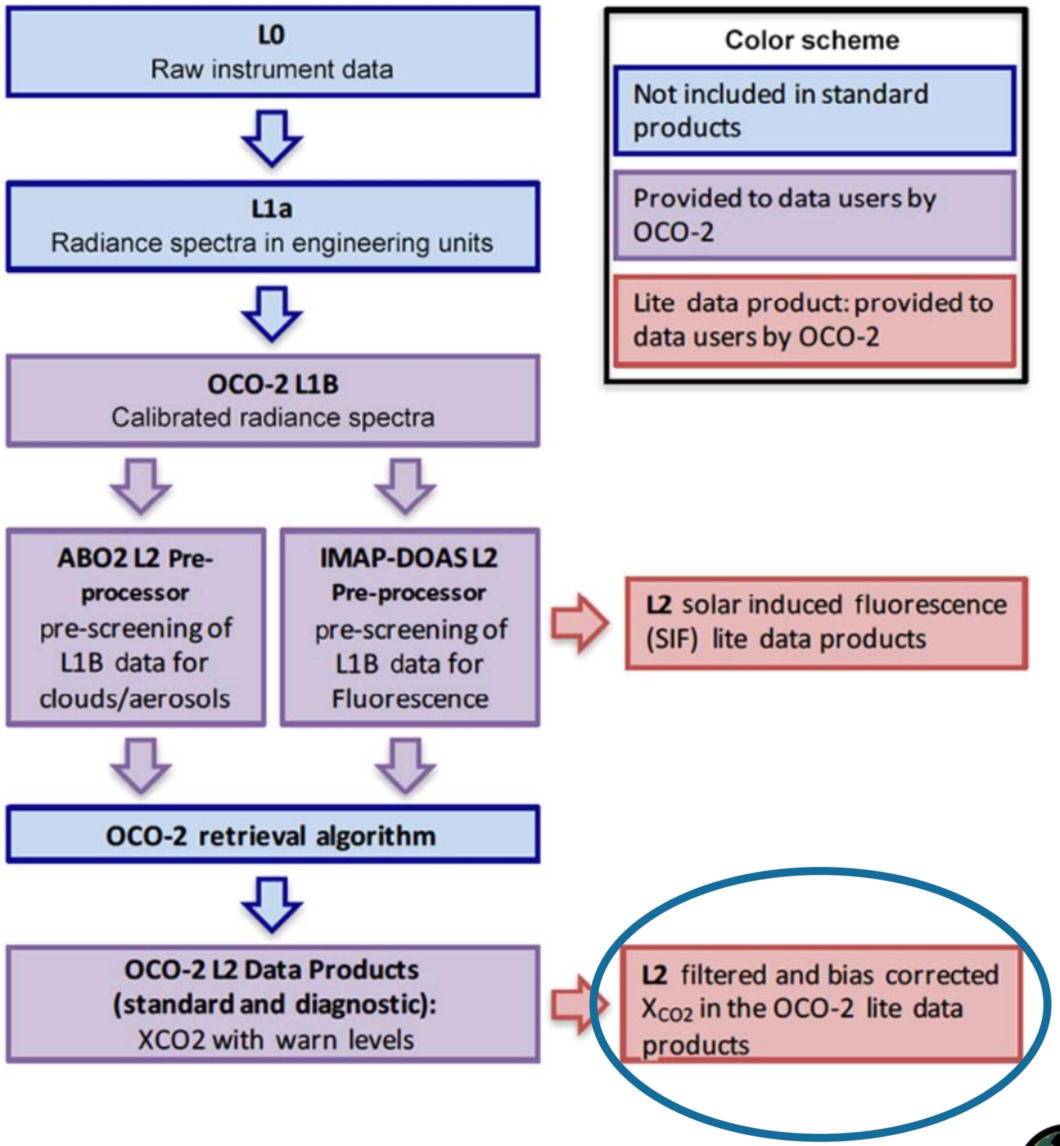
- Pre-screening removes measurements that are strongly contaminated by clouds and aerosols.
  - Overall, around 70% of the measurements are removed from consideration.
  - These measurements are not reported in the L2 Lite XCO_2 data products.

- Additional filtering is still needed to flag measurements with minor cloud/aerosol contamination.
  - Around 15% of the pre-screened measurements are flagged in a further filtering step. These measurements are reported, but flagged as suspect in the L2 Lite data products.

> "When using the data contained in the Lite files, filtering can be done with **xco2_quality_flag** ("0" is good). This filter has been derived by comparing retrieved *XCO_2* for a subset of the data to the various truth proxies and identifying thresholds for different variables that correlate with poor data quality. It applies quality filters based on a number of retrieved or auxiliary variables that correlate with excessive *XCO_2* scatter or bias."
>
> *- OCO-2 Level 2 Data User Guide*

Bias Correction

- Spaceborne CO_2 measurements are extremely challenging!
- Even after filtering, the OCO-2 and OCO-3 XCO_2 values show dependencies on surface and atmospheric parameters.
- A parametric bias correction is applied to the OCO-2 and OCO-3 XCO_2 measurements.
- The OCO-2 and OCO-3 L2 Lite XCO_2 product files contain bias-corrected XCO_2 values.
- For details on the approach for parametric bias correction, see O'Dell et al. (2018).



Are there remaining biases in the OCO-2 & OCO-3 XCO_2 data?

The Good News:

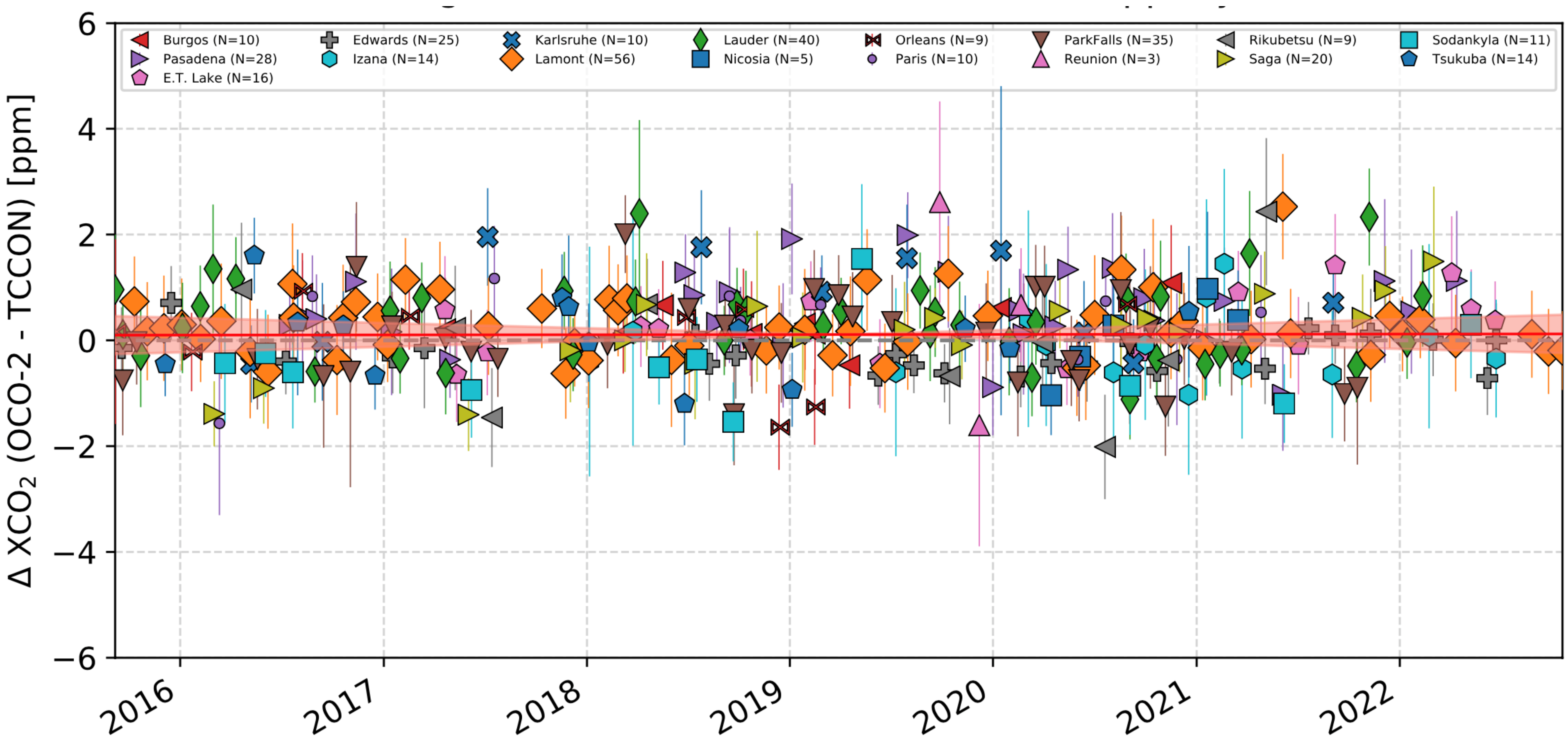
- OCO-2 and OCO-3 L2 Lite products that are available at the GES DISC have already been pre-screened, quality-flagged (filtered), and bias-corrected.
- The process for filtering and bias correction are described in the OCO-2/OCO-3 Level 2 Data User Guide.

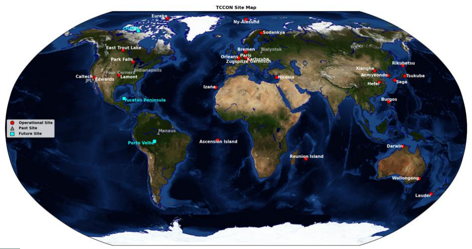
Caveat:

- There are very few in situ or remote sensing measurements that can be used for validation in the regions where the satellite XCO_2 measurements show the largest differences from current global models.

XCO_2 Measurements: Consistency Across Time

- **OCO-2:** No evidence of any significant time dependence in the v11.1 XCO_2 relative to TCCON.
- **OCO-3:** The latest public data version (v10.4) includes correction to account for time-dependent L1B calibration issues.

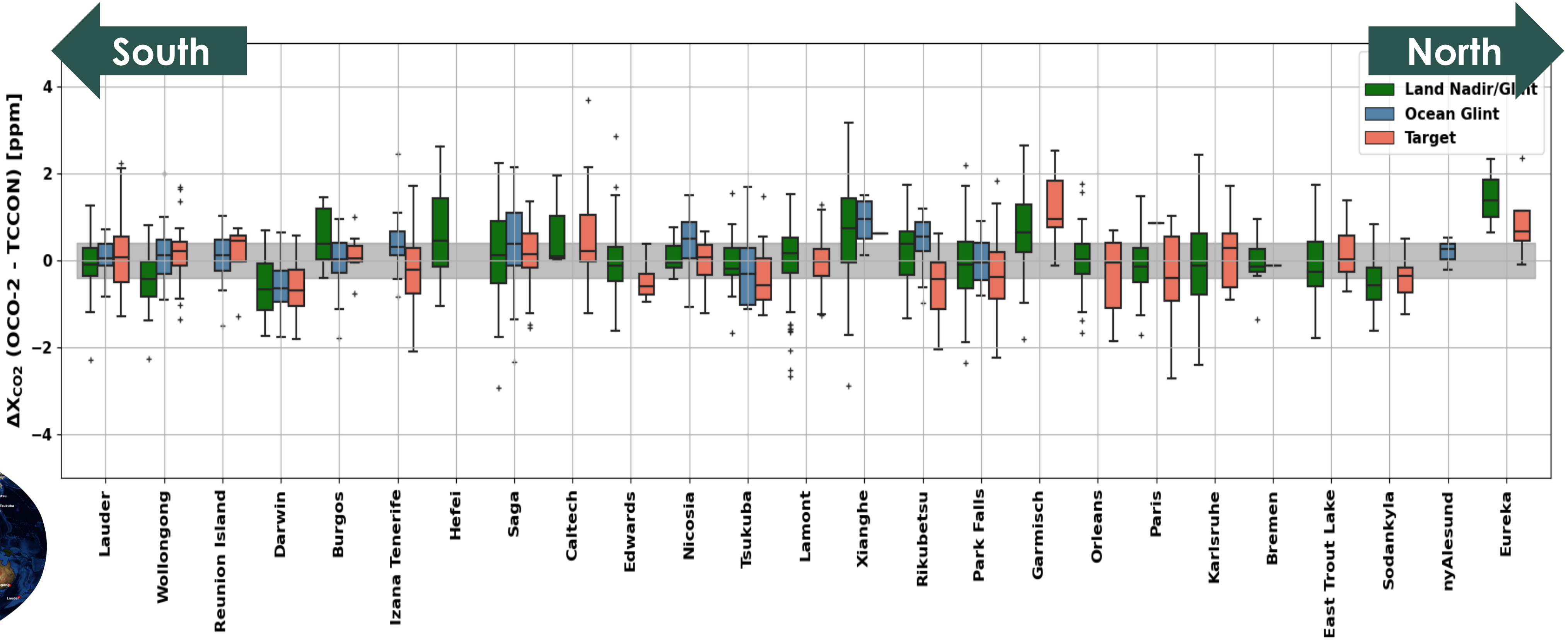




Comparison between XCO_2 from OCO-2 target observations and from the Total Carbon Column Observing Network (TCCON). Comparisons of OCO-2 v11 XCO_2 estimates with TCCON stations around the globe as a function of time show that the quality of the OCO-2 XCO_2 product has remained uniform over the mission life. Figure: M. Kiel/JPL

XCO_2 Measurements: Consistency Across Locations

- Comparisons of OCO-2 XCO_2 with TCCON stations around the globe show good overall consistency.



Comparison between XCO_2 from OCO-2 land, ocean, and target observations and from the Total Carbon Column Observing Network (TCCON). Figure: S. Das/JPL

XCO_2 Measurements: Estimated Accuracy

- OCO-2 v11.1 – TCCON rms differences in XCO_2 : < **0.8 ppmv**
- OCO-3 v10.4 – TCCON rms differences in XCO_2 : < **1.0 ppmv**

Can you combine OCO-2 and OCO-3 data?

Yes! Direct comparisons between OCO-2 and OCO-3 XCO2 show agreement within 0.5 ppmv, which is within the agreement of either sensor with TCCON.

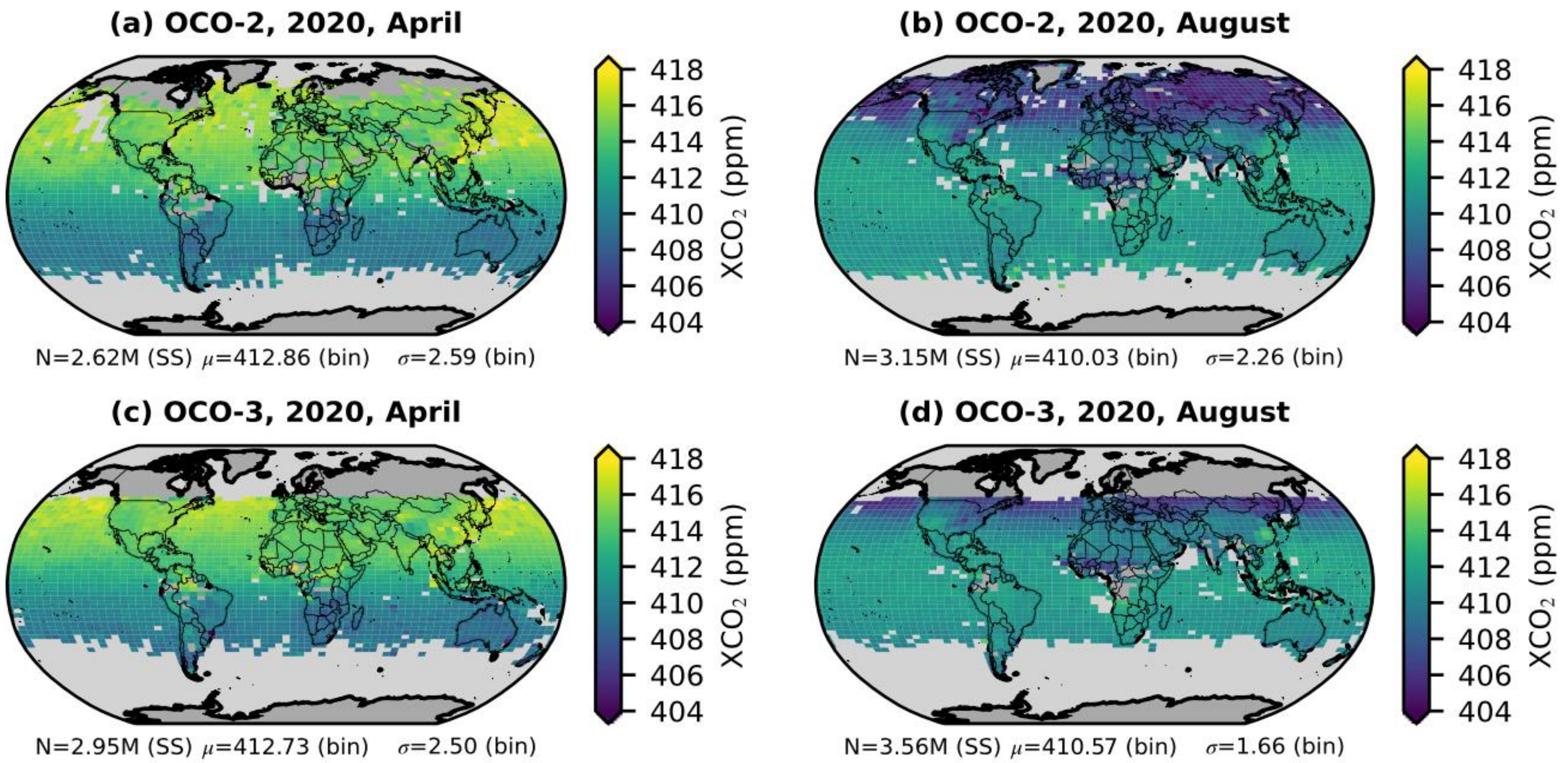
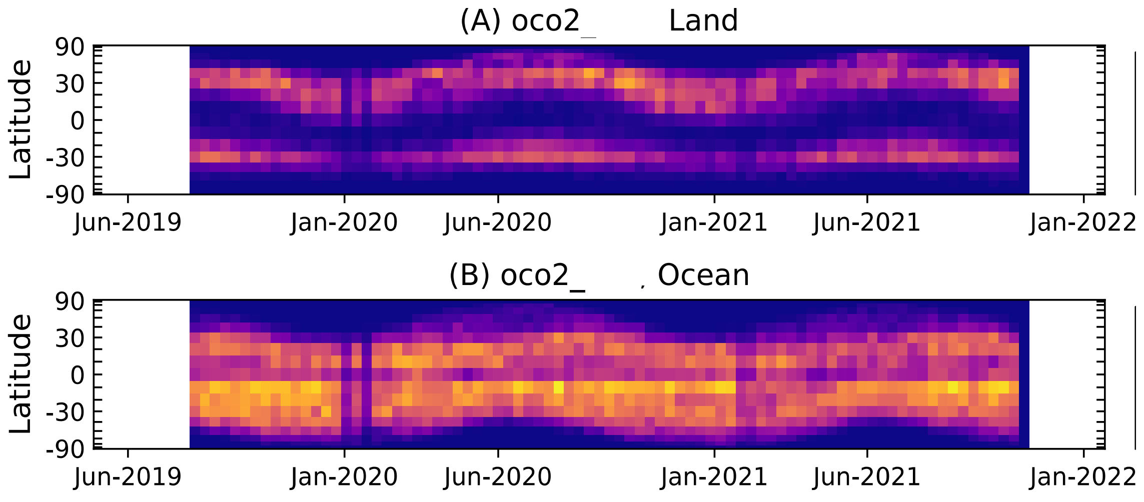
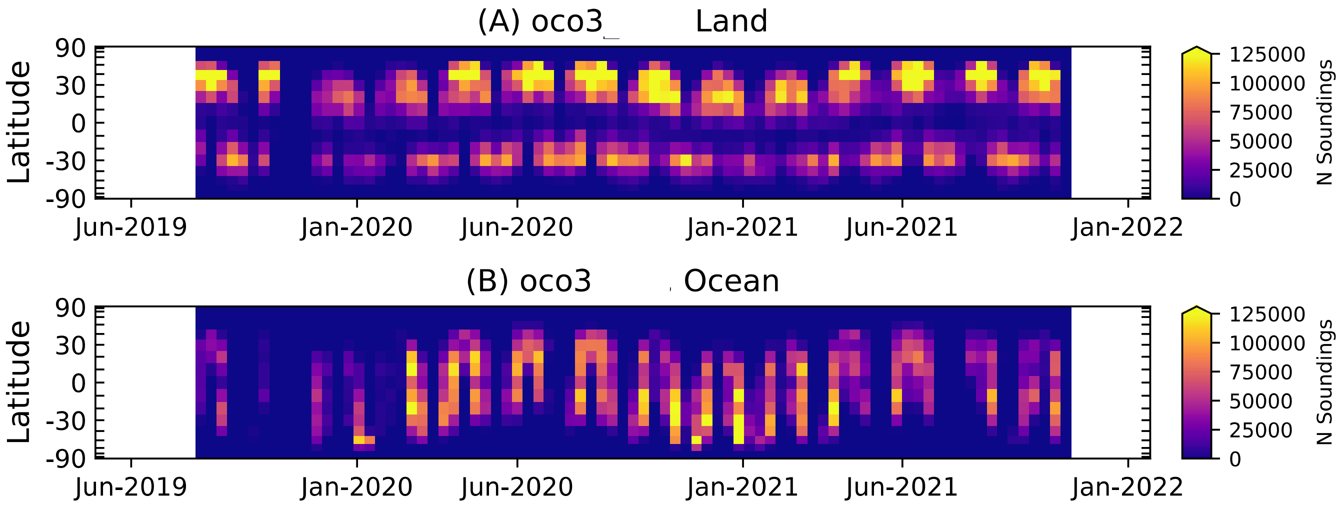


Figure: Monthly XCO_2 maps for OCO-2 (top) and OCO-3 (bottom) for April 2020 (left) and August 2020 (right) at 2.5◦ latitude by 5.0◦ longitude resolution. **Taylor et al., 2023**

Are OCO-2 and OCO-3 data complementary?

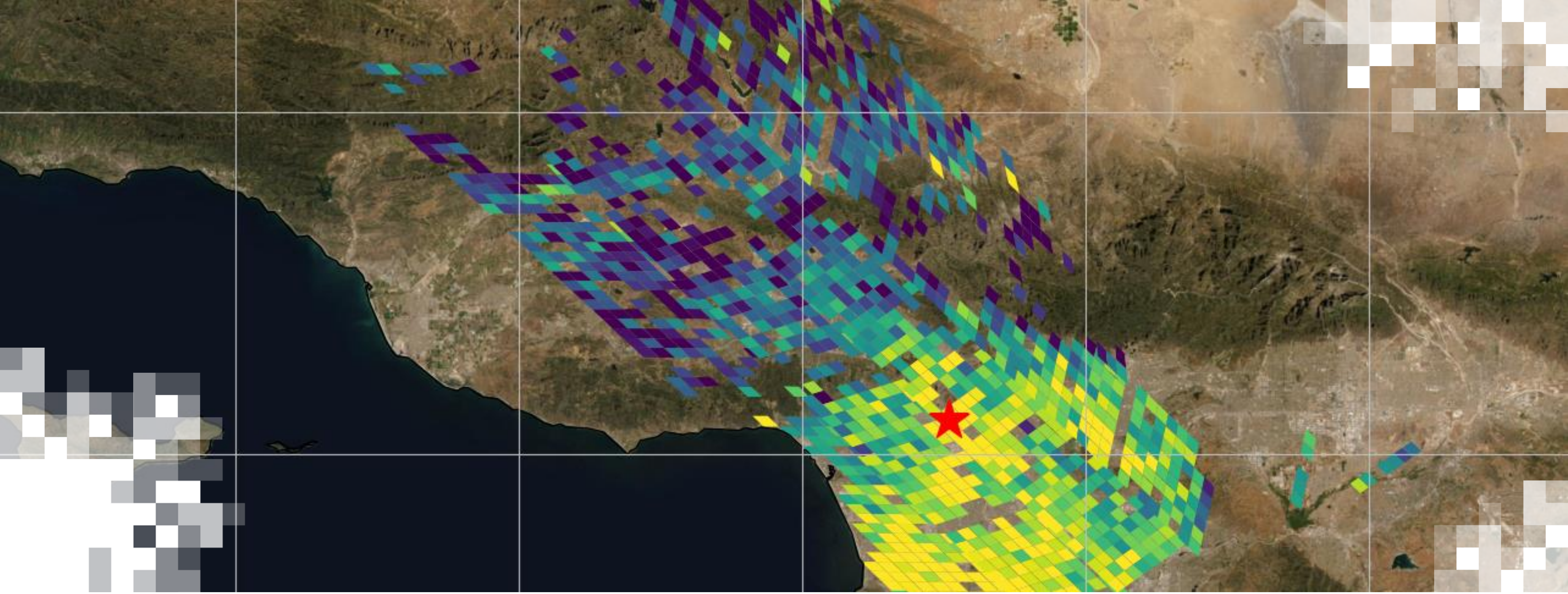
Yes! The two datasets have different but complementary coverage. The figures here show another way of looking at the density of the OCO-2 and OCO-3 coverage side by side.





Why are there different versions of OCO-2 and OCO-3 data?

- The calibration of the instruments and the data processing algorithms have been improved and refined over the lifetime of the missions.
- The OCO-2 and OCO-3 datasets have been reprocessed to incorporate improvements.
  - Reprocessing campaigns performed for full data record.
- We recommend to use the newest version of L2 Lite XCO_2 files available
  - OCO-2 (v11.1)
  - OCO-3 (v10.4)



Interpretation

Vertical Structure of CO_2 in the Atmosphere

- Profiles of CO_2 volume mixing ratio in the atmosphere show vertical structure associated with…
  - Sources (e.g., urban emissions)
  - Sinks (e.g., uptake by vegetation in the growing season)
  - Atmospheric Mixing and Transport
- This kind of vertical structure can be measured with **in situ** instrumentation flown on…
  - Balloons
  - Aircraft
- The OCO-2 and OCO-3 measurements are sensitive to CO_2 throughout the atmospheric column, but not to fine-scale details of vertical structure.

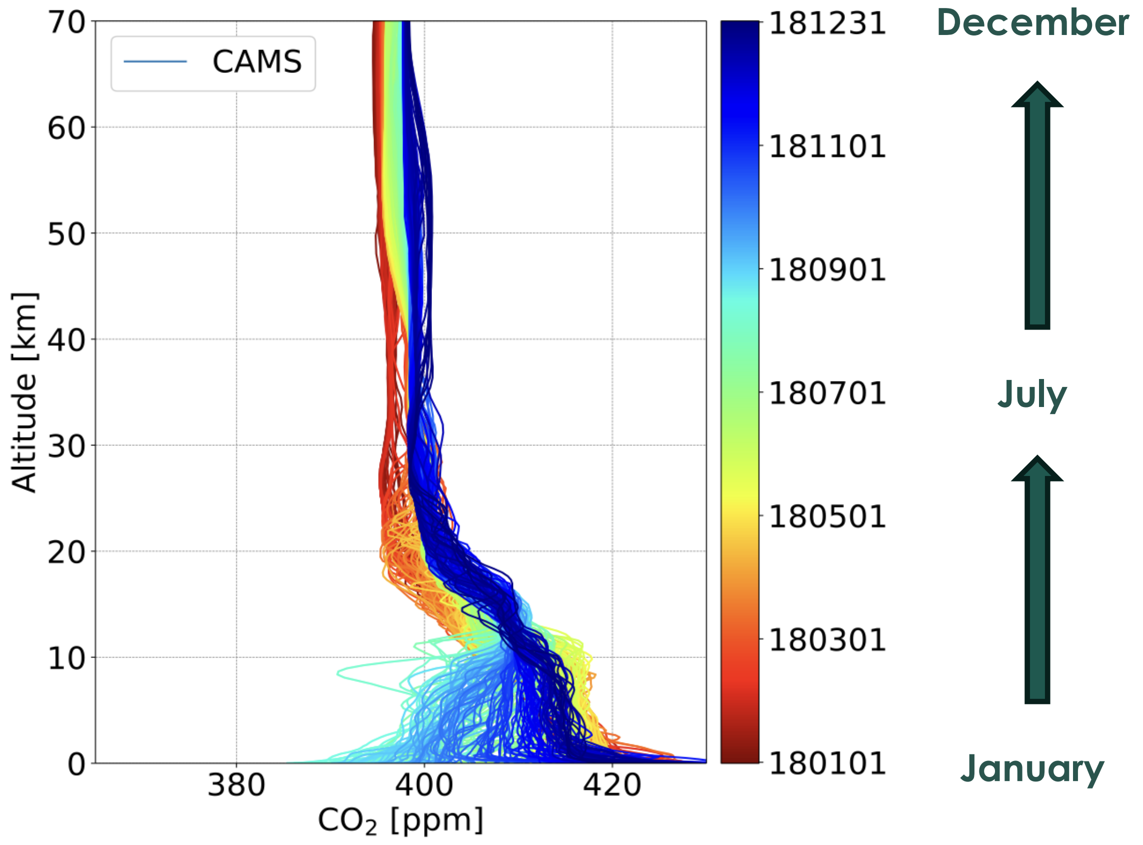


Figure: Vertical profiles of atmospheric CO_2 over Sodankyla, Finland, throughout the year of 2018, from the Copernicus Atmospheric Monitoring Service (CAMS) analysis model, showing the impact of uptake of CO_2 by plants during the summer (Tu et al., 2020).

Vertical Sensitivity of Spaceborne CO_2 Measurements

Near-Infrared (NIR)

- Sensitive to CO_2 throughout the atmospheric **column**.
- Can be used in the estimation of surface sources and sinks.

Thermal Infrared

- Sensitive to CO_2 in the **mid- and upper-troposphere**.

"**Averaging Kernel**"

- Shows how and where the remotely-sensed measurement is sensitive to the true atmospheric state.
- Column averaging kernels are provided as part of the OCO-2 and OCO-3 data products.

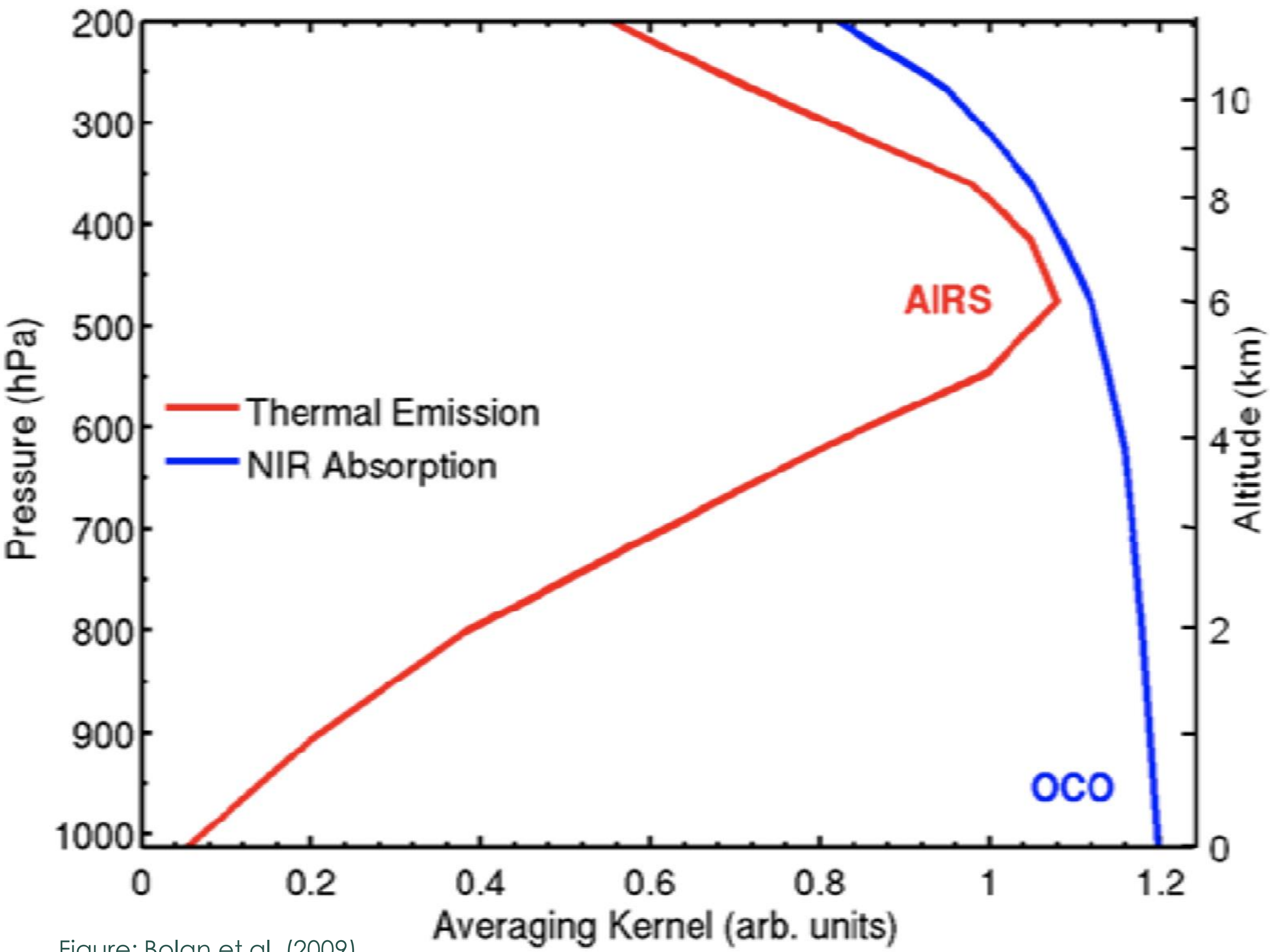
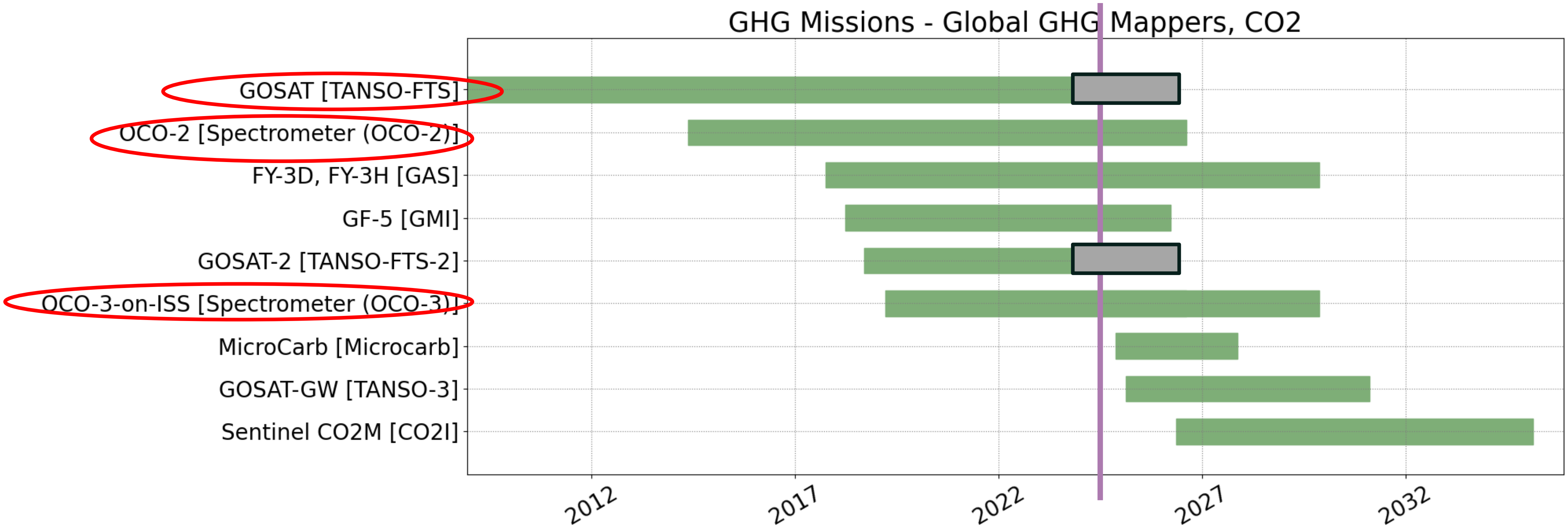


Figure: Bolan et al. (2009)

Satellite Observations in Near-Infrared CO_2 Bands

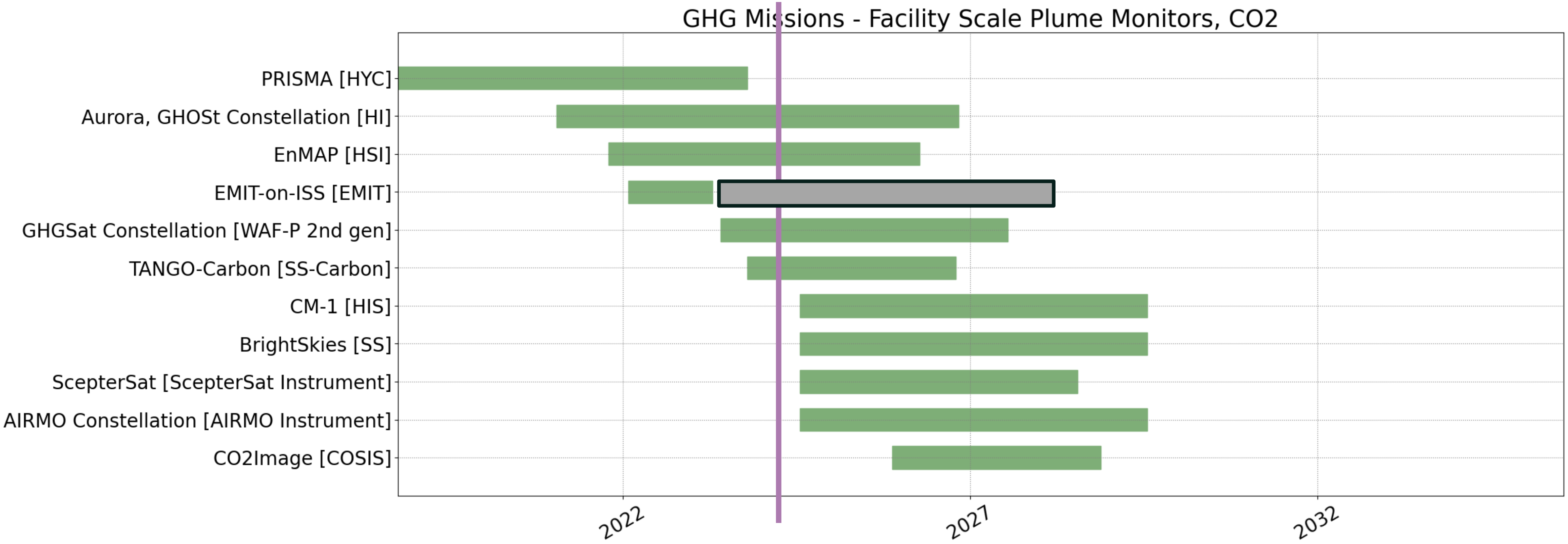
- **Global Mappers:**
  - Typically undertaken by space agencies.
  - These missions are the most important sources of information for tracking emissions and removals of GHGs from **natural as well as anthropogenic sources and sinks** on spatial scales spanning large urban areas to nations.
  - Typically do not have the spatial resolution to attribute emissions from individual facilities.
  - Sensors with the **precision and accuracy needed to track fluxes from diffuse sources of CO_2 from the biosphere and oceans**.
- **Facility-Scale Plume Monitors:**
  - A wide range of public, commercial, and NGO groups are operating or planning missions (often smallsats) in this category.
  - Many of the relevant sensors are multi-purpose hyperspectral imagers, which can track **intense plumes of CO_2**.
  - Sensors assigned to this category must have a **spatial resolution of 1 square km or finer**.
  - Do not require the precision, accuracy, or coverage of the Global GHG Mappers.
- Descriptions from Committee on Earth Observation Satellites (CEOS) Greenhouse Gas Satellite Missions Portal

“Global Mappers” vs. “Facility-Scale Plume Monitors”



- Red ovals show CO_2 “global mappers” for which data are publicly available via NASA.
- Datasets from GOSAT, OCO-2, and OCO-3 have been processed using the Atmospheric Carbon Dioxide from Space (ACOS) algorithm.

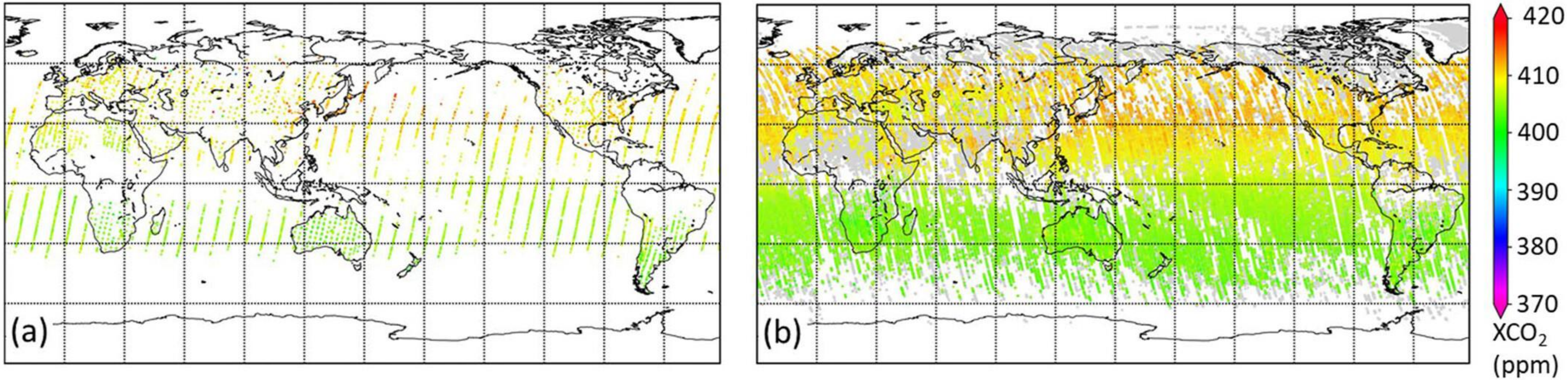
“Global Mappers” vs. “Facility-Scale Plume Monitors”



Figures: CEOS

What distinguishes the XCO_2 records from GOSAT and OCO-2?

- GOSAT has been providing high quality measurements since 2009.
- OCO-2 (2014 onwards) provides greater data density.



Monthly maps of XCO_2 estimates derived from (a) GOSAT and (b) OCO-2 measurements for April 2018. OCO-2 collects ~100 times as many samples each day as GOSAT, providing much greater data density. For both satellite products, the coverage at high latitudes varies with the availability of sunlight. Persistent optically thick clouds and airborne dust (Sahara) limit the coverage. Images from the World Data Center for Greenhouse Gases.

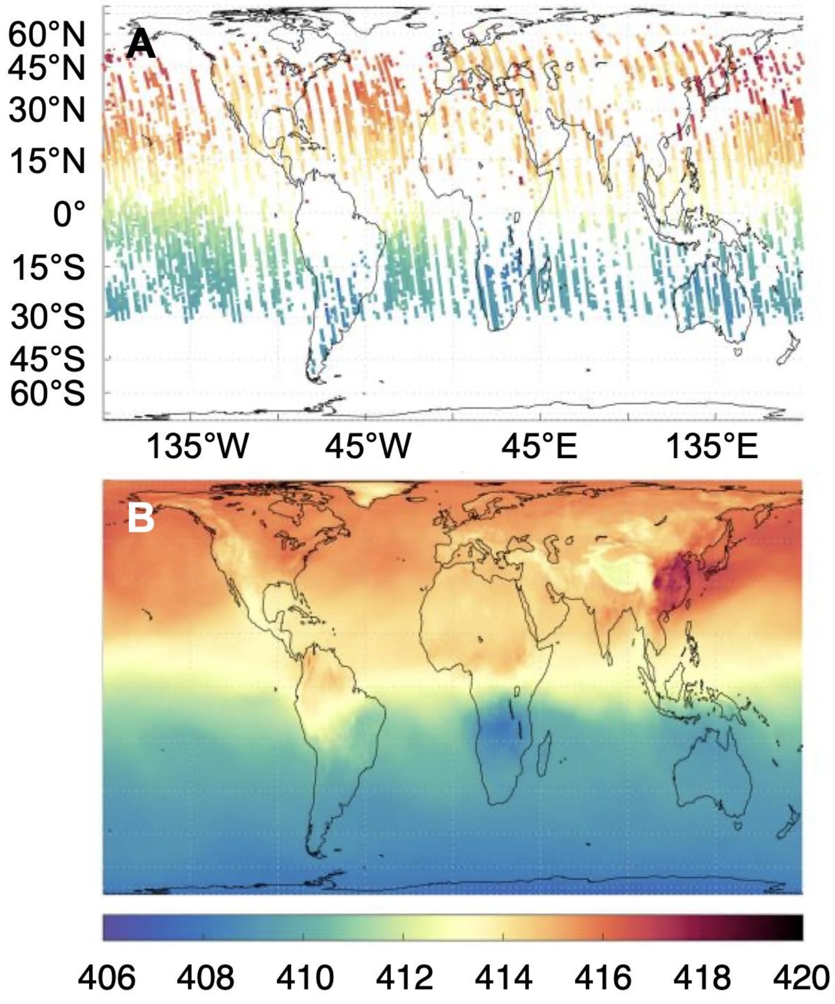
OCO-2/3 Data Processing Levels

- General information on data processing levels can be found at NASA Earthdata.
- Descriptions of data processing levels for OCO-2 and OCO-3 are provided below.

Data Level	Description
L1B	Geolocated, Calibrated Radiance Spectra
L2	Column average volume mixing ratio (XCO2), solar induced fluorescence (SIF), provided at the same resolution and locations as the L1B source data
L3	XCO_2 (and SIF) on uniform space/time grids
L4	CO2 Fluxes, inferred using inversion models (see Part 2!) as well as XCO_2 fields derived from multiple measurements

Example of a Level 3 XCO_2 Product: OCO-2 GEOS L3 XCO_2

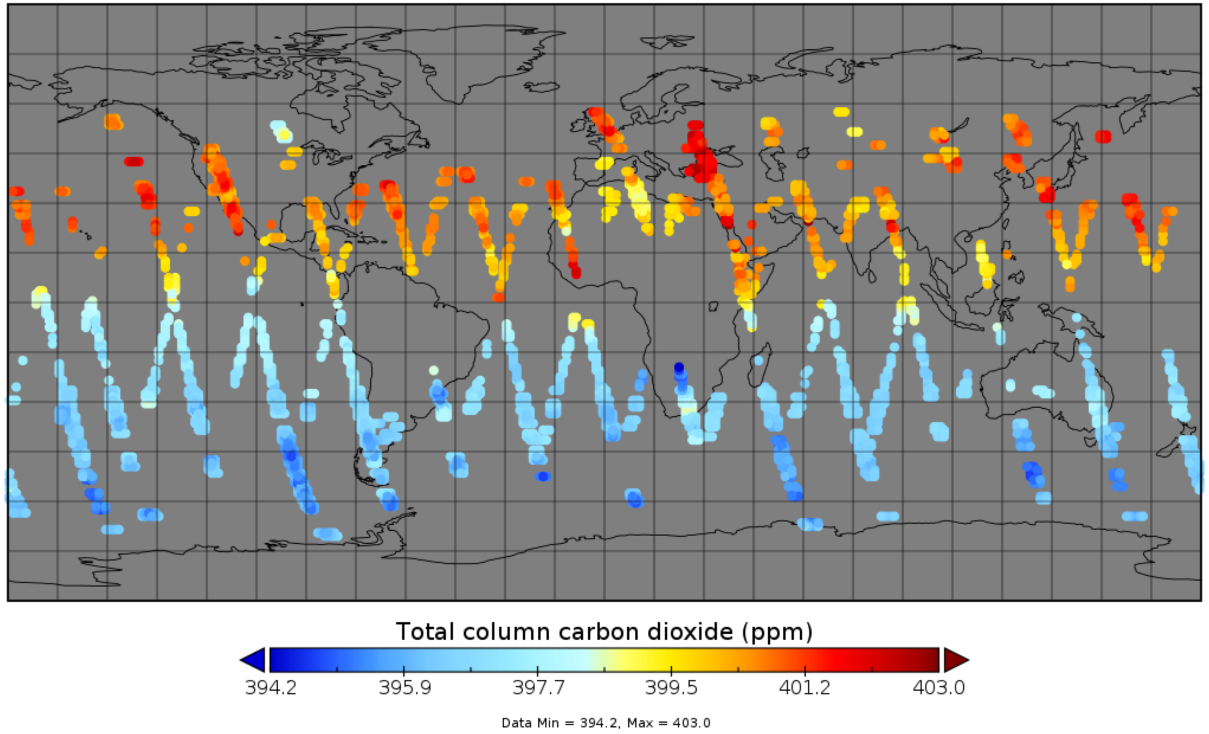
- OCO-2 L2 data have gaps in coverage due to…
  - Narrow (10 km) ground track
  - Clouds and thick aerosols
- Possible Approaches for Producing Spatially Complete, Gridded L3 XCO_2 Fields:
  - Averaging
  - Kriging
  - Data Assimilation
- Figure B shows fields produced using a data assimilation technique called "state estimation" that synthesizes model simulations and OCO-2 observations.
- The OCO-2 GEOS L3 XCO_2 product is publicly available.



Snapshots of 16 days of OCO-2 L2 soundings (A) and assimilated OCO-2 GEOS L3 fields (B).
From OCO-2 GEOS L3 XCO2 Data User Guide

Example of a Level 4 XCO_2 Product: Multi-Instrument Fused XCO_2

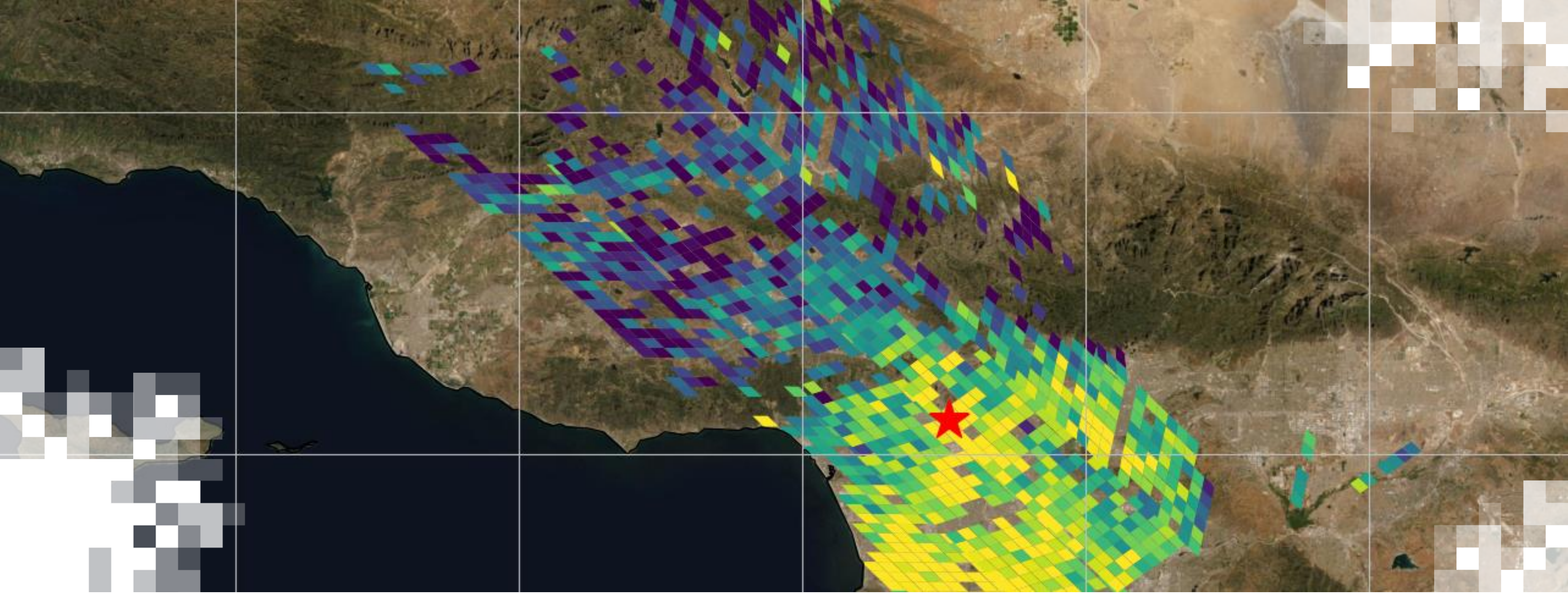
- This is an example of a Level 4 product that combines OCO-2 and GOSAT measurements.
- Here, gridded XCO_2 and other select variables were created by applying local kriging (also known as optimal interpolation) to daily aggregates of OCO-2 and GOSAT bias corrected data.
- This product is publicly available.
- Example L4 flux products will be discussed in Part 2.



Sample image of the L4 Multi-Instrument Fused bias-corrected XCO_2 product for one day.

What can we do with the OCO-2 and OCO-3 data?

- Measurements from NASA's OCO-2 and OCO-3 missions have been used to…
  - Provide global measurements of the rise of atmospheric CO_2 over time.
  - Quantify how CO_2 emissions are offset by natural carbon sinks.
  - Show two-way interactions between carbon and climate.
  - Demonstrate that spaceborne measurements can be used to accurately quantify CO_2 emissions from power plants and cities.



Part 1:
Summary

Summary

- OCO-2 and OCO-3 provide long-term, stable XCO_2 records for carbon cycle science.
  - 10 years of OCO-2
  - 5 years of OCO-3
- The OCO-2 and OCO-3 measurements provide complementary coverage and sampling.
- Filtered, bias-corrected Level 2 Lite XCO_2 products are publicly available.
  - Access via the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC)

Contact Information:

- Invited Instructor:
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- Training website:
  - https://appliedsciences.nasa.gov/get-involved/training/english/arset-applications-carbon-dioxide-measurements-climate-related
- ARSET:
  – https://appliedsciences.nasa.gov/arset
- Twitter: @NASAARSET

Looking Ahead to Part 2

- From atmospheric XCO_2 to fluxes!
- 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 areas impacted by drought and perform an interpretative and comparative 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

Thank You!