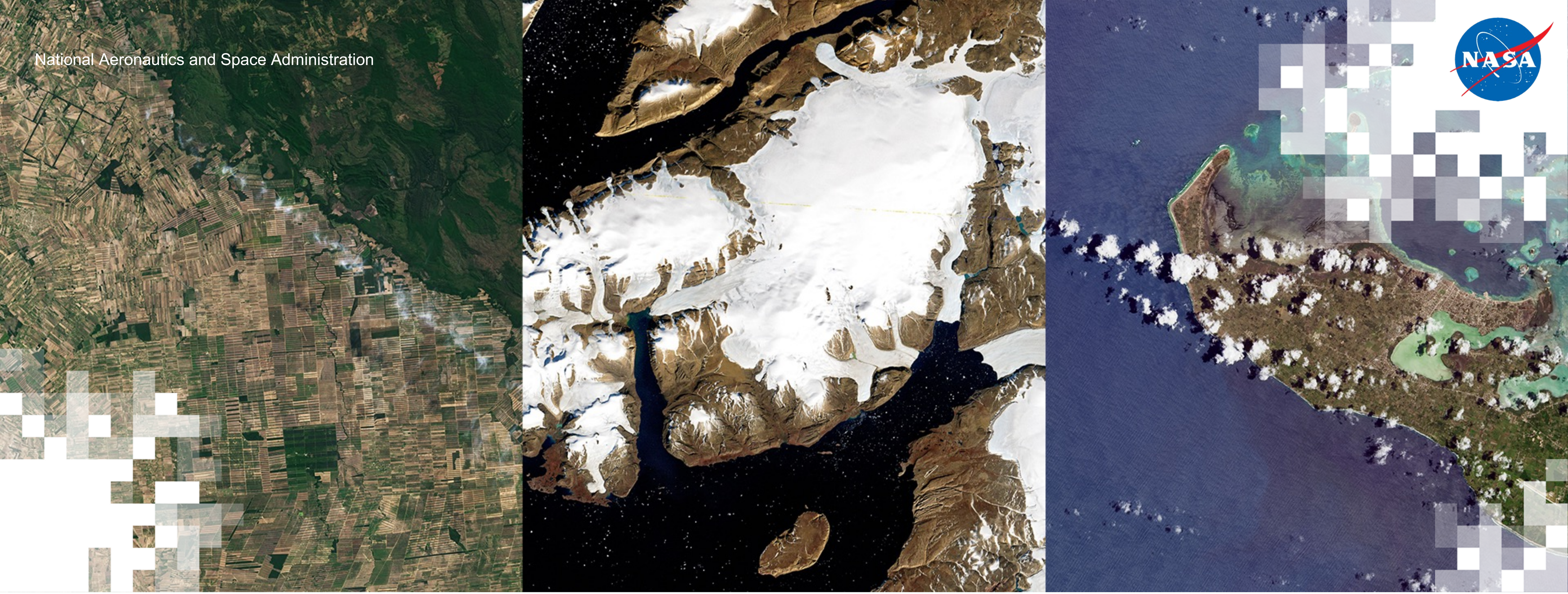


Climate Change Monitoring and Impacts Assessment using NASA Earth Observations

Melanie Follette-Cook and Sean McCartney

22nd William T. Pecora Memorial Remote Sensing Symposium – October 24, 2022

NASA Applied Remote Sensing Training (ARSET)

https://appliedsciences.nasa.gov/arset

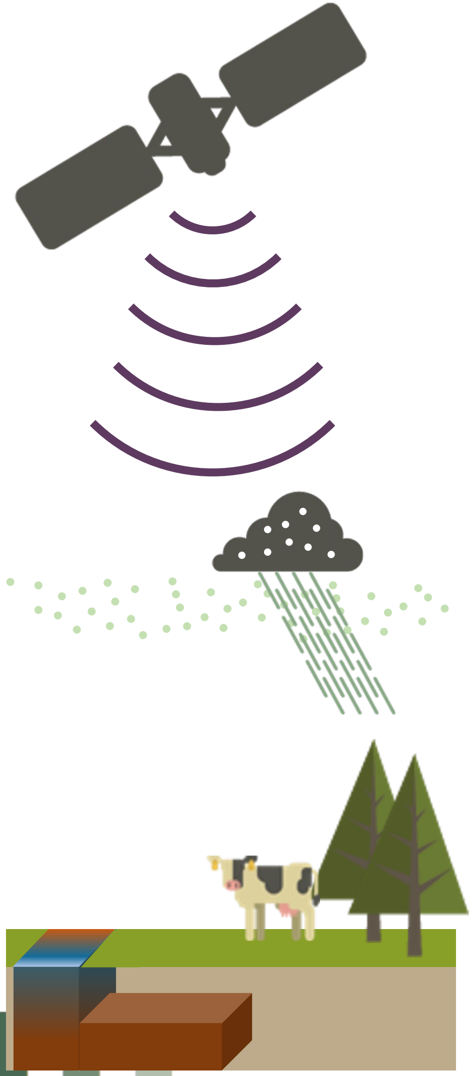
The ARSET Program delivers cost-free training on the use of Earth Observations for decision making.

- Our trainings are:
  - Online and in-person
  - Live, instructor-led, or self-guided
  - Provided at no cost, with materials and recordings available from our website
  - Often multi-lingual
  - Range in level from **introductory** to **advanced**

ARSET Training Themes

Disasters | Agriculture | Land | Water Resources | Climate | Health & Air Quality

ARSET Trainings Are Designed to Meet Audience Knowledge Levels



Advanced
Requires introductory or intermediate training or equivalent knowledge
In-depth and highly focused topics
Advanced Webinar: SAR Image and Data Processing

Intermediate
Requires introductory training or equivalent knowledge
Covers specific applications
Remote Sensing for Disasters Scenarios

Introductory
Requires fundamentals training or equivalent knowledge
Covers specific applications
Introduction to Synthetic Aperture Radar

Fundamentals
Assumes no prior knowledge of remote sensing
Fundamentals of Remote Sensing

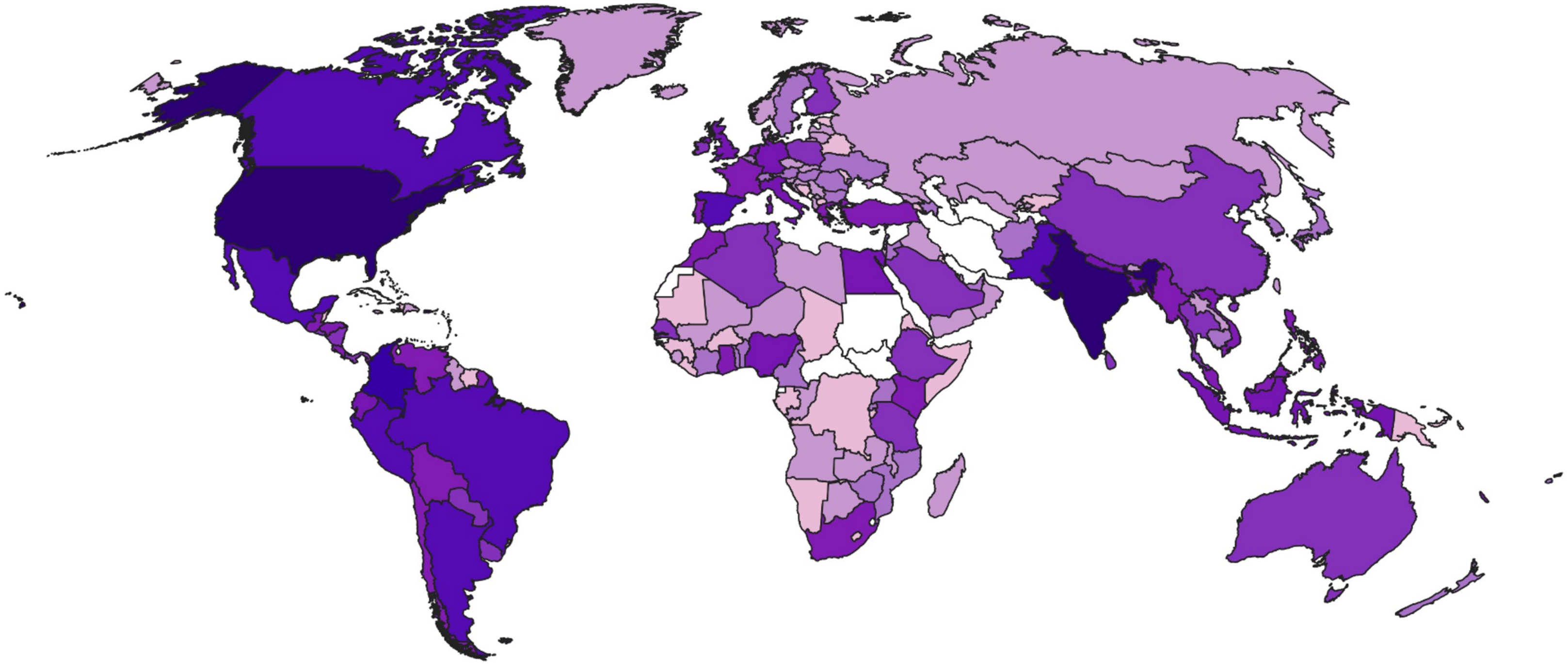
ARSET Training Impacts – 2009-2021

162 trainings

86,000+ participants

179 countries

14,000+ organizations



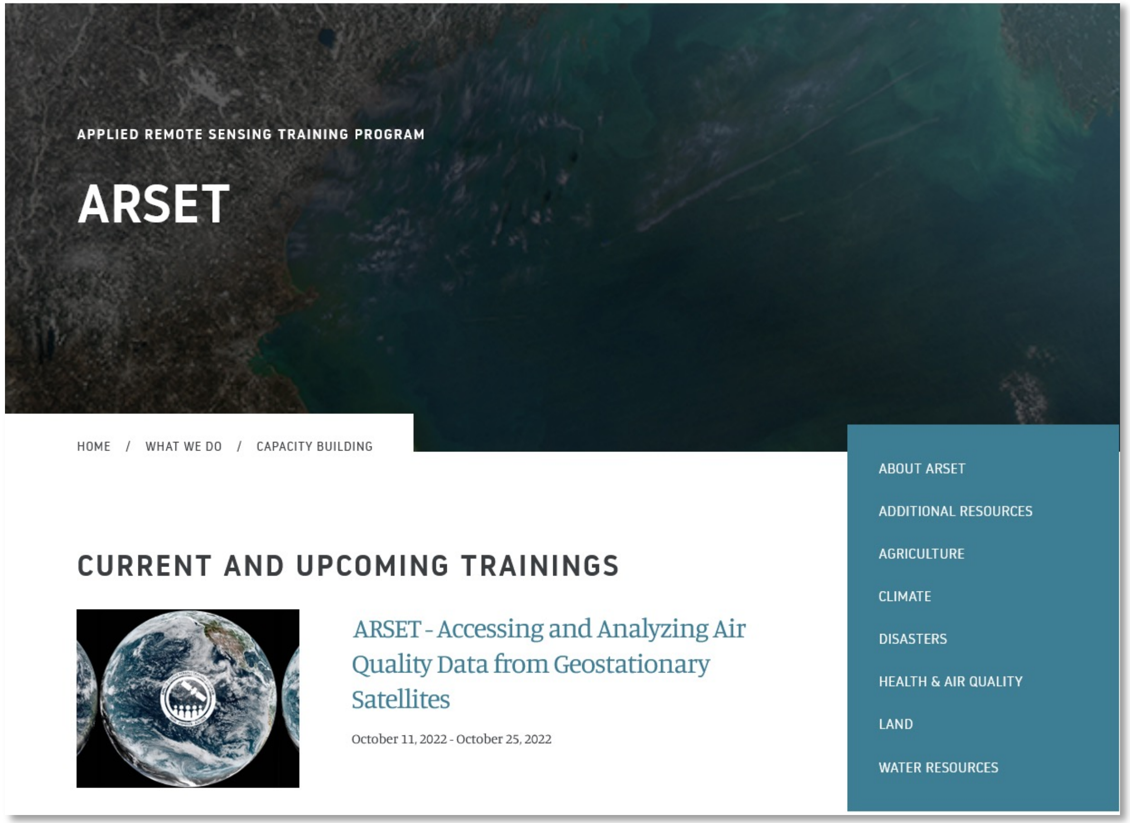
2021 Total – 27,182

Number of Participants

- No Participation
- 0 - 5
- 6 - 25
- 26 - 50
- 51 - 100
- 101 - 250
- 251 - 500
- 501 - 1000
- 1001 - 2000
- 2000+

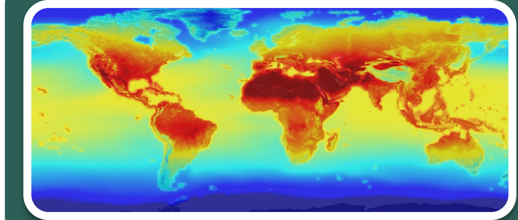
Explore our Website

https://appliedsciences.nasa.gov/arset



- Register for trainings
- Access past training materials
- Online Resource Guide
- Sign up for our listserv
- Follow us on Twitter or YouTube

Workshop Agenda

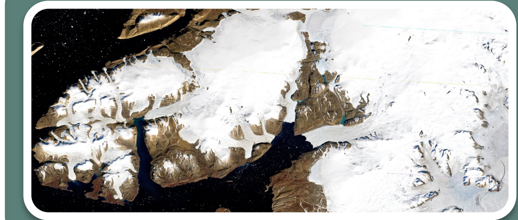


Session I: Introduction to Climate Change

- Overview of climate change
- Monitoring climate change drivers using NASA data

Session II: Earth Observations for Climate Change Impacts (Land & Atmosphere)

- Overview
- Focus Area: Drought
- Focus Area: Urban Heat Islands & Extreme Heat
- Focus Area: Wildfires & Smoke

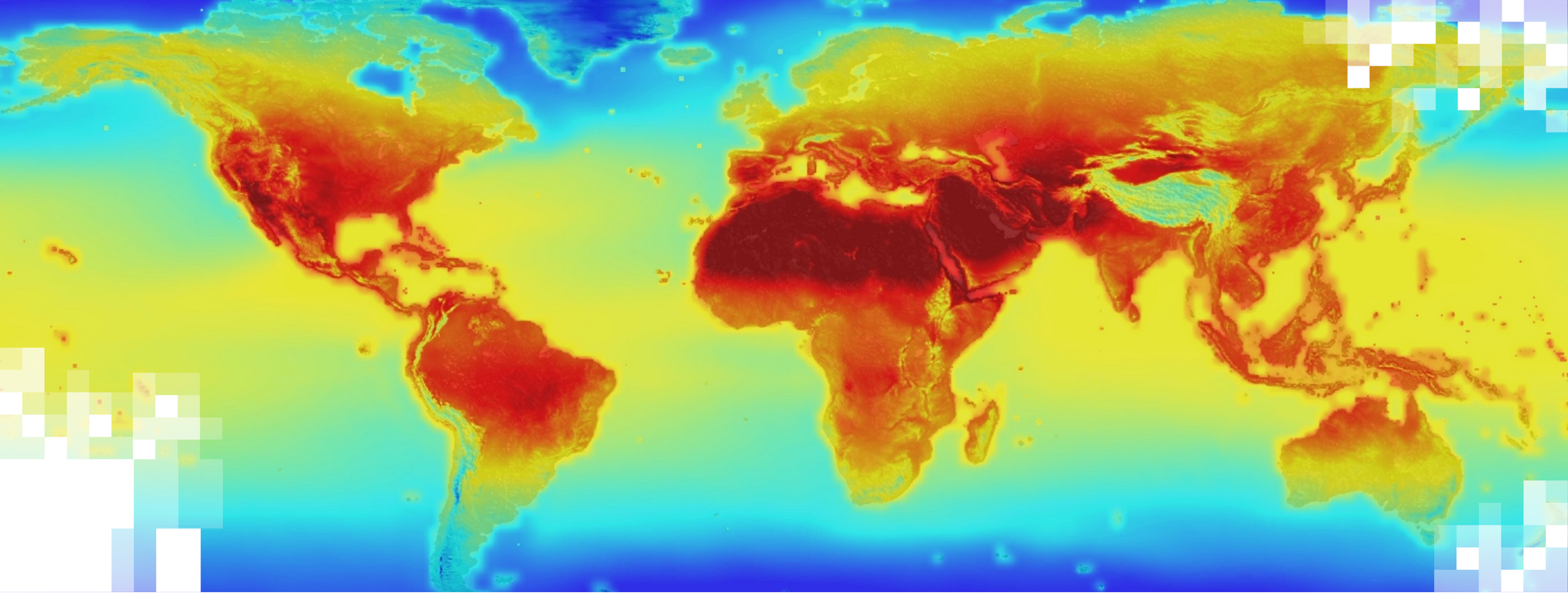


Session III: Earth Observations for Climate Change Impacts (Ocean & Ice)

- Overview
- Focus Area: Sea Level Rise

Session IV: Climate Models, Policy, & Decision making

- Climate Modeling
- NASA ESO



Overview of Climate Change

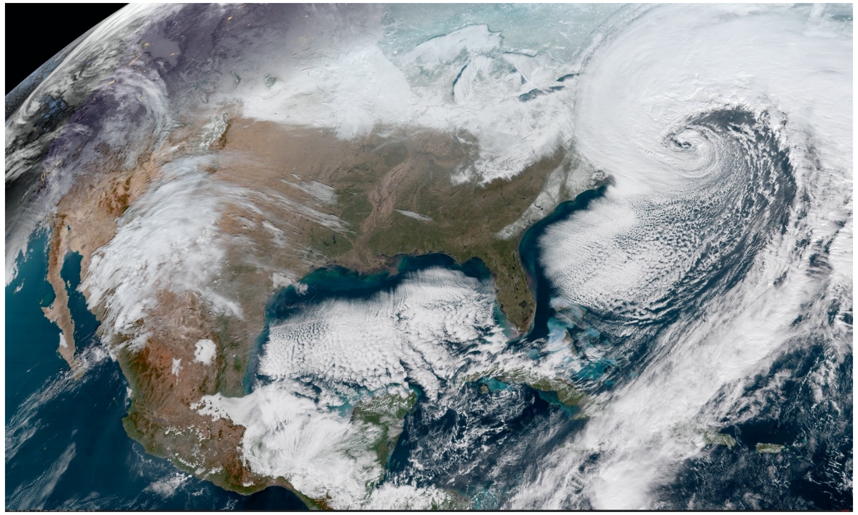
Weather vs. Climate

- The terms "weather" and "climate" are sometimes confused, though they refer to events with broadly different spatial and temporal scales.
- Similarly, the terms “climate change” and “global warming” are often used interchangeably but have distinct meanings.

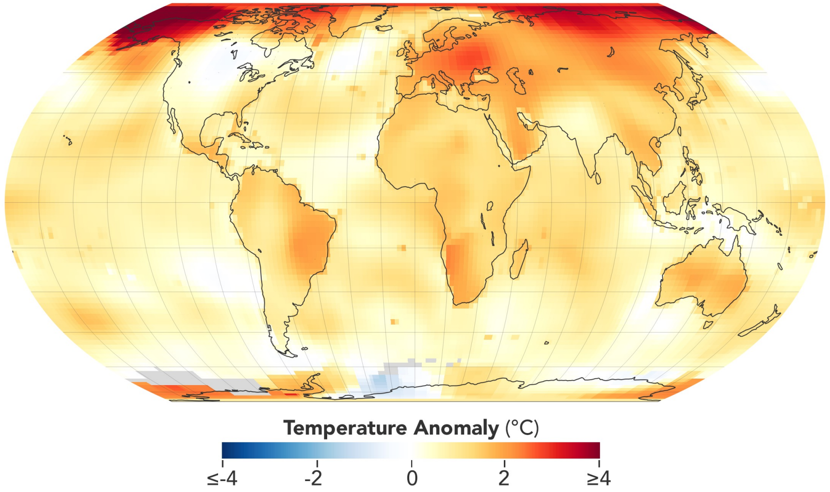
Weather vs. Climate

Weather: Atmospheric conditions that occur locally over short periods of time—from minutes to hours, days to weeks. Examples: Rain, snow, clouds, winds, or thunderstorms.

Climate: Long-term regional or global average of temperature, humidity, and rainfall patterns over a period of time, often 30+ years.



Credit: NOAA



Credits: NASA/Josh Stevens

Weather tells you what to wear each day. Climate tells you what types of clothes to have in your closet.

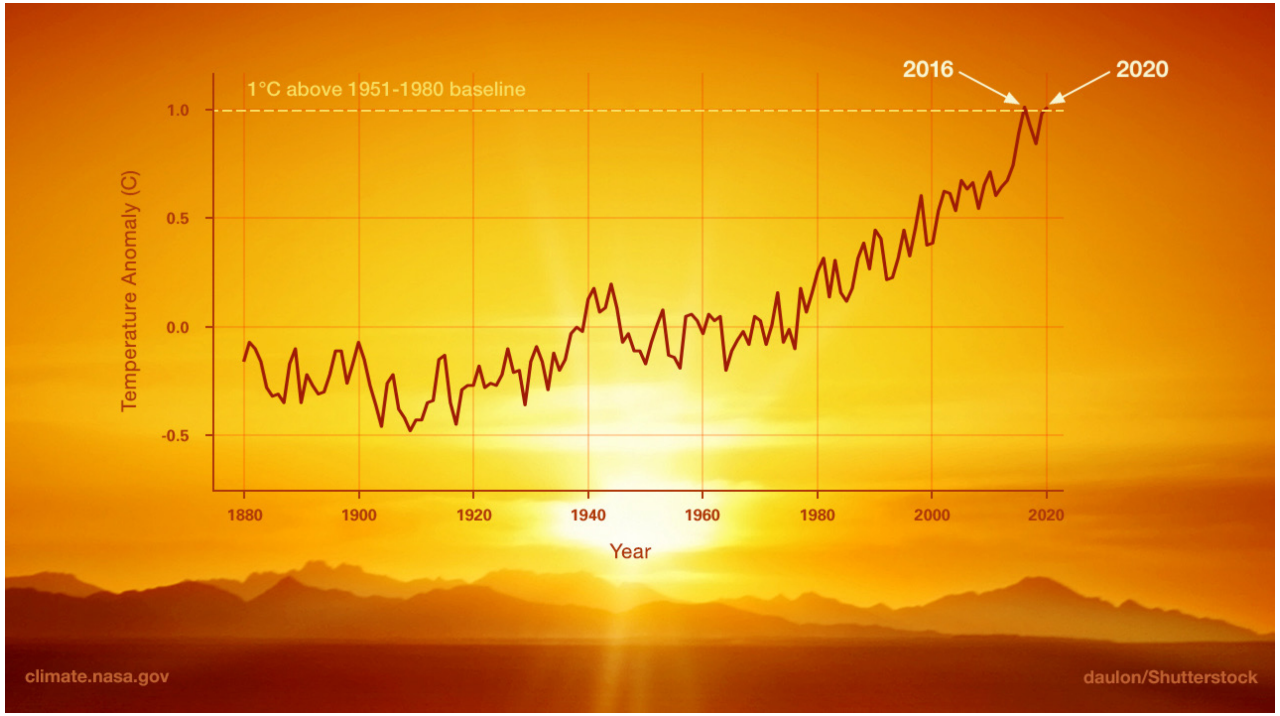
Global Warming vs. Climate Change

- **Global Warming:** The monotonic, long-term heating of Earth's climate system observed since the pre-industrial period (between 1850 and 1900) due to human activities, primarily fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere.

- **Climate Change:** Long-term change (30+ years) in the **average** weather patterns that define Earth's local, regional, and global climates.
- Encompasses global warming but refers to the **broader range of changes** that are happening to our planet, e.g.:
  - Shrinking mountain glaciers
  - Accelerating ice melt at poles
  - Rising sea levels
  - Shifts in phenology
  - Ocean acidification
  - Coral bleaching
  - Extreme weather

Overview: Climate Change

- Earth's climate has changed continuously throughout its history.
- In the last 650,000 years, there have been seven cycles of glacial advance and retreat, with the abrupt end of the last ice age about 11,700 years ago, marking the beginning of the modern climate era—and of human civilization.
- The current warming trend is of particular significance because has been accelerated by human activity since the mid-20th century.

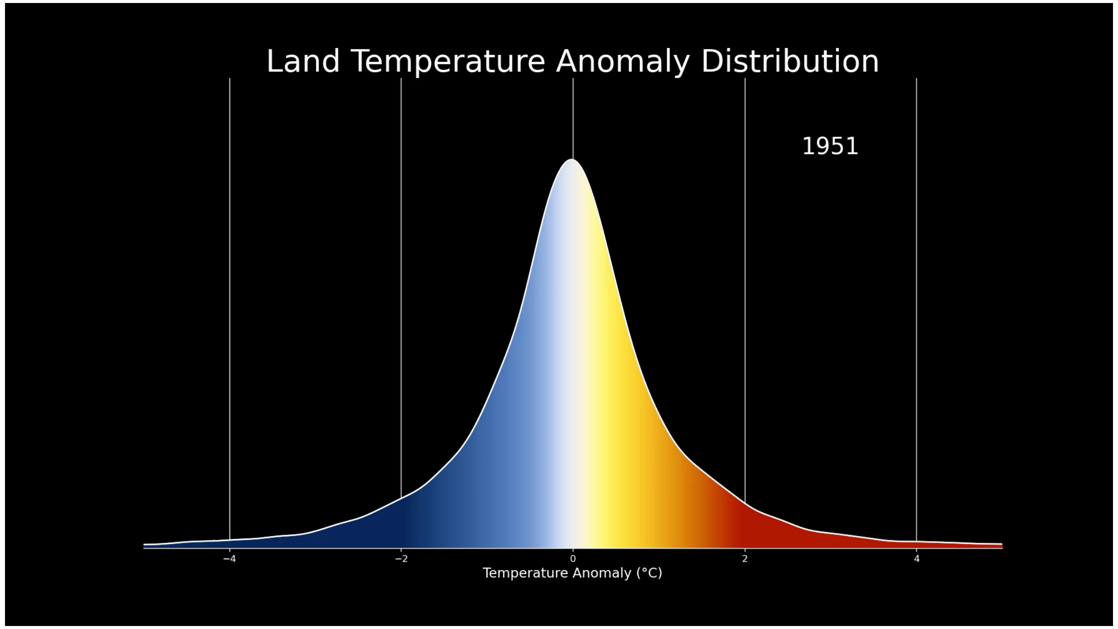


Change in global surface temperature relative to 1951-1980 average temperatures, with the year 2020 tying with 2016 for warmest on record (Source: NASA's Goddard Institute for Space Studies). Credit: NASA/JPL-Caltech

https://climate.nasa.gov/evidence/

Overview: Climate Change

- The planet's average surface temperature has risen about 1.18 degrees Celsius (2.12 degrees Fahrenheit) since the late 19th century, a change driven largely by **increased greenhouse gas emissions** into the atmosphere.
- Observed increases in well-mixed greenhouse gas concentrations since around 1750 are unequivocally caused by human activities (IPCC, 2021).
- Most of the warming has occurred in the past 40 years, with the seven most recent years being the warmest.



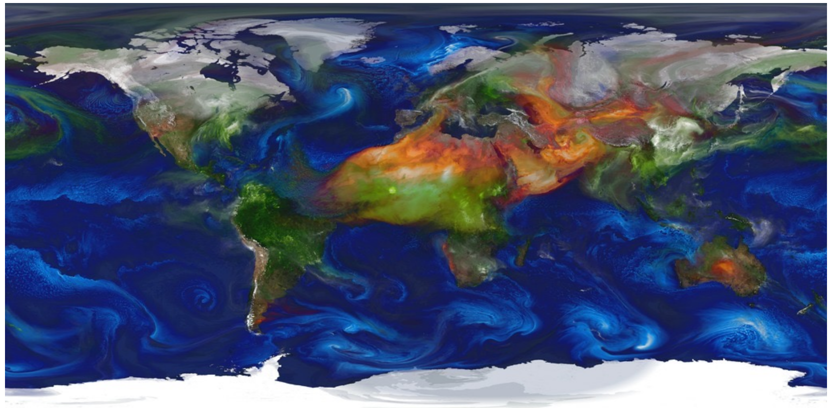
Distribution of land temperature anomalies (1951-2020) over time. Warming temperatures → the peak of the distribution shifts to the right.
Credit: [NASA's Scientific Visualization Studio]

NASA Global Climate Change : https://climate.nasa.gov/evidence/

NASA Goddard Institute for Space Studies: https://data.giss.nasa.gov/gistemp/

Climate Change: Forcings, Feedbacks, and Tipping Points

- **Forcings:** The initial drivers of climate
  - Solar Irradiance
  - Greenhouse Gas Emissions
  - Aerosols, Dust, Smoke, and Soot



GEOS-5 Aerosols Simulation
Credit: NASA's Goddard Space Flight Center/Global Modeling and Assimilation Office

- **Feedbacks:** Processes that can either amplify or diminish the effects of climate forcings.
  - Clouds
  - Precipitation
  - Greening of the Forests
  - Ice Albedo
- **Climate Tipping Points:** When Earth's climate abruptly moves between relatively stable states.
  - Ocean Circulation
  - Ice Loss
  - Rapid Release of Methane

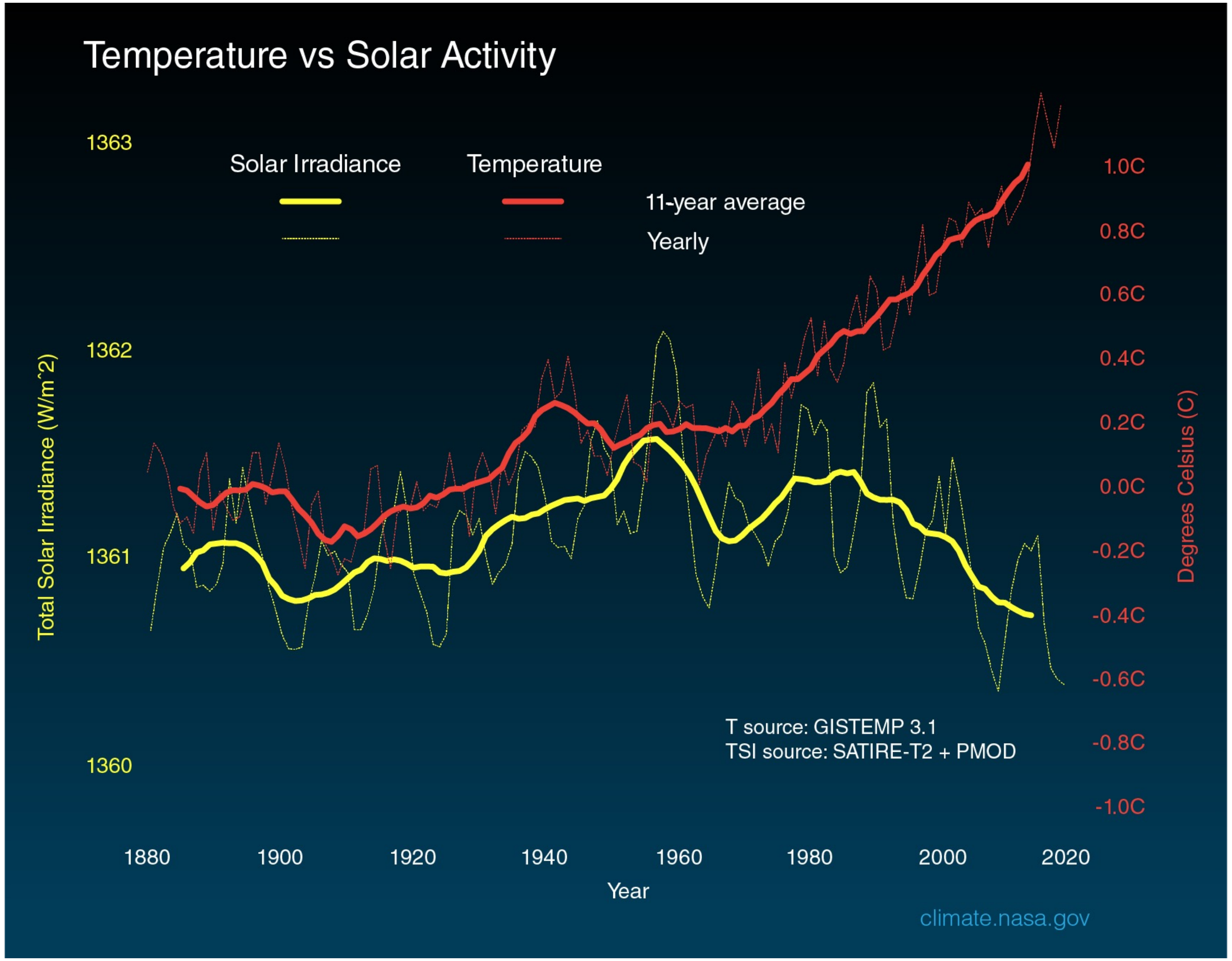
https://climate.nasa.gov/nasa_science/science/

Climate Change Forcings: Natural vs. Anthropogenic

- **Natural Processes:**
  - Changes in the Sun’s energy output
  - Variations in Earth’s orbit
  - Volcanic activity
  - Internal variability (e.g., cyclical ocean patterns like El Niño and La Niña)

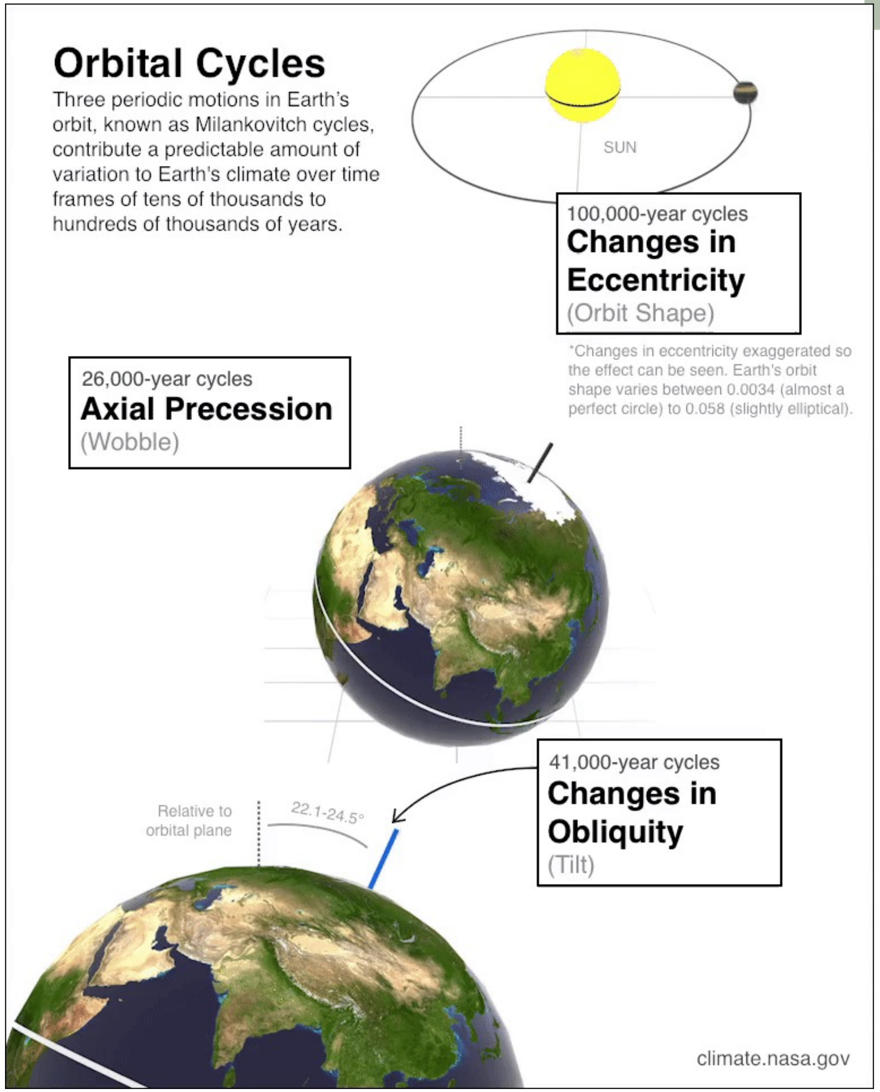
The Sun’s Impact on Climate

- Solar energy reaching Earth follows the Sun’s natural 11-year cycle with **no net increase since the 1950s**.
- Over the same period, global temperature has risen markedly. It is therefore **extremely unlikely** that the Sun has caused the observed global temperature warming trend over the past half-century.
- If the Sun were responsible for global warming, we would expect to see warming throughout all layers of the atmosphere. What we observe is warming at the surface and cooling in the stratosphere. This is consistent with warming caused by a buildup of heat-trapping gases near Earth's surface.



Milankovitch Cycles

- **Eccentricity** - The shape of Earth's orbit
- **Precession** - The direction that Earth's spin axis is pointed
- **Obliquity** - The angle that Earth's axis is tilted with respect to Earth's orbital plane
- Can't explain current changes
- Time scales (>10,000 years) much longer than current warming (decades)
- If no human influence, Milankovitch forcings indicate cooling period



Credit: NASA/JPL-Caltech

https://climate.nasa.gov/blog/2949/why-milankovitch-orbital-cycles-cant-explain-earths-current-warming/

Volcanic Eruptions

- Particles and gases spewed from volcanoes **cool the planet** by shading incoming solar radiation. The cooling effect can last for months or years.
- Overall, volcanoes release about 1% of the equivalent amount of CO_2 released by human activities.
- By comparison, human activities emit a Mount St. Helens eruption of CO_2 every 2.5 hours and a Mount Pinatubo eruption of CO_2 twice daily (NASA Global Climate Change).

Mount Pinatubo, June 13, 1991 (Image courtesy of NOAA)

https://scied.ucar.edu/learning-zone/how-climate-works/how-volcanoes-influence-climate

Climate Change Forcings: Natural vs. Anthropogenic

- **Anthropogenic:**
  - Fossil fuel burning
  - Deforestation

Greenhouse Gases

- Most of the energy that reaches Earth's surface is short wave (UV, visible, and infrared), which warms the surface and is radiated back toward space in long-wave infrared.
- **Greenhouse Gases** – Such as water vapor, carbon dioxide, and methane – occur naturally in small amounts and **absorb and release heat energy** more efficiently than abundant atmospheric gases like nitrogen and oxygen.

A simplified animation of the greenhouse effect. Credit: NASA/JPL-Caltech

https://www.climate.gov/teaching/essential-principes-climate-literacy/teaching-essential-principle-2-climate-regulated

Greenhouse Gases

Water Vapor (H_2O)

- The most abundant greenhouse gas in the atmosphere.
- Changes in its concentration are considered to be a result of the warming of the atmosphere rather than a direct result of industrialization and are an important positive climate feedback.

Chlorofluorocarbons (CFCs)

- No natural source
- Synthesized for use as refrigerants, aerosol propellants, and cleaning solvents.
- Can destroy stratospheric ozone, so production halted
- Long atmospheric lifetimes - will remain in the atmosphere for 100+ years.

Methane (CH_4)

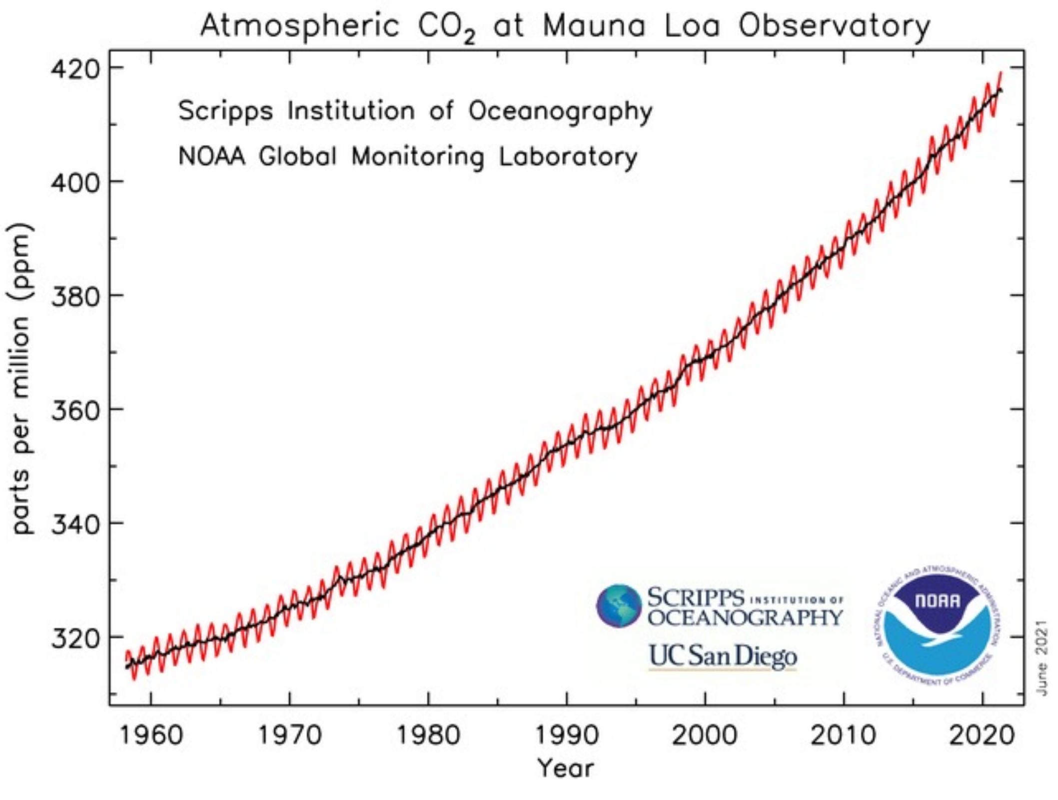
- Extremely effective absorber of radiation
- Shorter lifetime in the atmosphere (10-12 years)
- Released with biological processes in low-oxygen environments (e.g., swamplands or rice production)
- Human Activities: Growing rice, raising cattle, using natural gas, mining coal

Nitrous Oxide (N_2O)

- Produced by microbial processes in soil and water, including those reactions which occur in fertilizer containing nitrogen
- Some industrial processes (fossil fuel-fired power plants, nylon production, nitric acid production, and vehicle emissions) also contribute to its atmospheric load.

Carbon Dioxide (CO_2)

- Natural production and absorption of CO_2 is through the terrestrial biosphere and the ocean.
- Humankind has altered the natural carbon cycle by burning coal, oil, natural gas, and wood.
- Prior to the industrial revolution, CO_2 concentrations were fairly stable at 280 parts per million (ppm). In May 2021, the monthly average was 419 ppm, a ~49% increase.
- Charles David Keeling was the first to observe seasonal rise and fall in CO_2 levels every year **(Keeling Curve)** and was also the first to recognize that, despite the seasonal fluctuation, CO_2 levels were rising every year.

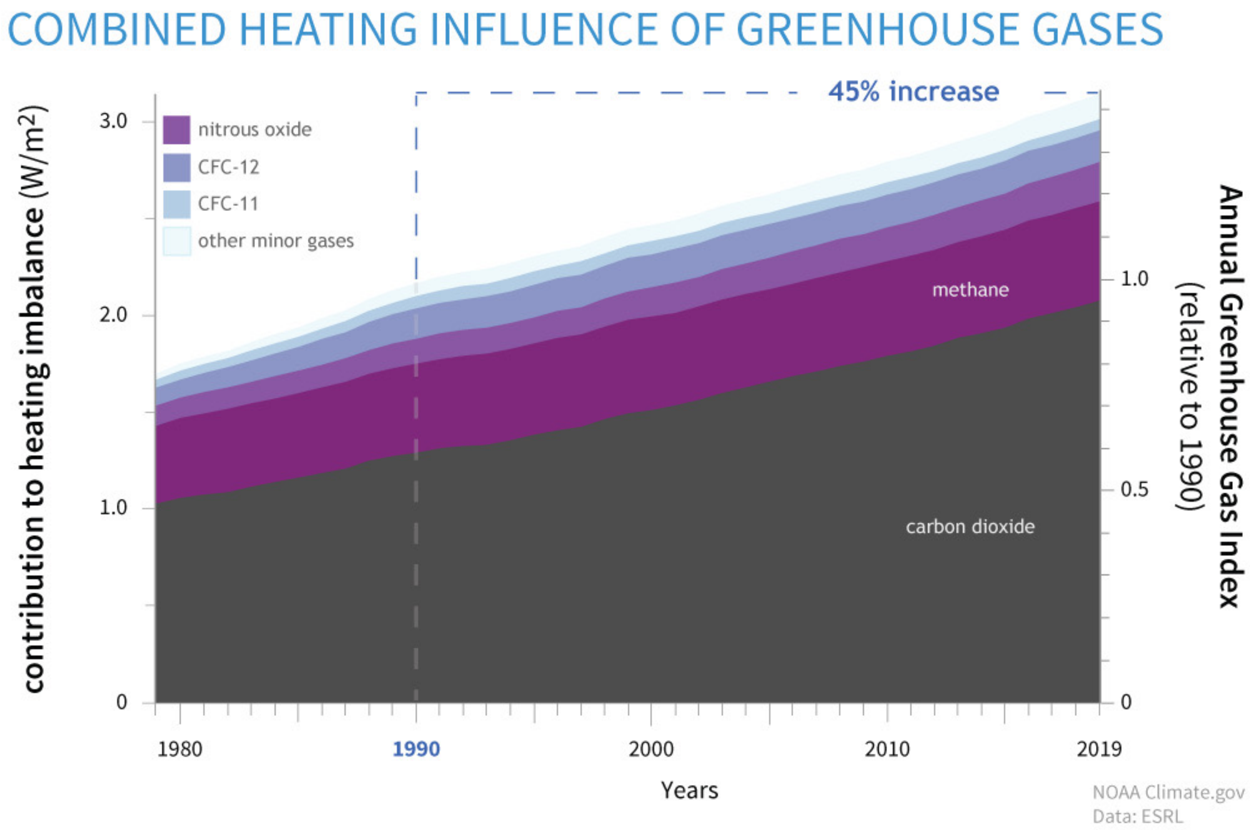


This graph depicts the upward trajectory of carbon dioxide in the atmosphere as measured at the Mauna Loa Atmospheric Baseline Observatory by NOAA and the Scripps Institution of Oceanography. The annual fluctuation is known as the Keeling Curve. Credit: NOAA Global Monitoring Laboratory

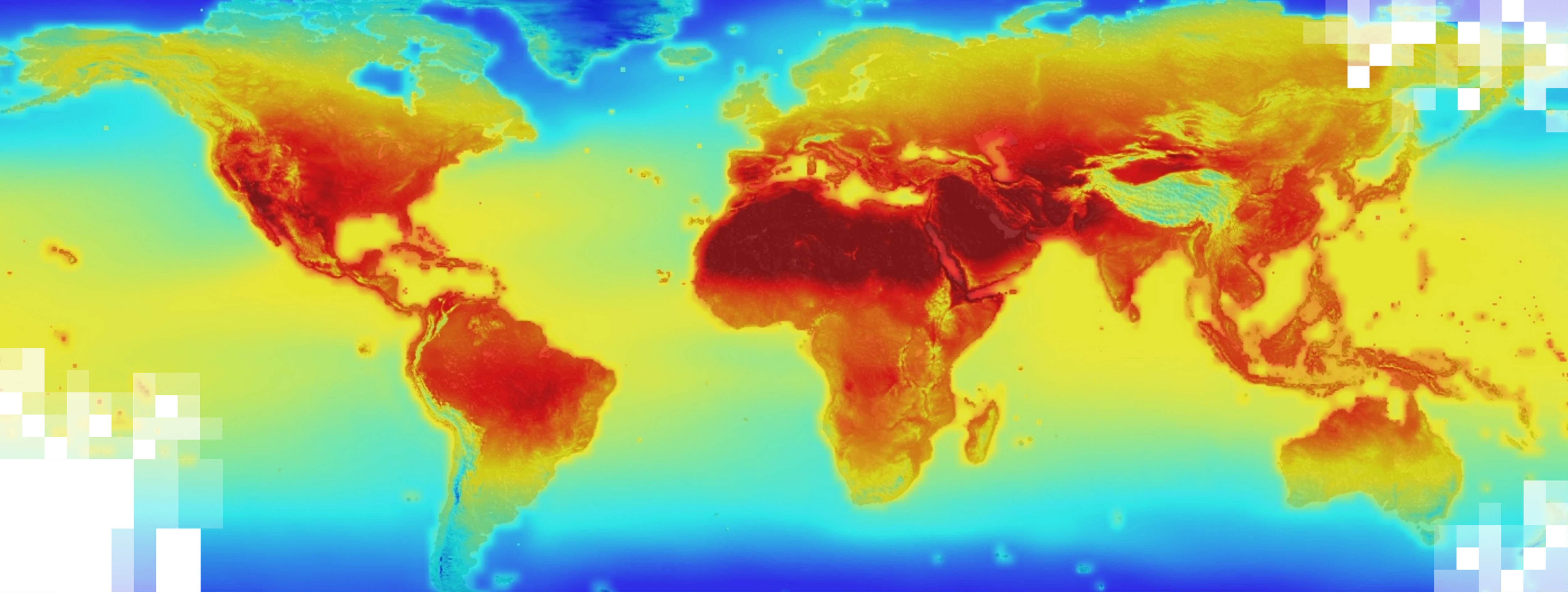
Credit: NOAA

Why Carbon Dioxide Matters

- Carbon dioxide is the most important of Earth’s long-lived greenhouse gases.
- Carbon dioxide absorbs less heat per molecule than the greenhouse gases methane or nitrous oxide, but it’s more abundant and stays in the atmosphere longer (300 to 1,000 years).
- Increases in atmospheric carbon dioxide are responsible for about two-thirds of the total energy imbalance that is causing Earth's temperature to rise.

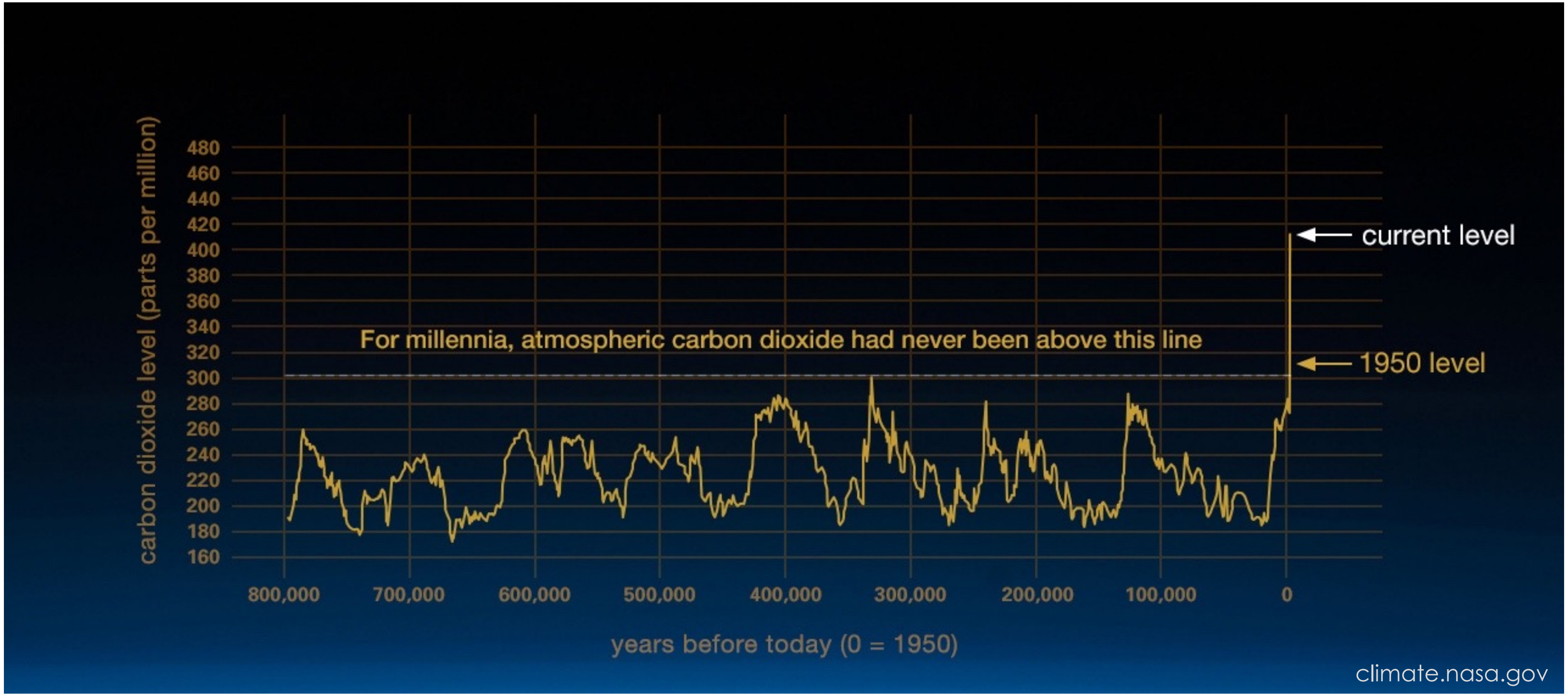


This graph shows the heating imbalance in watts per square meter relative to the year 1750 caused by all major human-produced greenhouse gases: carbon dioxide, methane, nitrous oxide, chlorofluorocarbons 11 and 12, and a group of 15 other minor contributors. Today's atmosphere absorbs about 3 extra watts of incoming solar energy over each square meter of Earth's surface. According to NOAA's Annual Greenhouse Gas Index (right axis) the combined heating influence of all major greenhouse gases has increased by 43% relative to 1990. Credit: NOAA Climate.gov, based on data from NOAA ESRL.



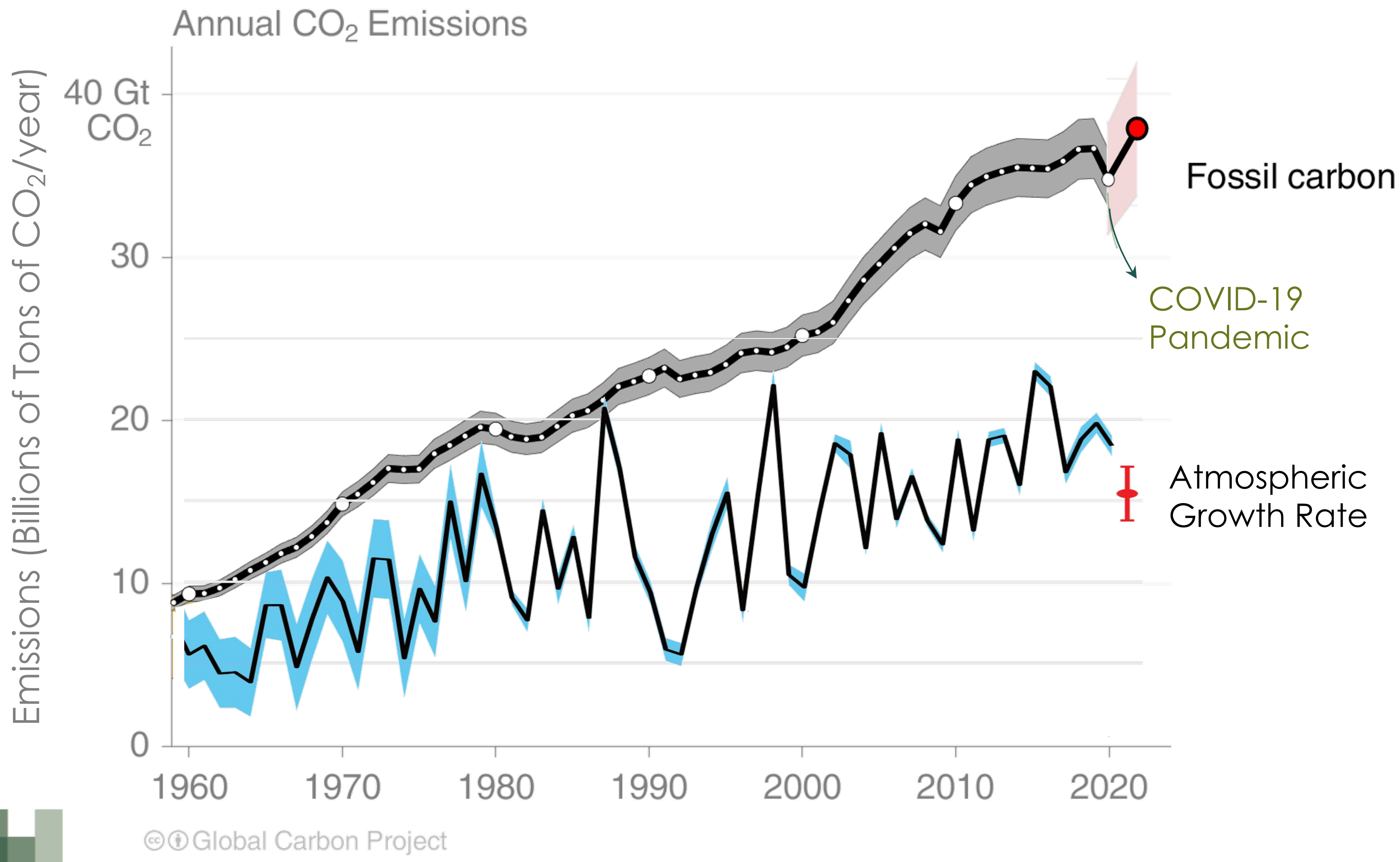
Monitoring Climate Change Drivers Using NASA Data

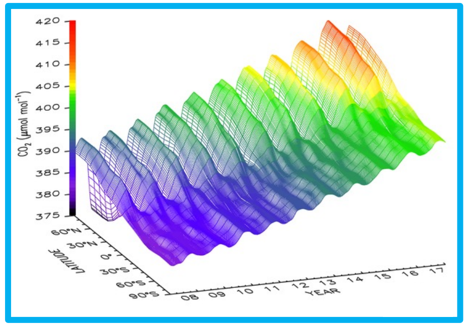
Atmospheric CO_2 Levels Over the Past Millenia



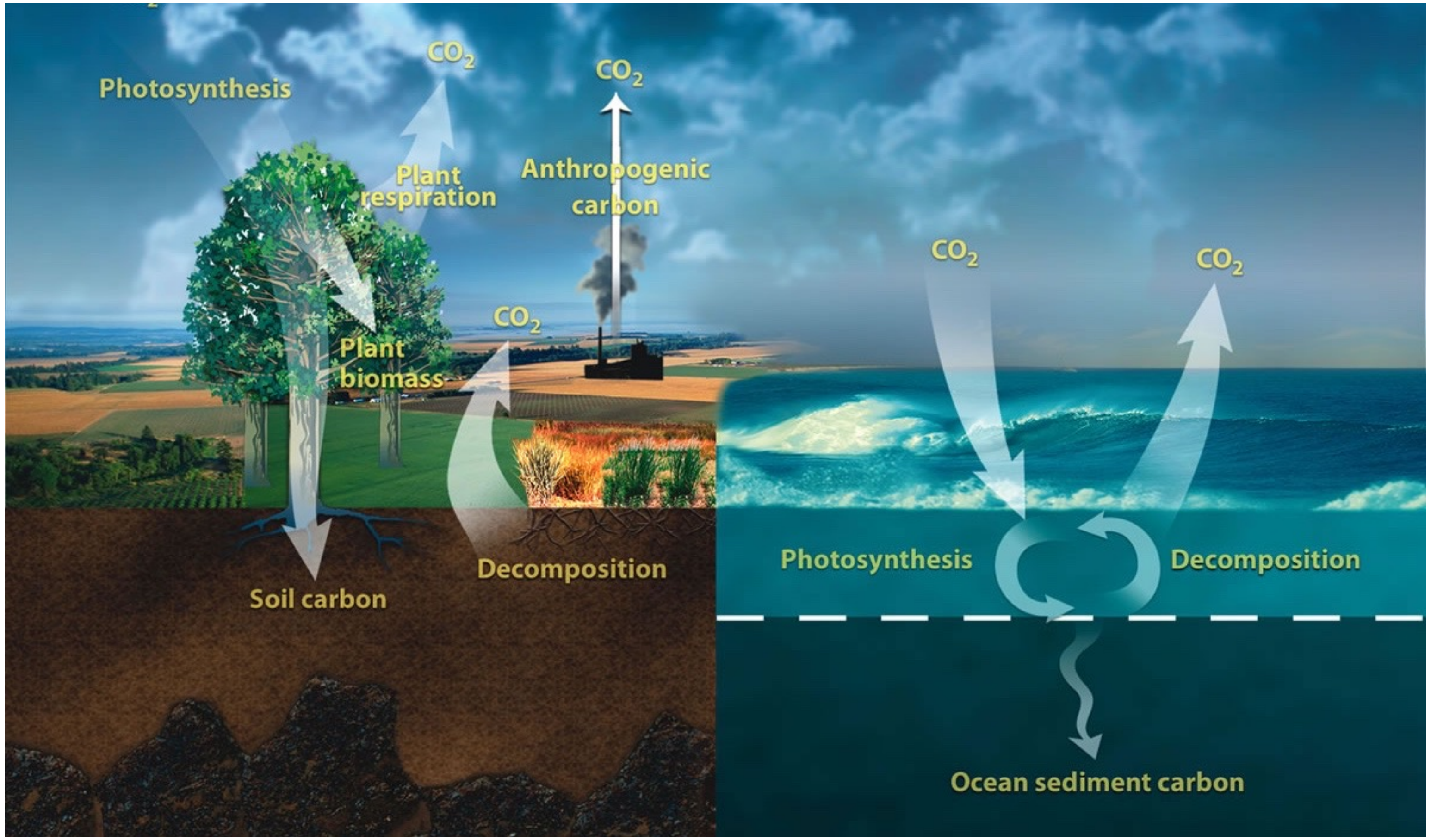
This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO_2 has increased since the Industrial Revolution.
Credit: Luthi, D., et al.. 2008; Etheridge, D.M., et al. 2010; Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record.

Human Activities Impact CO_2 Concentrations





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}

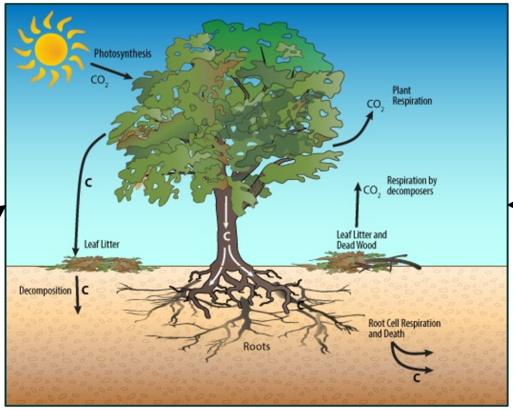
Ocean
- Emissions ~330 Pg CO_2 yr^{-1}
- Removals ~340 Pg CO_2 yr^{-1}

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

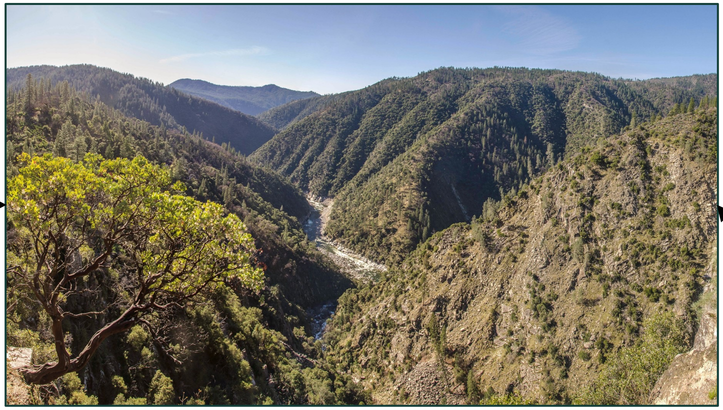
(1 Pg = 1 petagram = 1 billion metric tonnes = 10^{15} grams)

Carbon Cycle Operates at Various Spatial and Temporal Scales

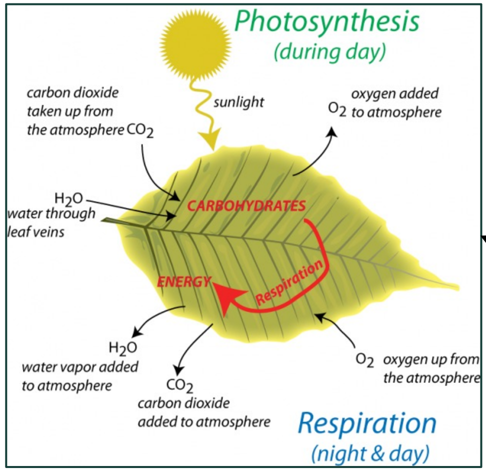
Tree Scale



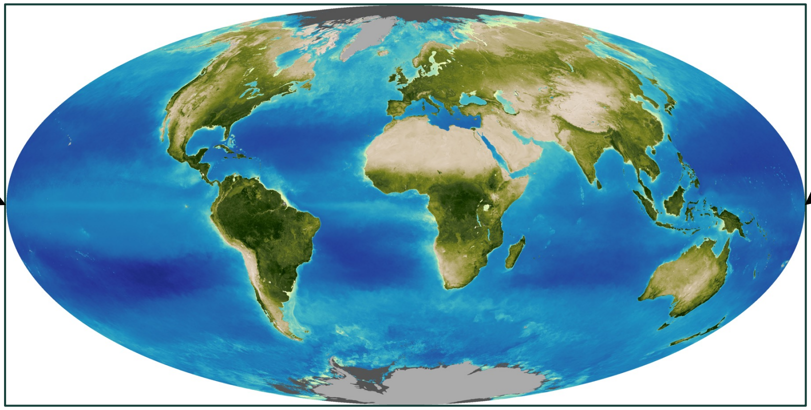
Regional Scale

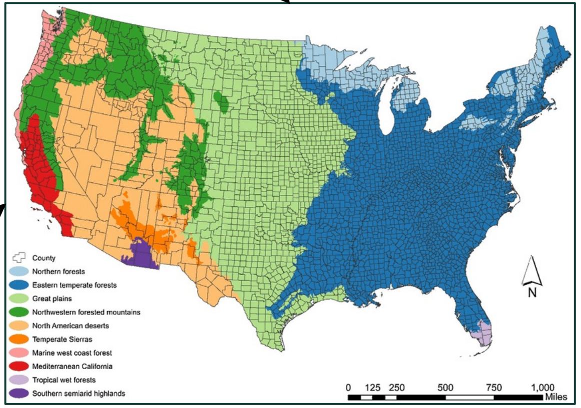


Leaf Scale



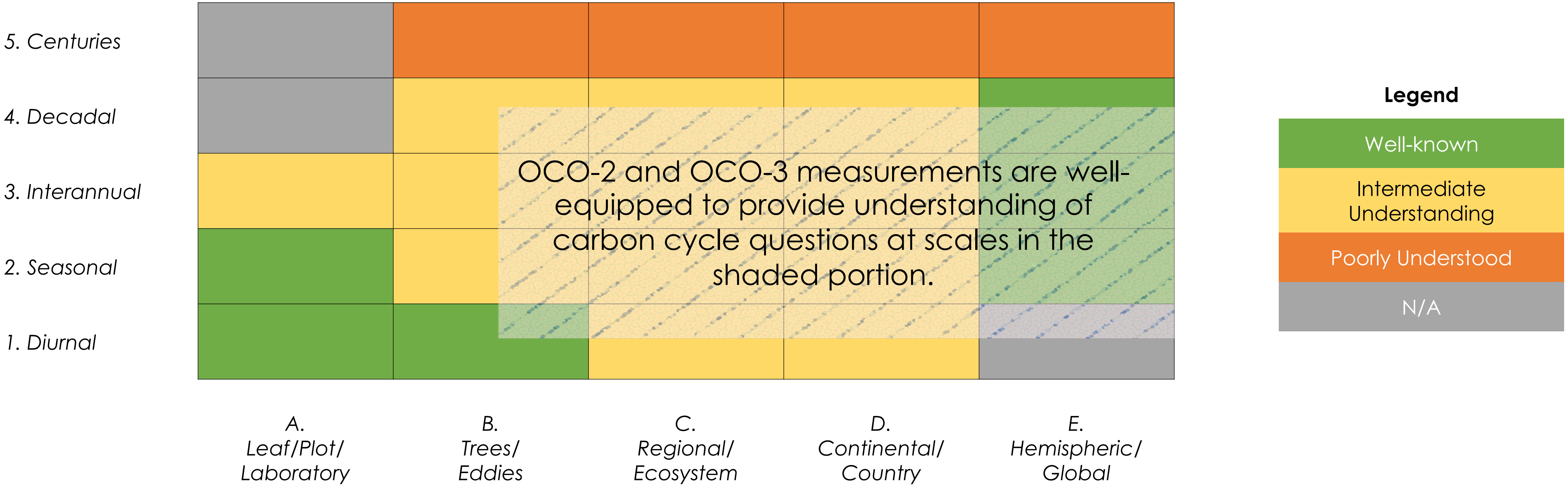
Global Scale





Country/
Continental Scale

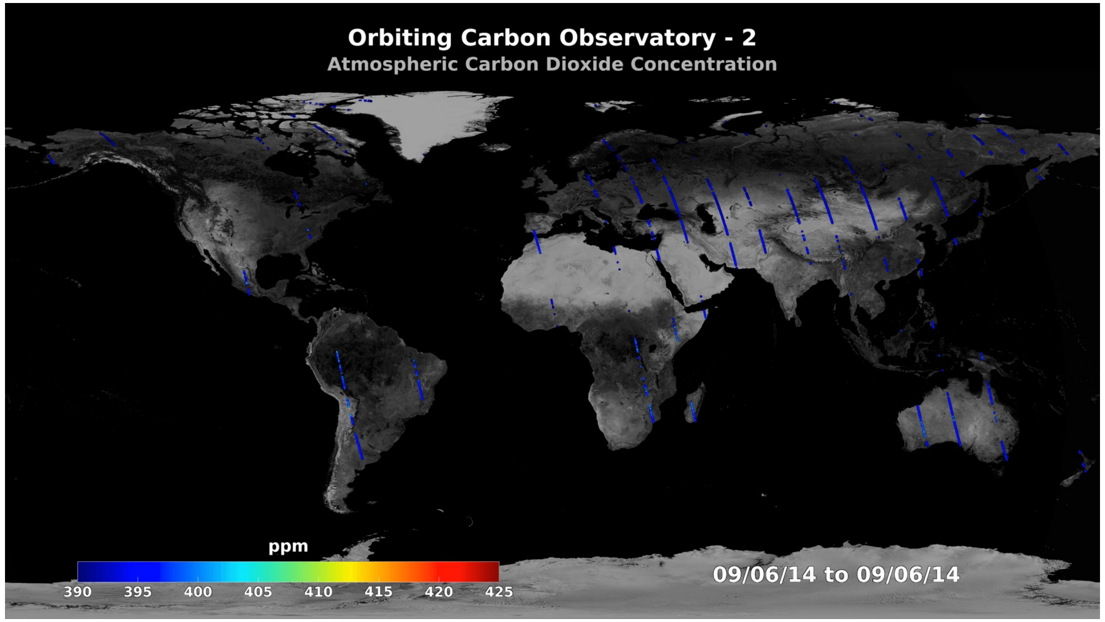
The Most Pressing Questions in Carbon Cycle Science



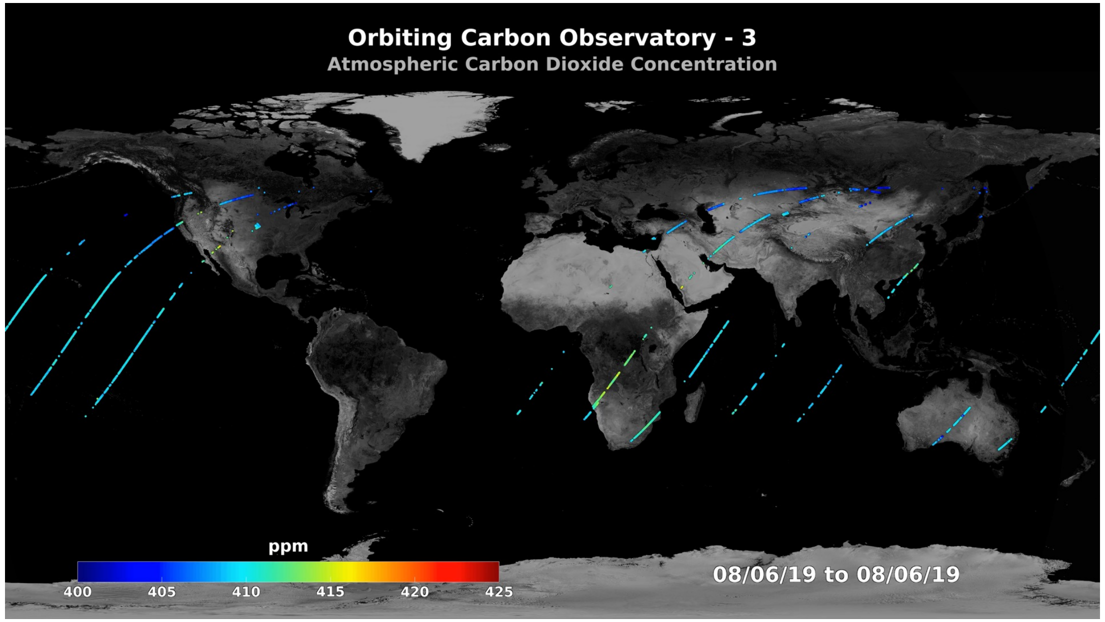
Carbon Cycle Science Questions	*Grids*	*Carbon Cycle Science Questions*	*Grids*
Marine physical - biogeochemical coupling	A1, B1	**Disturbance & recovery**	B3, B4, C3, C4, D3, D4
Coastal & inland processes	B2, C2	**Contemporary net carbon sink**	D2, D3, D4, E2, E3, E4
Phenology	A1, A2, A3	**Land and 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

Recap of OCO-2 and OCO-3 XCO_2 Measurements

OCO-2 (2014 - Present)



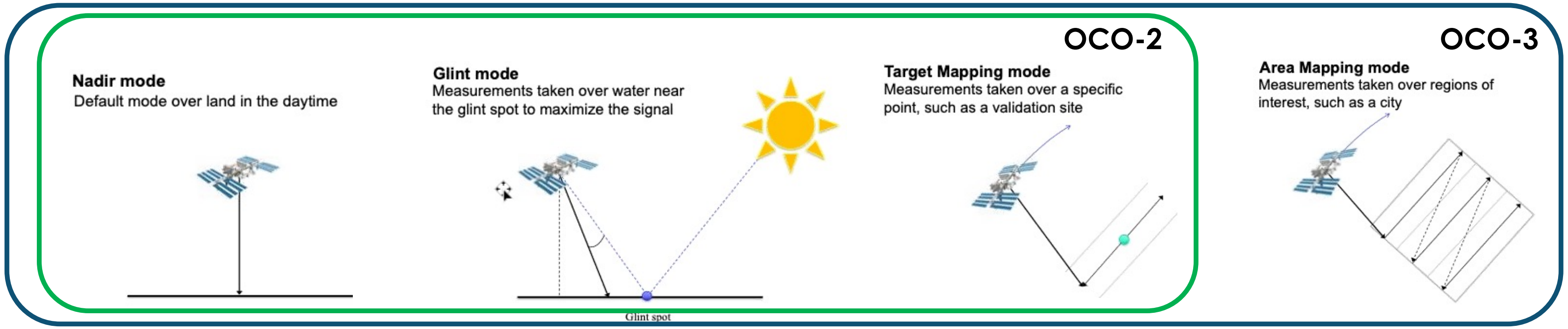
OCO-3 on ISS (2019 - Present)



- 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.

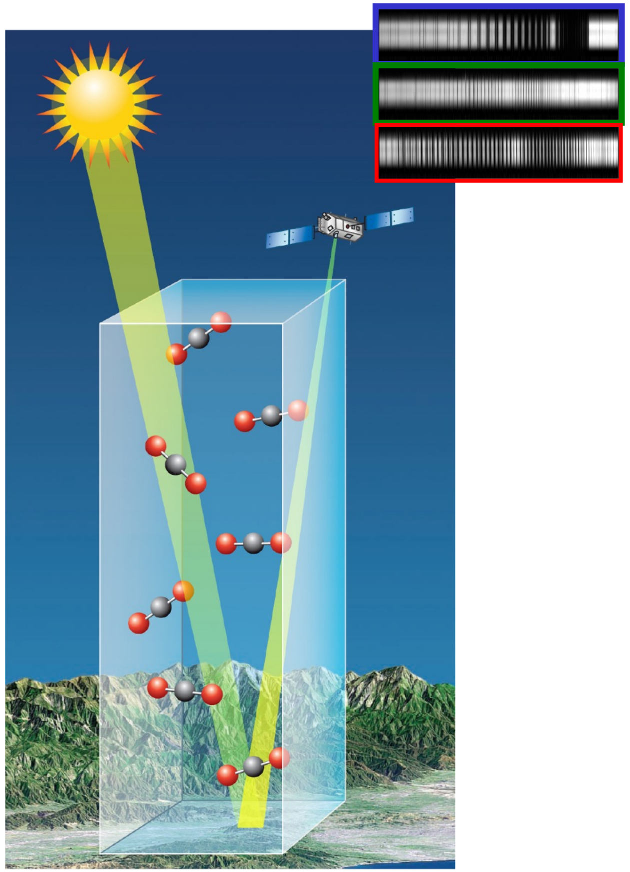
Recap of OCO-2 and OCO-3 XCO_2 Measurements

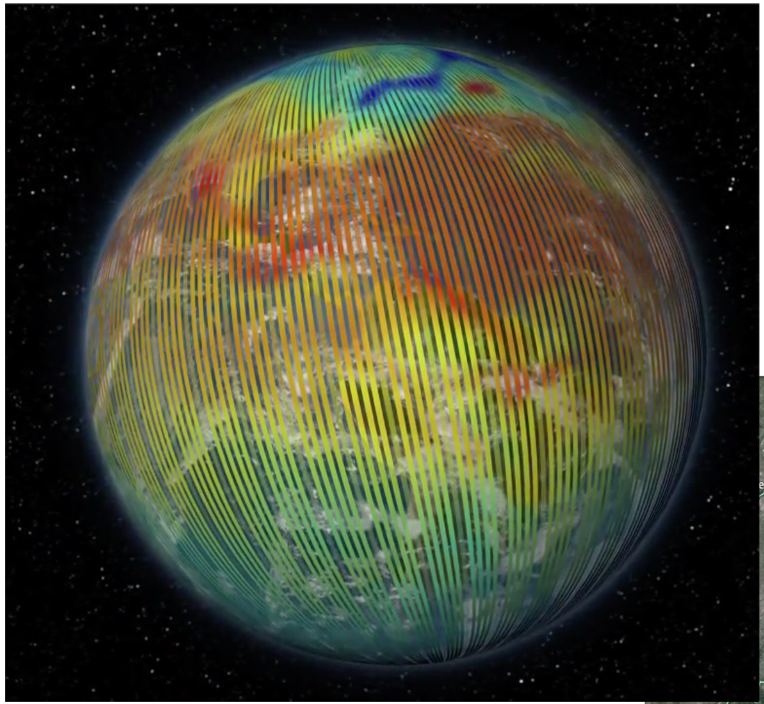
- OCO-2 launched on July 2014 (data record spans 7.5+ years) and OCO-3 launched in May 2019 (data record spans 2.5+ years)
- Mission Objectives:
  - Retrieve estimates of the column-averaged dry air mole fraction of carbon dioxide (XCO_2) at regional scales (>1,000 km) and with precision better than 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

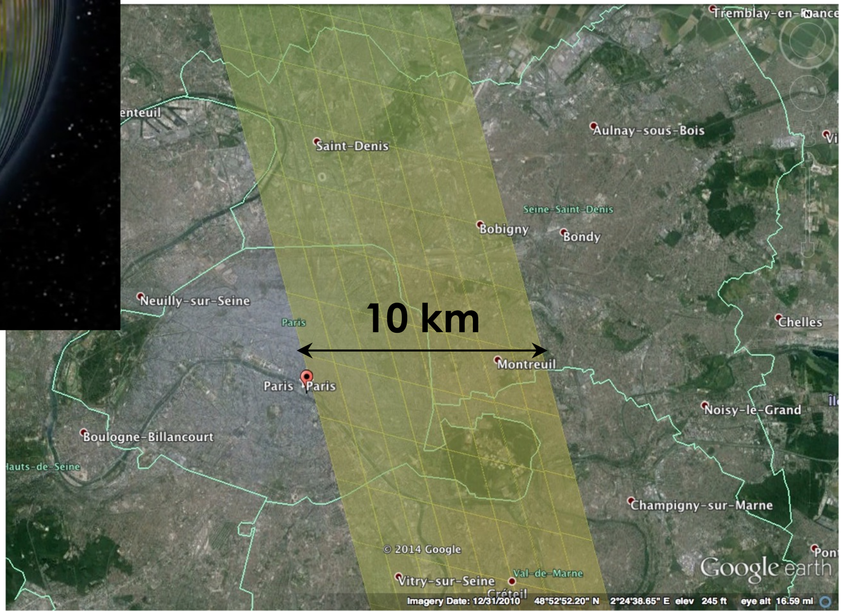


OCO-2 Measurement Approach

Collect spectra of CO_2 & O_2 absorption in reflected sunlight over the globe





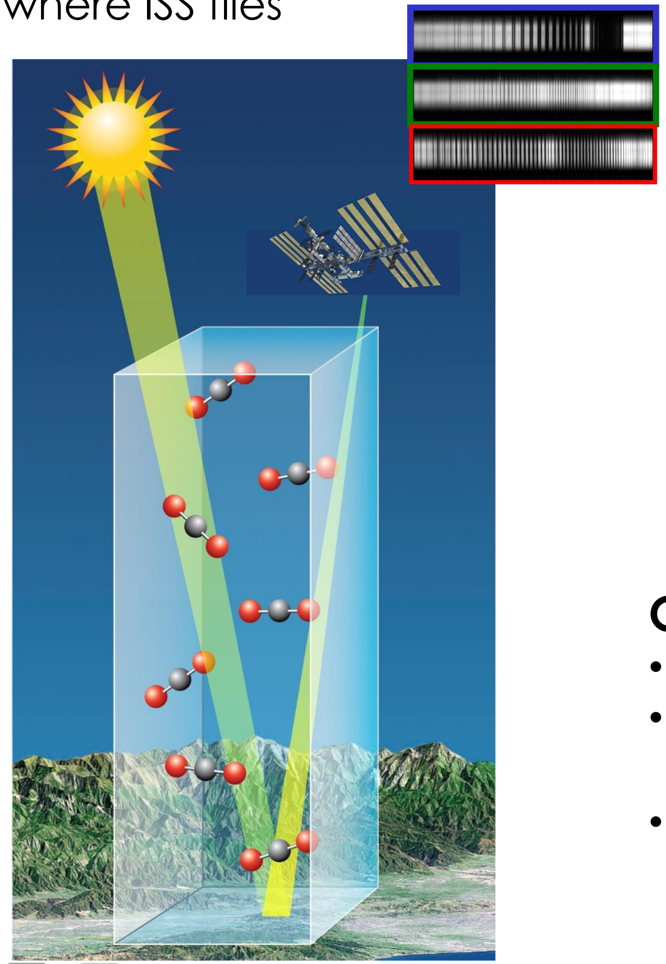


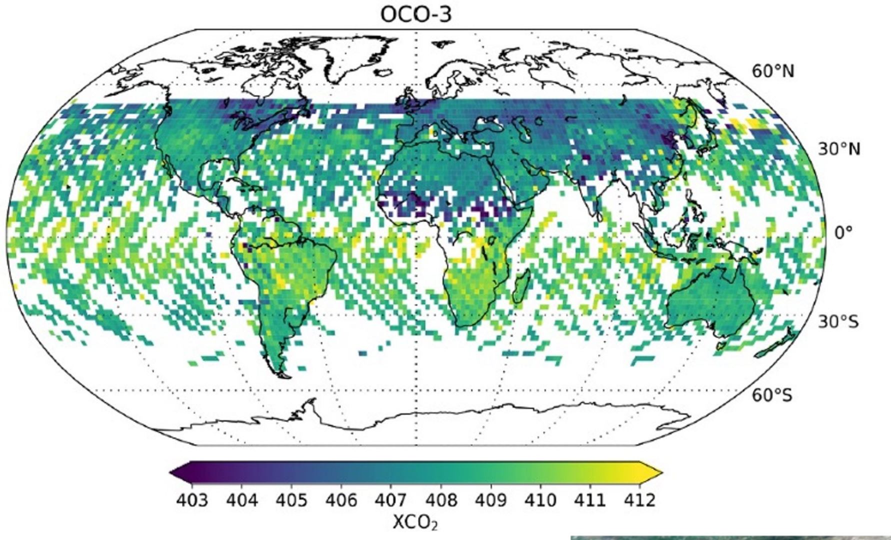
OCO-2 Measurements:

- Global
- Precise
- Small Footprints

OCO-3 Measurement Approach

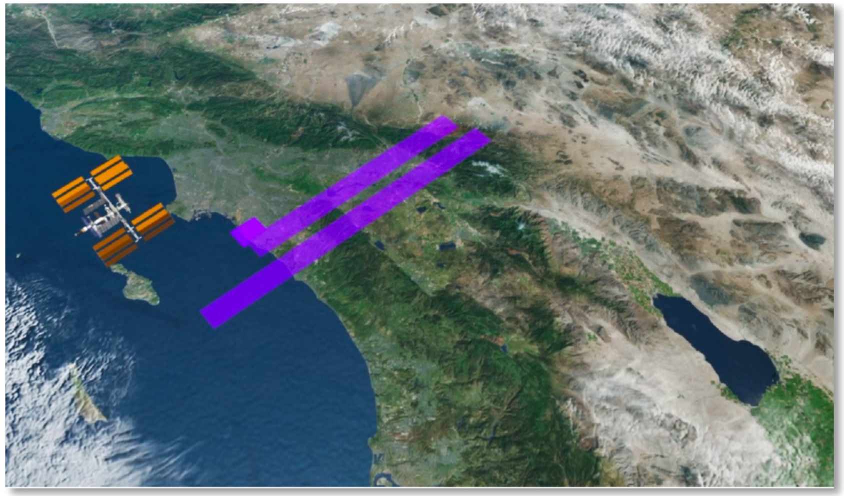
Collect spectra of CO_2 & O_2 absorption in reflected sunlight over where ISS flies





OCO-3 Measurements:

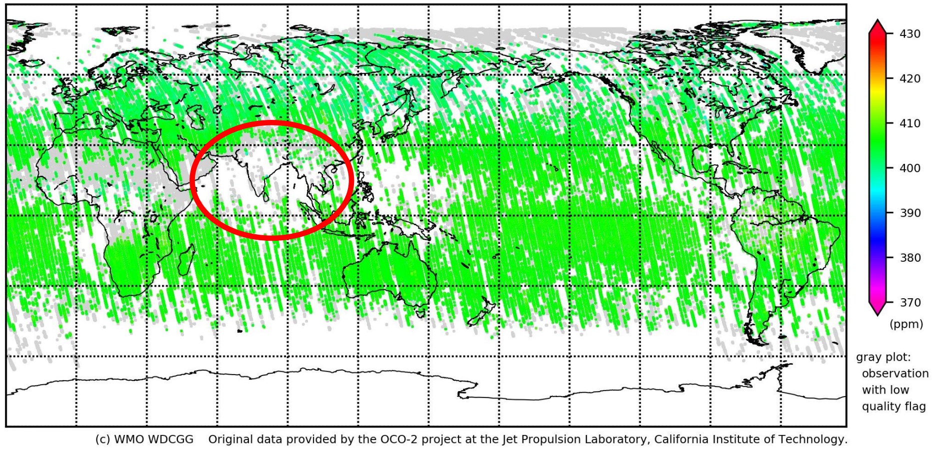
- 52 Degrees North/South Latitude
- More Precise and Denser Footprint than OCO-2
- Mapping Capability of 80 x 80 km

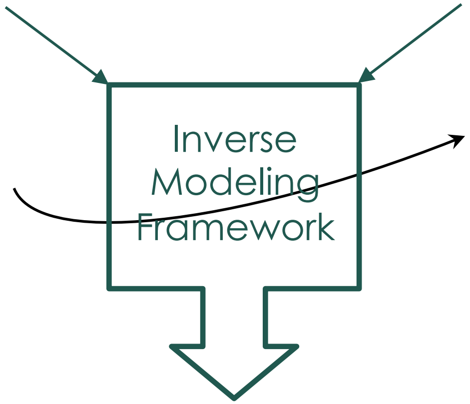


OCO-3 coverage is denser than OCO-2 but geographically more limited. In the regions where both datasets overlap, there will be science and applications that can be explored.

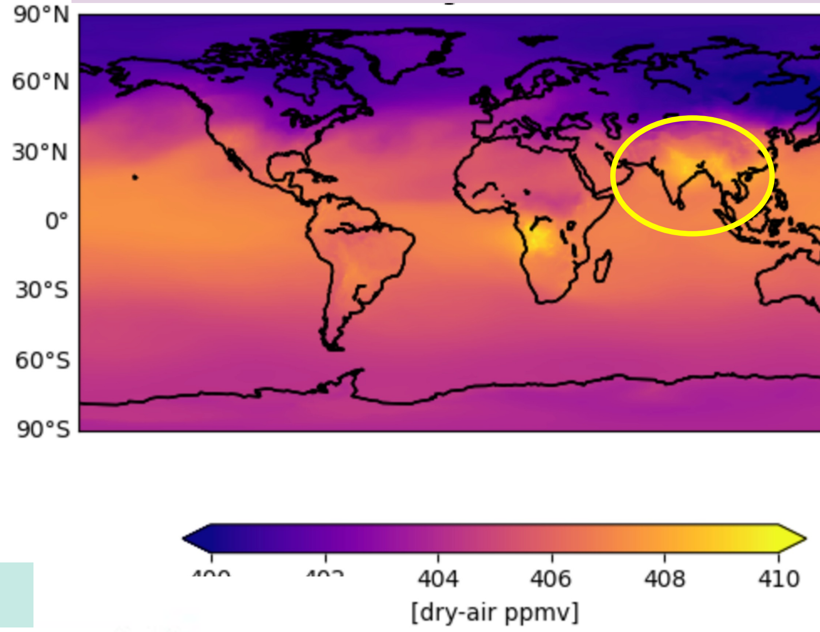
Higher-Order Products From Level 2 XCO_2 Data

Level 2 Product (August 2018)

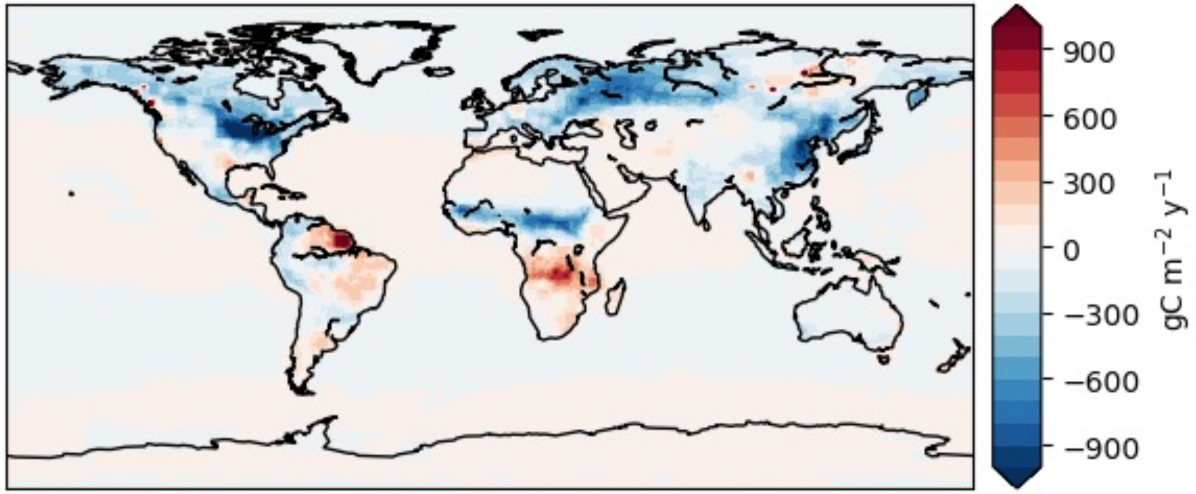




Level 3 (Aug 2018) – Gap-Filled XCO_2 Product

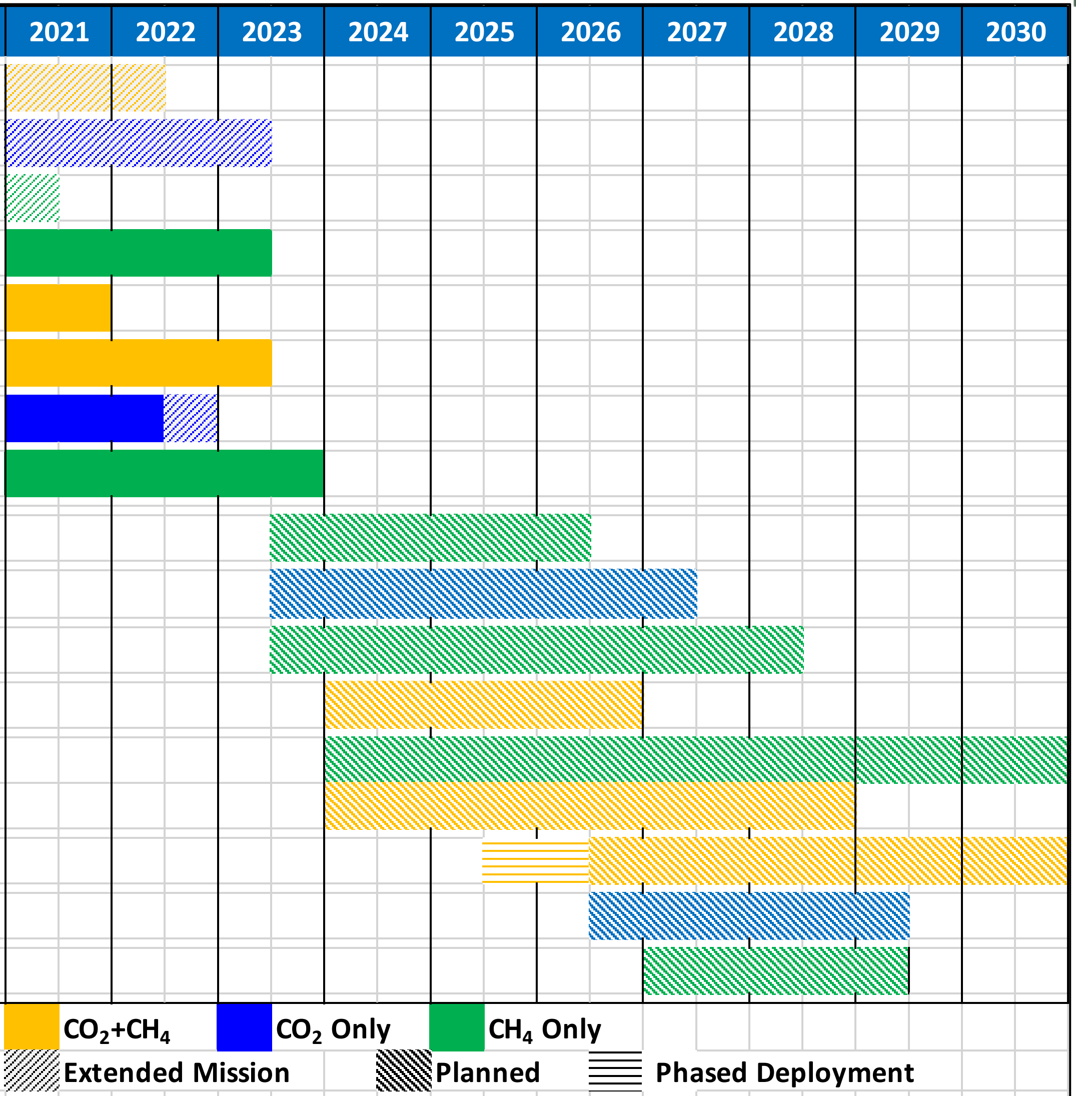


Level 4 (Aug 2018) – CO_2 Flux Product



The Growing Fleet of GHG Satellites

Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan	●	●	●	
OCO-2	NASA/USA	●		●	
GHGSat-D - Claire	GHGSat/Canada		●		●
Sentinel 5P TROPOMI	ESA/Europe		●	●	
GaoFen-5 GMI	CHEOS/China	●	●	●	
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan	●	●	●	
OCO-3	NASA/USA	●			
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada		●		●
MethaneSAT	EDF/USA	●	●		●
MicroCarb	CNES/France	●		●	
Carbon Mapper[1]	Carbon Mapper LLC/USA	●	●	●	●
GeoCarb	NASA/USA	●	●	●	
MetOp Sentinel-5 series	EC Copernicus/Europe		●	●	
GOSAT-GW	JAXA-NIES-MOE/Japan	●	●	●	
CO2M	EC Copernicus/Europe	●	●	●	
CO2Image	DLR/Germany	●		●	
MERLIN	DLR/Germany-CNES/France		●	●	

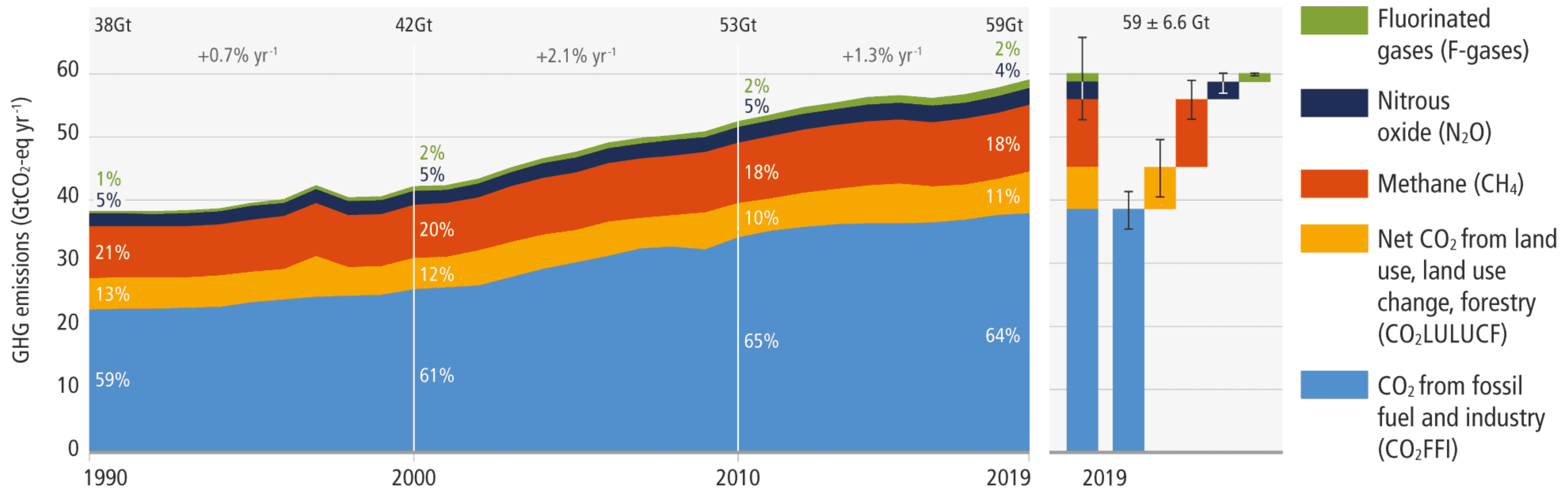


[1] Carbon Mapper is a public/private partnernship between California and Carbon Mapper LLC.

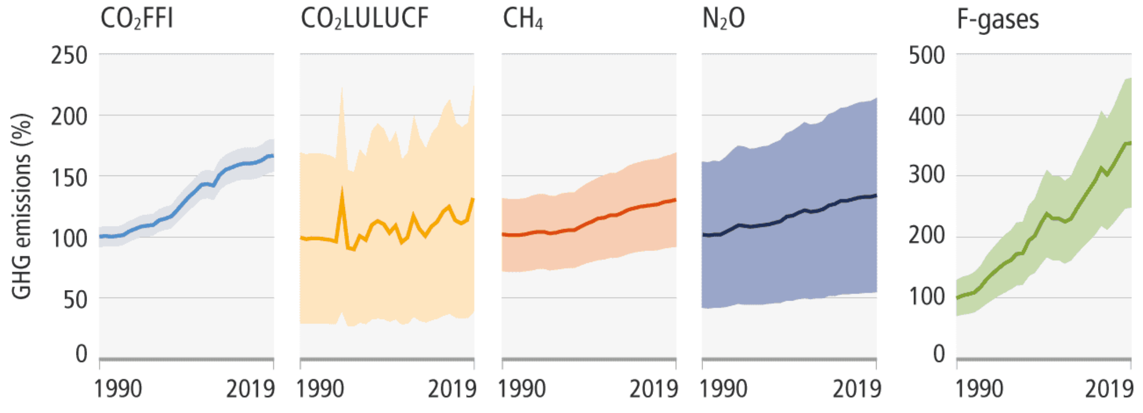
Global Net Anthropogenic GHG Emissions (GtCO2-eq yr-1) 1990–2019

Global net anthropogenic emissions have continued to rise across all major groups of greenhouse gases.

a. Global net anthropogenic GHG emissions 1990–2019 [5]



b. Global anthropogenic GHG emissions and uncertainties by gas – relative to 1990



	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2 FFI	38±3	15	167
CO_2 LULUCF	6.6±4.6	1.6	133
CH_4	11±3.2	2.4	129
N_2O	2.7±1.6	0.65	133
F-gases	1.4±0.41	0.97	354
Total	59±6.6	21	154

The solid line indicates central estimate of emissions trends. The shaded area indicates the uncertainty range.

Global net anthropogenic GHG emissions include CO_2 from fossil fuel combustion and industrial processes; net CO_2 from land use, land use change and forestry; methane; nitrous oxide; and fluorinated gases. (IPCC, AR6, 2022)

Agriculture, Forestry, and Other Land Use (AFOLU)

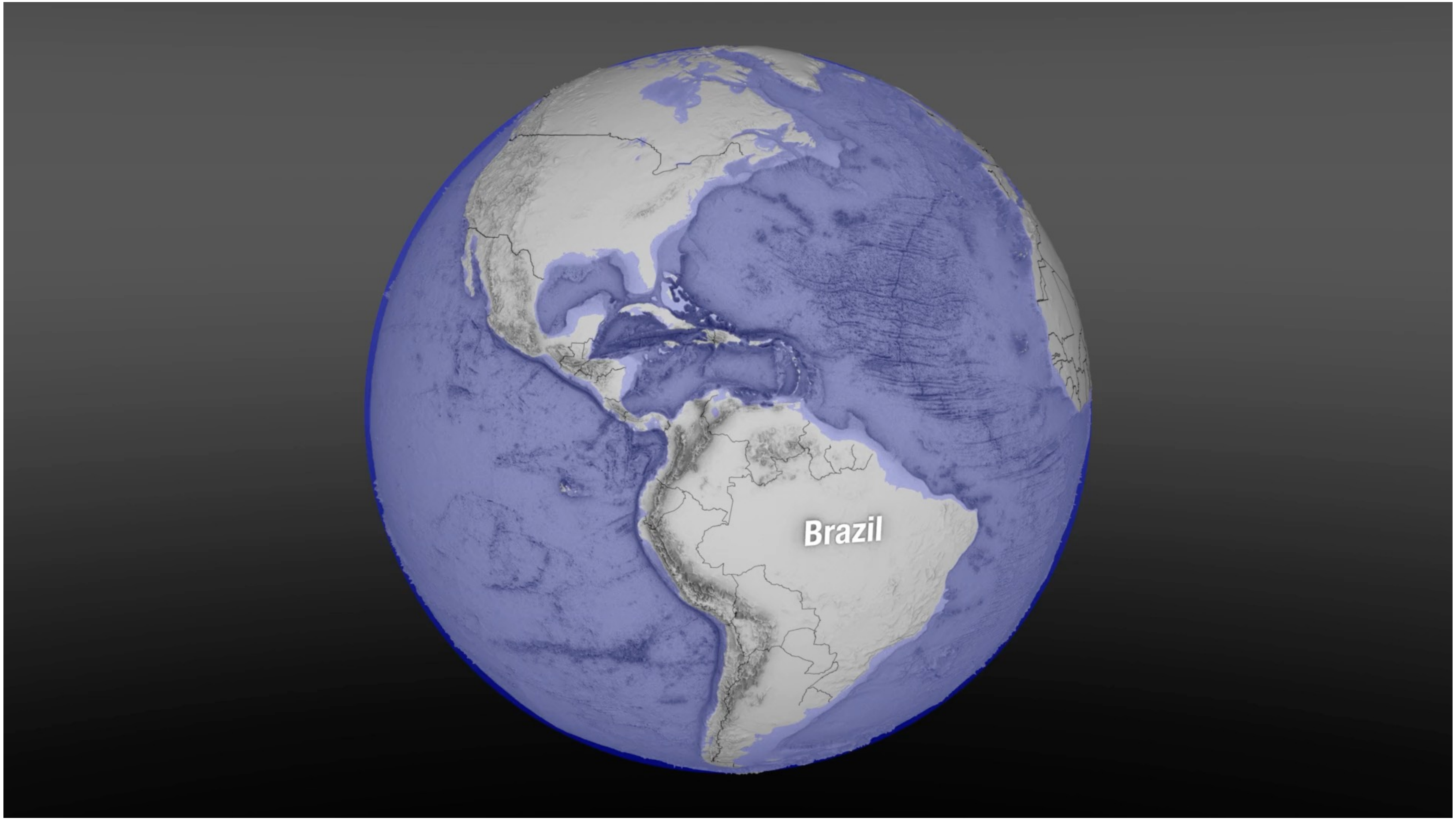
- 2nd largest source of GHG emissions – most uncertain sector (called Land Use and Land Use Change and Forestry [LULUCF] by UNFCCC)
- The AFOLU (managed land) sector, on average, accounted for just under a quarter (~10–12 GtCO2eq/yr) of global total anthropogenic greenhouse gas (GHG) emissions in the period 2010-2019 (medium confidence). At the same time managed and natural terrestrial ecosystems were a carbon sink, absorbing around one third of anthropogenic CO_2 emissions (IPCC, 2022).
- Between 2020 and 2050, mitigation measures in forests and other natural ecosystems provide the largest share of the economic (up to USD100 tCO_2-eq) AFOLU mitigation potential, followed by agriculture and demand-side measures (IPCC, 2022).

Landsat's Critical Role – Forest Management

- Landsat satellites provide key data for forest monitoring and management across the planet.
- Landsat gives us consistent views of the health, composition, and extent of forest ecosystems as they change over time.
- Landsat satellites have recorded global forest conditions since the 1970's. The U.S. Geological Survey provides this valuable data to the public at no cost.
- July 23, 2022, Landsat marked a half century of providing a continuous record of the Earth's land surfaces.


Credit: USGS

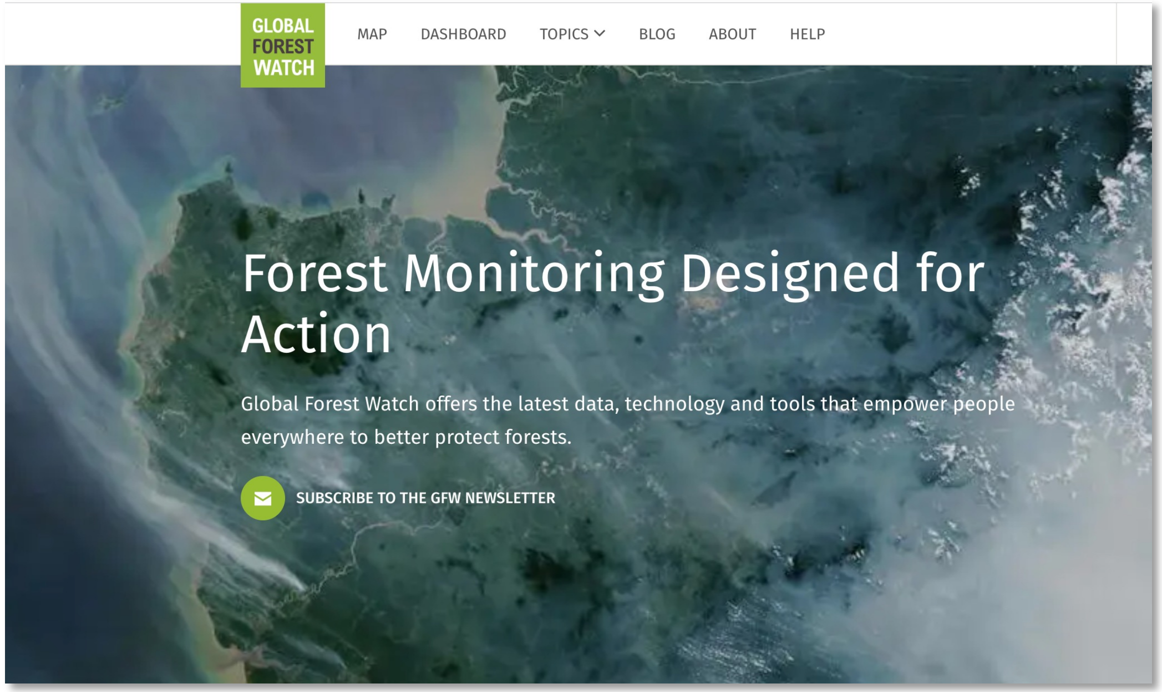
Deforestation in the Amazon



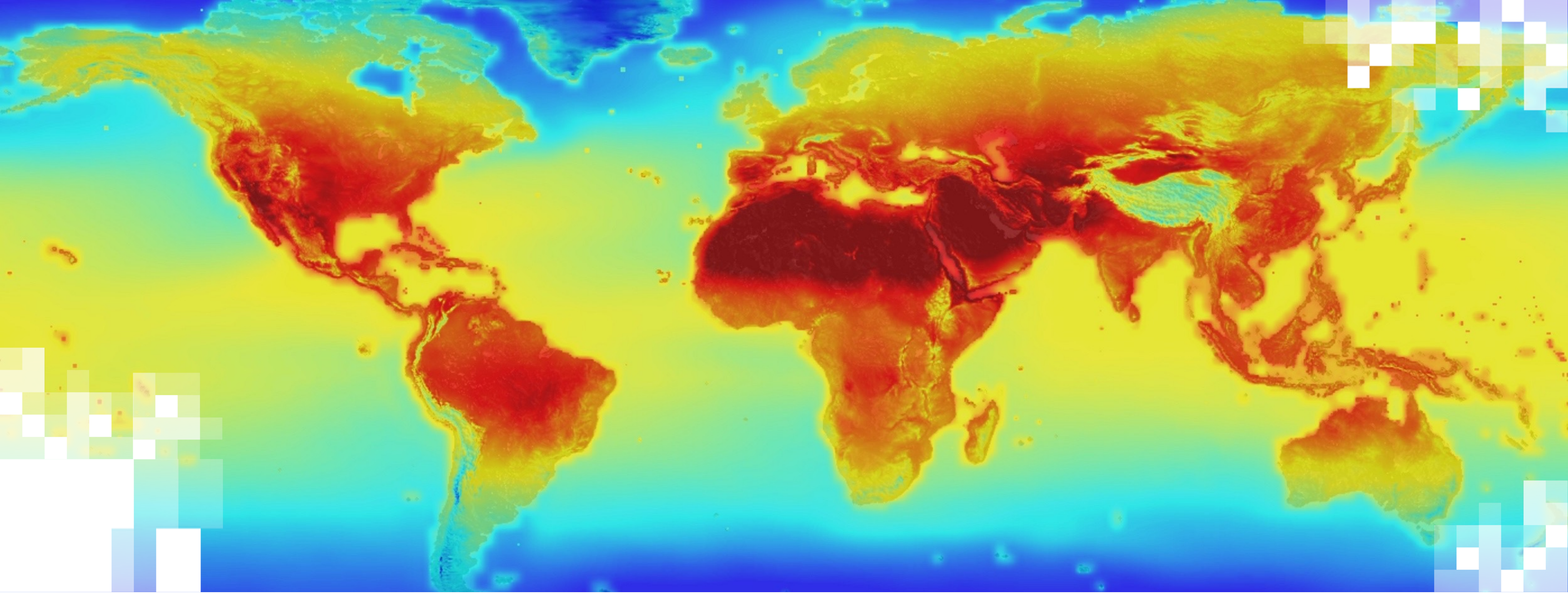
Credit: NASA SVS

Global Forest Watch – World Resources Institute

- Global Forest Watch (GFW) is an online platform that provides data and tools for monitoring forests.
- GFW allows anyone to access near real-time information about where and how forests are changing around the world.
- Algorithms developed by the Global Land Analysis and Discovery (GLAD) laboratory in the Department of Geographical Sciences at the University of Maryland
- Landsat-based product at 30-meter spatial resolution



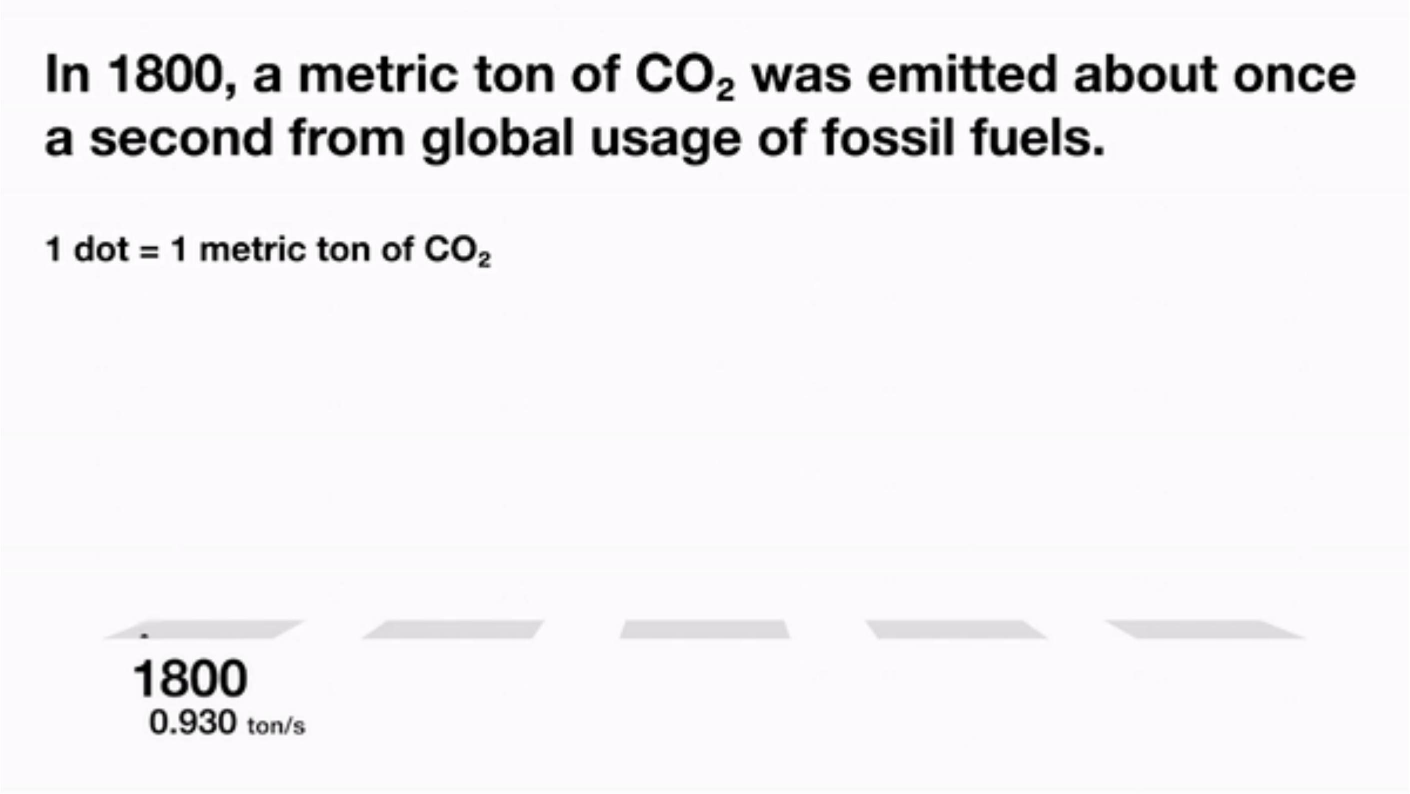
Credit: USGS



Demo – Global Forest Watch

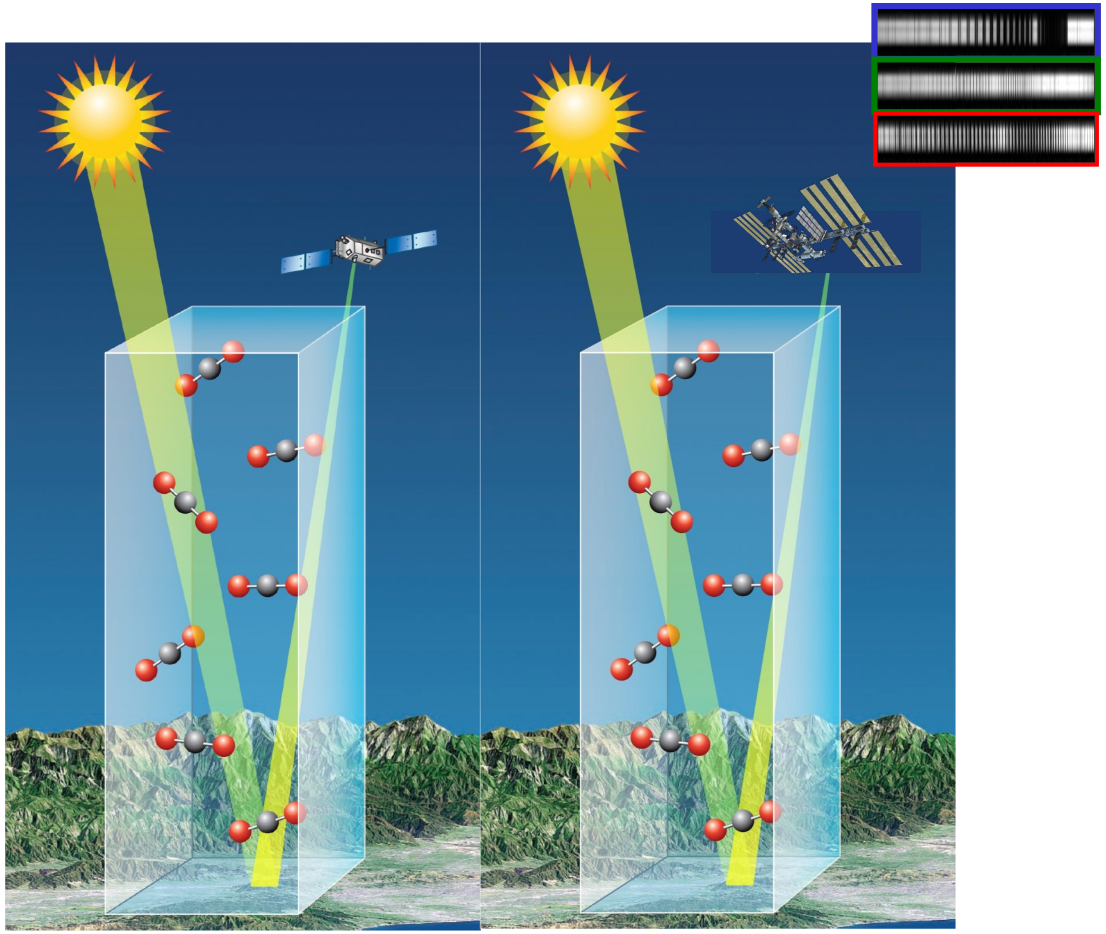
Thank You!

Atmospheric CO_2 Levels Over the Past Two Centuries

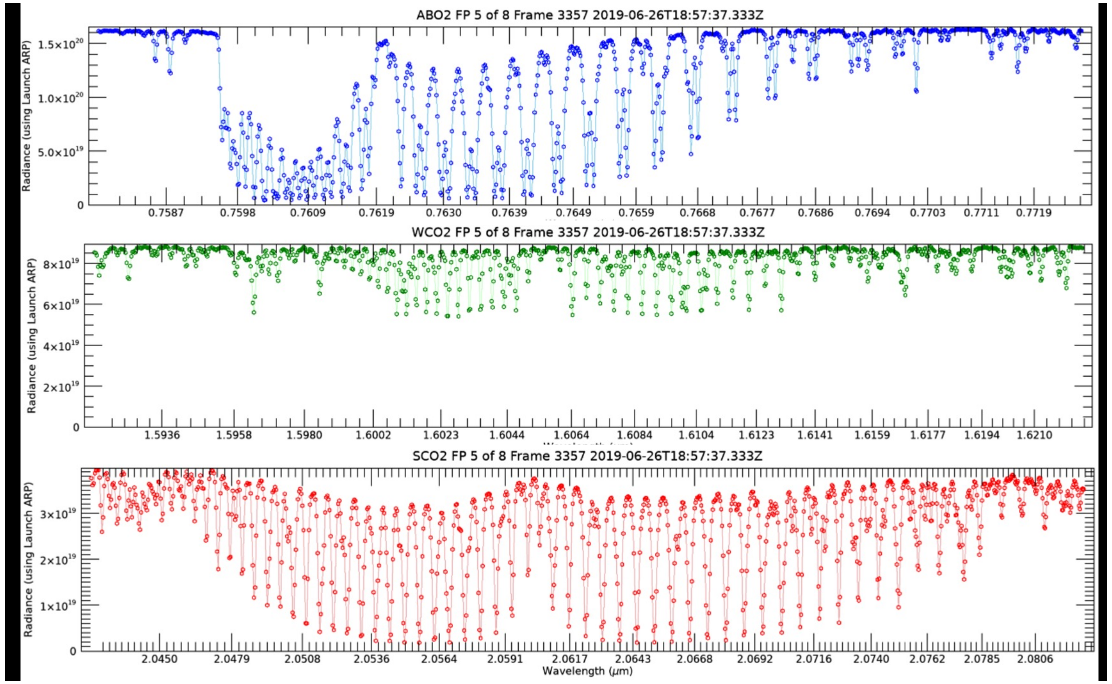


The amount of carbon dioxide released due to burning fossil fuels has been increasing since the start of the Industrial Revolution in the mid-18th century. In 1900, almost 2 billion metric tons of CO_2 were released due to fossil fuel usage. The Carbon Dioxide Information Analysis Center (CDIAC) shows that over 35 billion metric tons of CO_2 were released in 2014. Credit: CDIAC and NASA Global Climate Change.

Recap of the XCO_2 Measurement



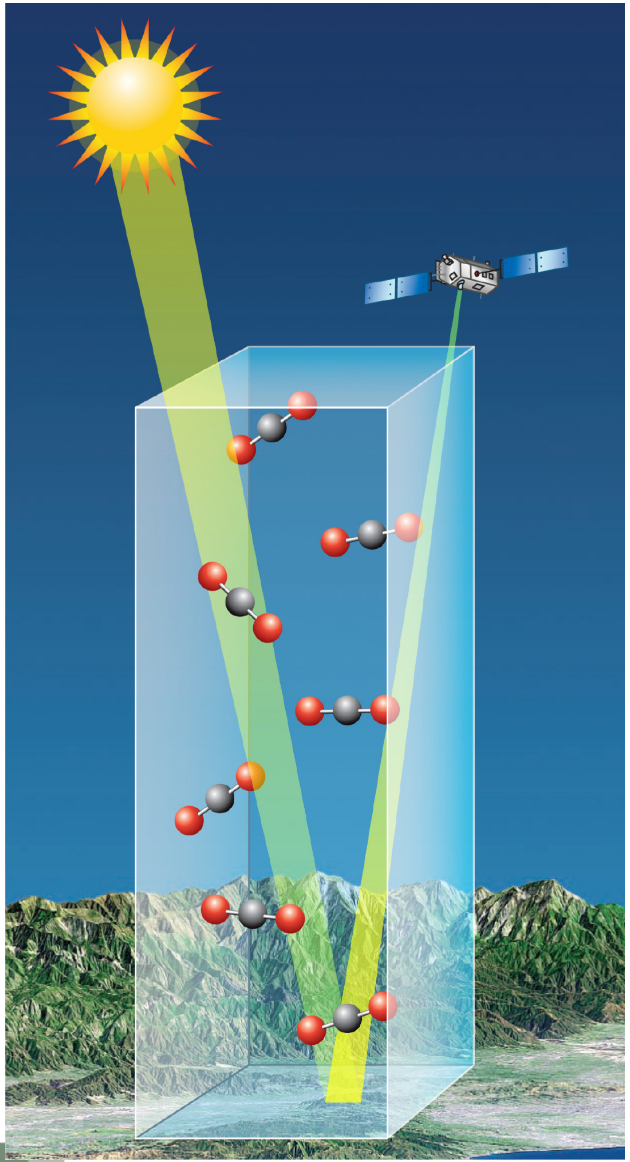
XCO_2 is the column average volume mixing ratio. This is a measure of the amount of carbon dioxide in the atmosphere within the column.



Gas molecules in the Earth's atmosphere absorb the sunlight at specific wavelengths, creating "fingerprints" that can be detected by a spectrometer.

A spectrometer creates spectra, or photos of these "fingerprints". Then the absorption levels shown in these spectra, like a captured image, tells us how many molecules were in the region where the instrument measured.

What is the XCO_2 measurement and how is it measured?



XCO_2 is the column average volume mixing ratio. This is a measure of the amount of carbon dioxide in the atmosphere.

Gas molecules in the Earth's atmosphere absorb the sunlight at specific wavelengths. When light passes through the Earth's atmosphere, the gases that are present leave a distinguishing “fingerprint” that can be captured.

The OCO-2 and OCO-3 spectrometers, working like cameras, detect these molecular “fingerprints”. Then the absorption levels shown in these spectra, like a captured image, tells us how many molecules were in the region where the instrument measured.