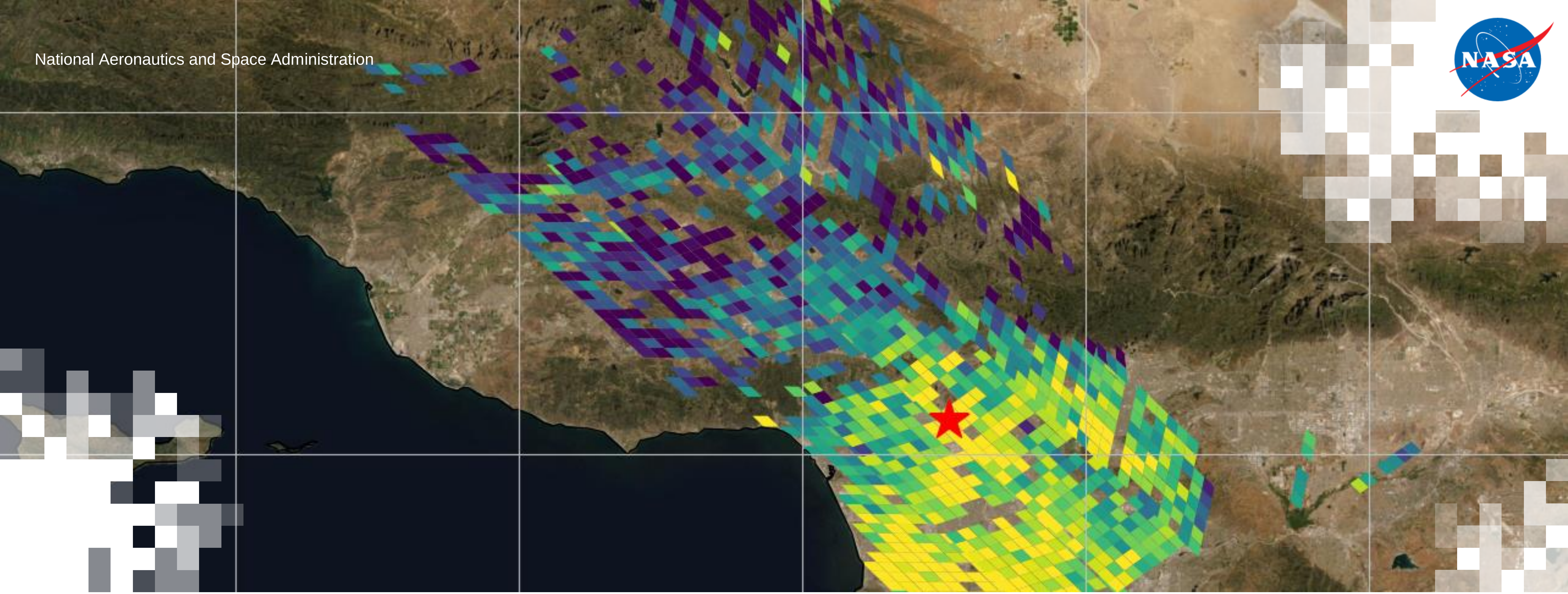
National Aeronautics and Space Administration



# Applications of Carbon Dioxide Measurements for Climate-Related Studies

## Part 3: $CO_2$ Measurements Over a Large Urban Area

**Abhishek Chatterjee**, OCO-3 Project Scientist (NASA JPL), **David Moroni**, OCO-2/3 ARSET Team Developer (NASA JPL), & **Karen Yuen**, OCO-2/3 Applications Lead (NASA JPL)

July 16, 2024

# 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: Aug. 14, 2024**

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

# Part 3 – Trainers

**Abhishek Chatterjee**

OCO-3 Project Scientist, OCO-2 Deputy Project Scientist

JPL/NASA


**David Moroni**

OCO-2/3 ARSET Team Developer

JPL/NASA


**Karen Yuen**

OCO-2/3 Applications Lead

JPL/NASA

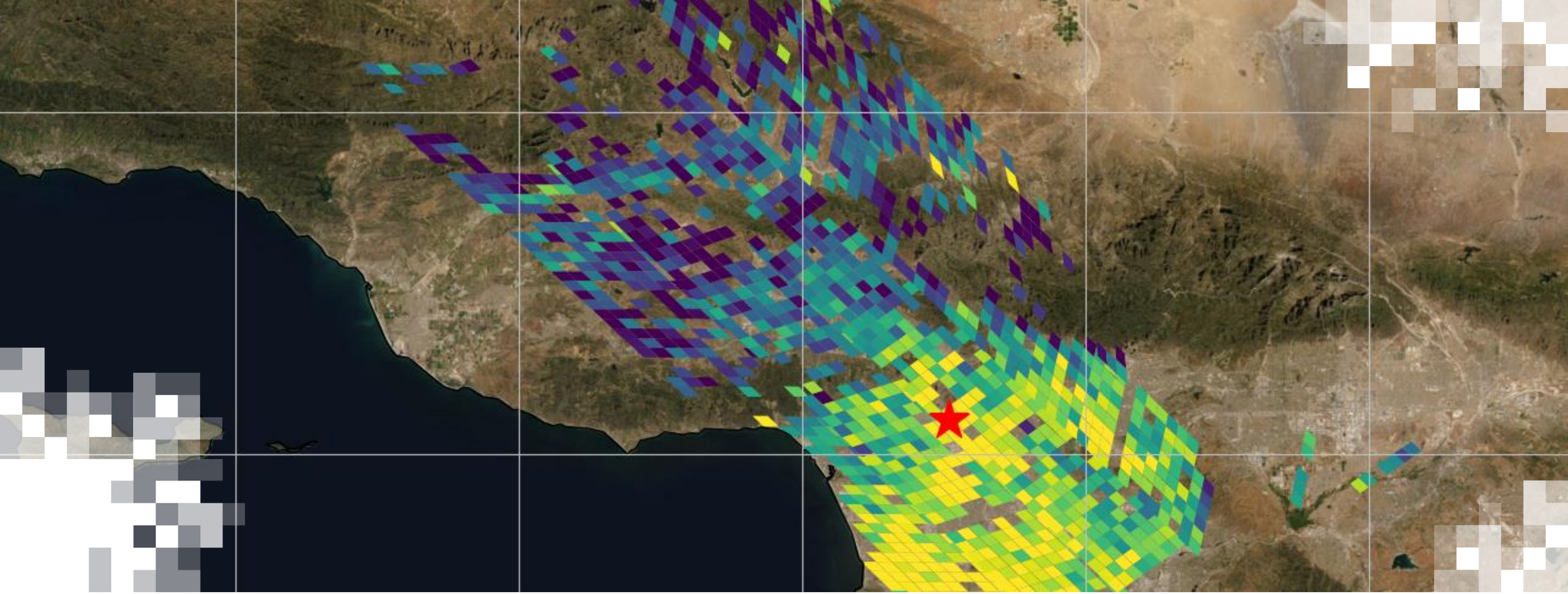
# Part 3 Objectives

By the end of Part 3, participants will be able to:

- Recognize the importance of observing carbon dioxide over metropolitan areas.
- Identify important aspects of space-based carbon dioxide measurements over urban areas.
- Access, subset, download, and analyze a multi-year OCO-3 SAM dataset using a provided Jupyter notebook.
- Visualize OCO-3 SAM data over urban areas and be able to do interpretive and comparative analysis.

# How to Ask Questions

- Please write your questions in the Questions box and we will answer 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.

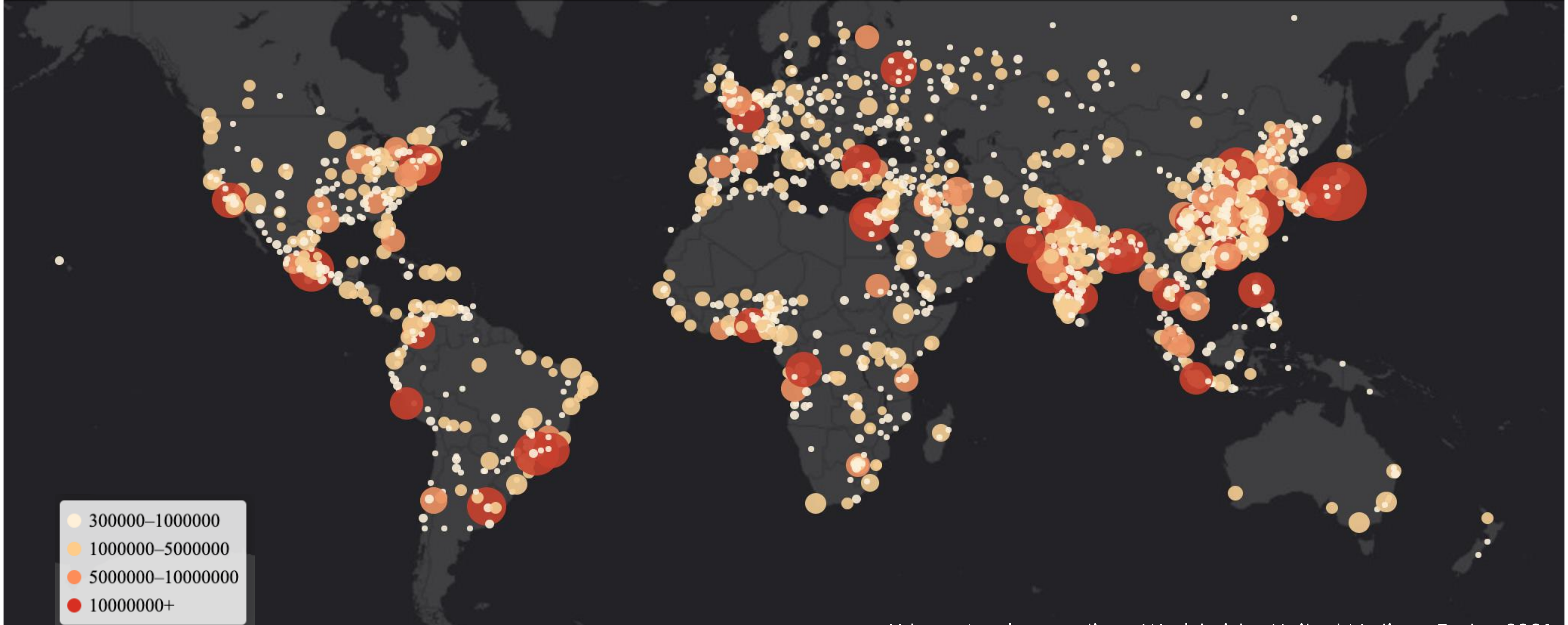


Part 3:

## Section 1: Urban Areas and $CO_2$ Emissions

# Urban Areas

**Urban Areas** → Where more than 50% of the global population reside, cover only 2% of the world's surface, consume 78% of the world's energy, and are responsible for **more than 60% of fossil fuel $CO_2$ emissions.**



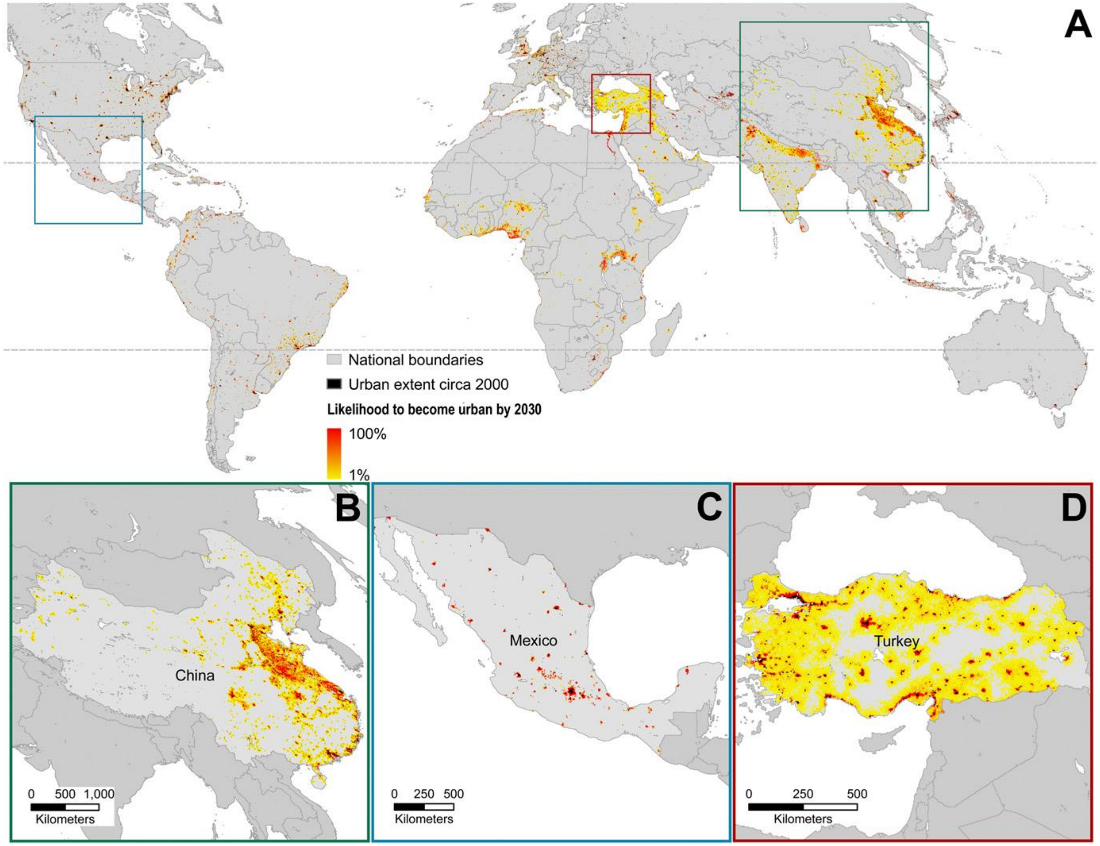

Urban Agglomerations Worldwide, United Nations Data, 2021

# Expected Growth of Urban Areas

Global forecasts of probabilities of urban expansion, 2030:

A. Significant variation in the amount and likelihood of urban expansion.
B. Much of the forecasted expansion is likely to occur in eastern China.
C. Some regions have high probability of urban expansion in specific locations.
D. Others have large areas of low probability of urban growth.

Dashed lines denote northern and southern boundaries of the tropics. From [Seto et al. 2012](#) (PNAS)

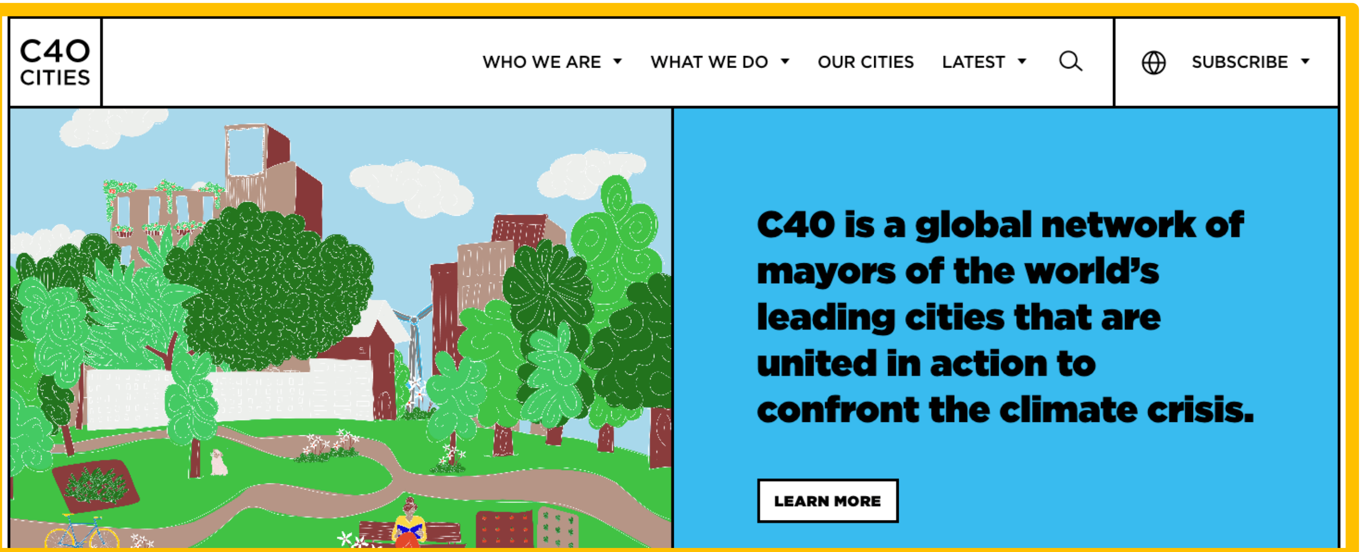



With 68% of the world's population projected to live in urban areas by 2050, it is not surprising to see various entities now taking a keen interest in climate action, monitoring and measuring GHG emissions from cities.

See more resources on [Urbanization](#) and [Environmental Impacts of Urban Growth](#).

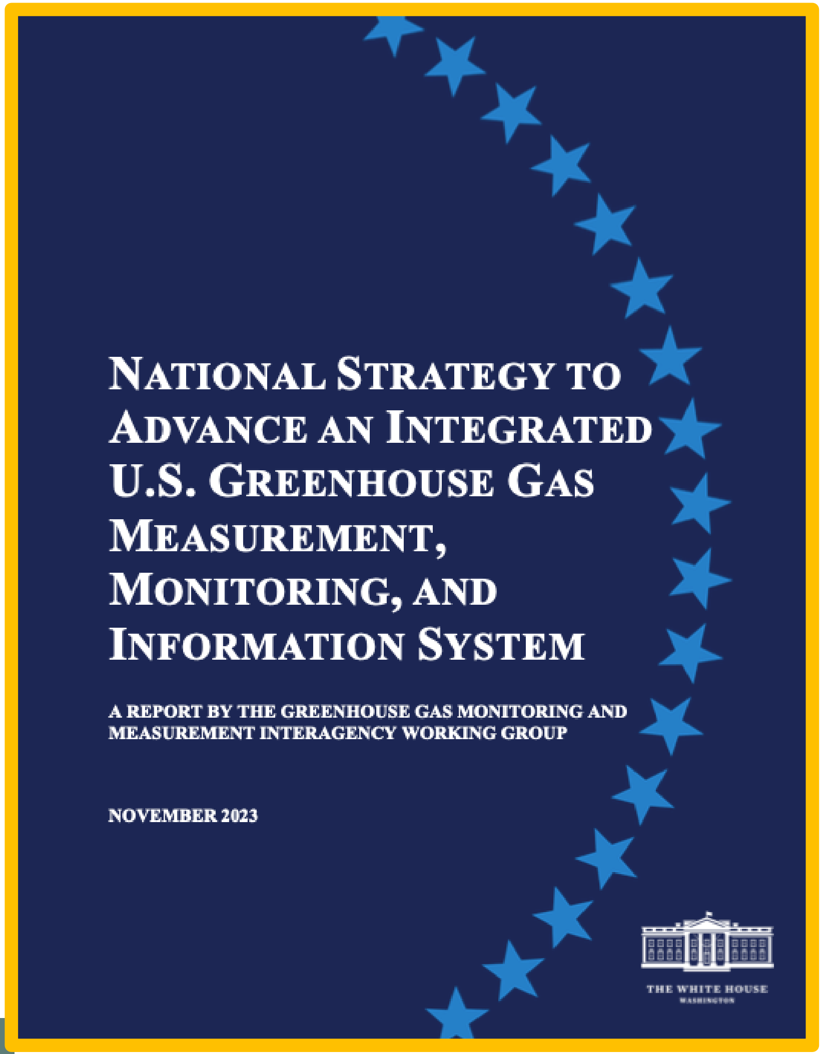
# Significance of Urban GHG Emission Monitoring


WORLD BANK GROUP





# Urban-Scale Prototype for the U.S. GHGMMIS Framework


NATIONAL STRATEGY TO ADVANCE AN INTEGRATED U.S. GREENHOUSE GAS MEASUREMENT, MONITORING, AND INFORMATION SYSTEM

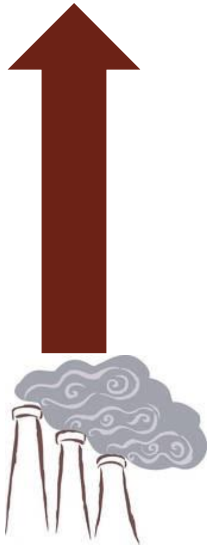
A REPORT BY THE GREENHOUSE GAS MONITORING AND MEASUREMENT INTERAGENCY WORKING GROUP

NOVEMBER 2023

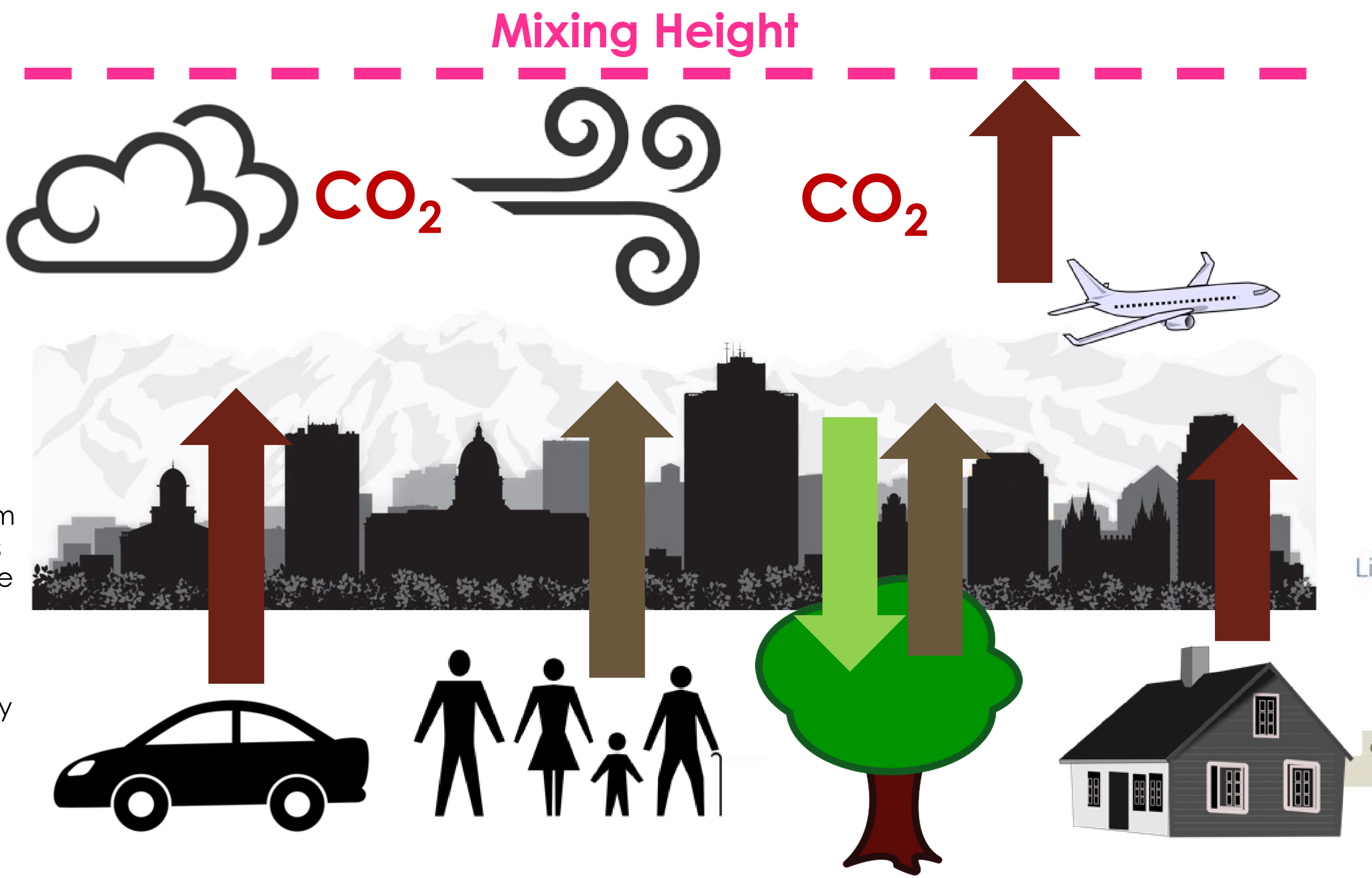
THE WHITE HOUSE

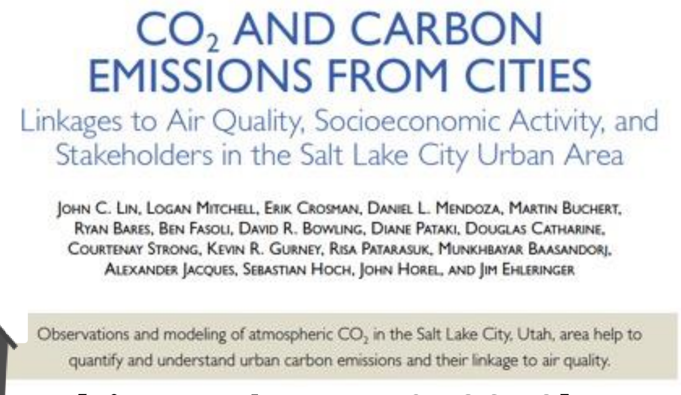
Conceptual illustration of how an urban-scale prototype could look like.

# Sources of Carbon Emission in Cities



Emissions from power plants (often outside cities) that generate electricity consumed by cities.



$CO_2$ AND CARBON EMISSIONS FROM CITIES

Linkages to Air Quality, Socioeconomic Activity, and Stakeholders in the Salt Lake City Urban Area

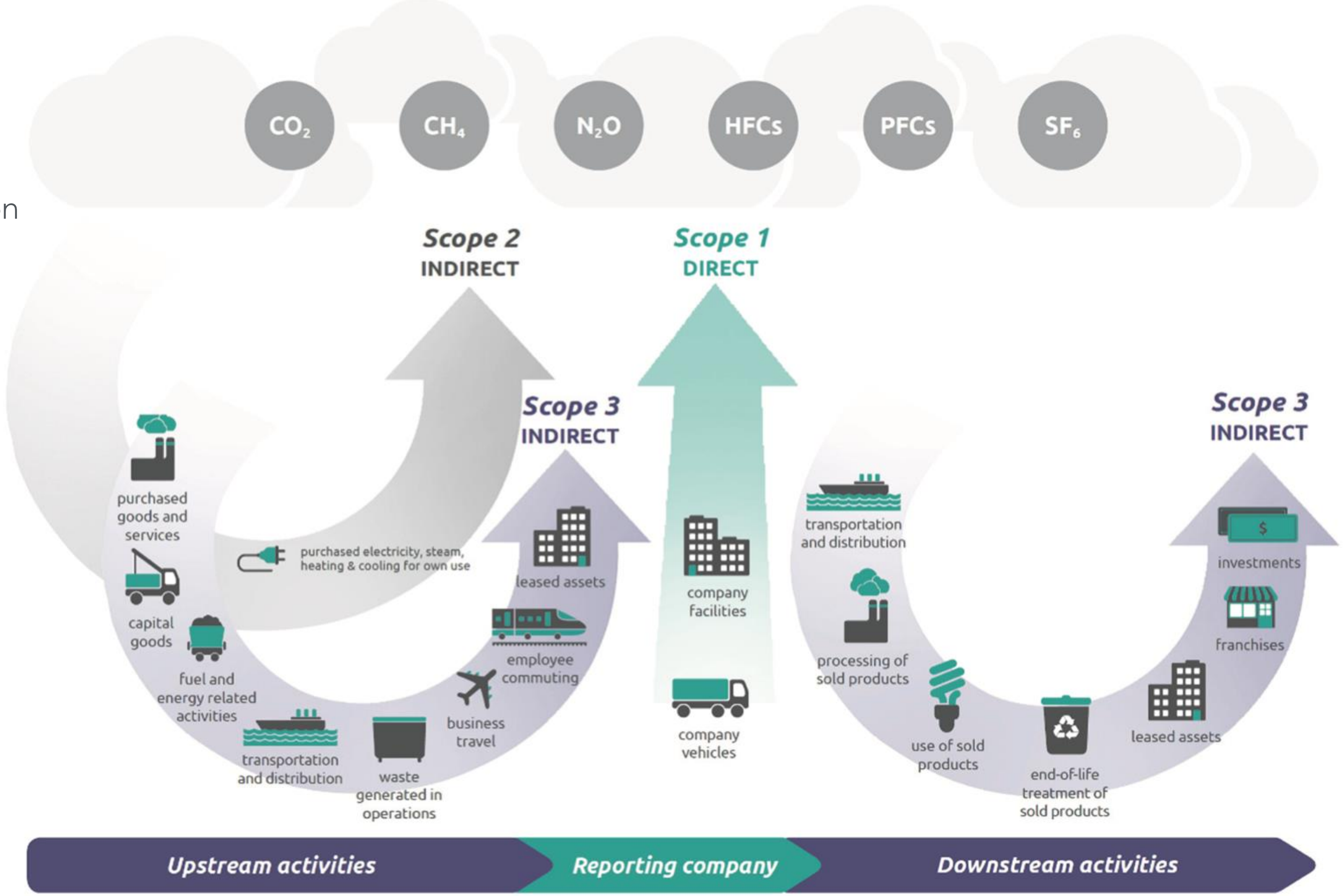
John C. Lin, Logan Mitchell, Erik Crosman, Daniel L. Mendoza, Martin Buchert, Ryan Bares, Ben Fasoli, David R. Bowling, Diane Pataki, Douglas Catharine, Courtenay Strong, Kevin R. Gurney, Risa Patarasuk, Munkhbayar Baasandorj, Alexander Jacques, Sebastian Hoch, John Horel, and Jim Ehleringer

Observations and modeling of atmospheric $CO_2$ in the Salt Lake City, Utah, area help to quantify and understand urban carbon emissions and their linkage to air quality.

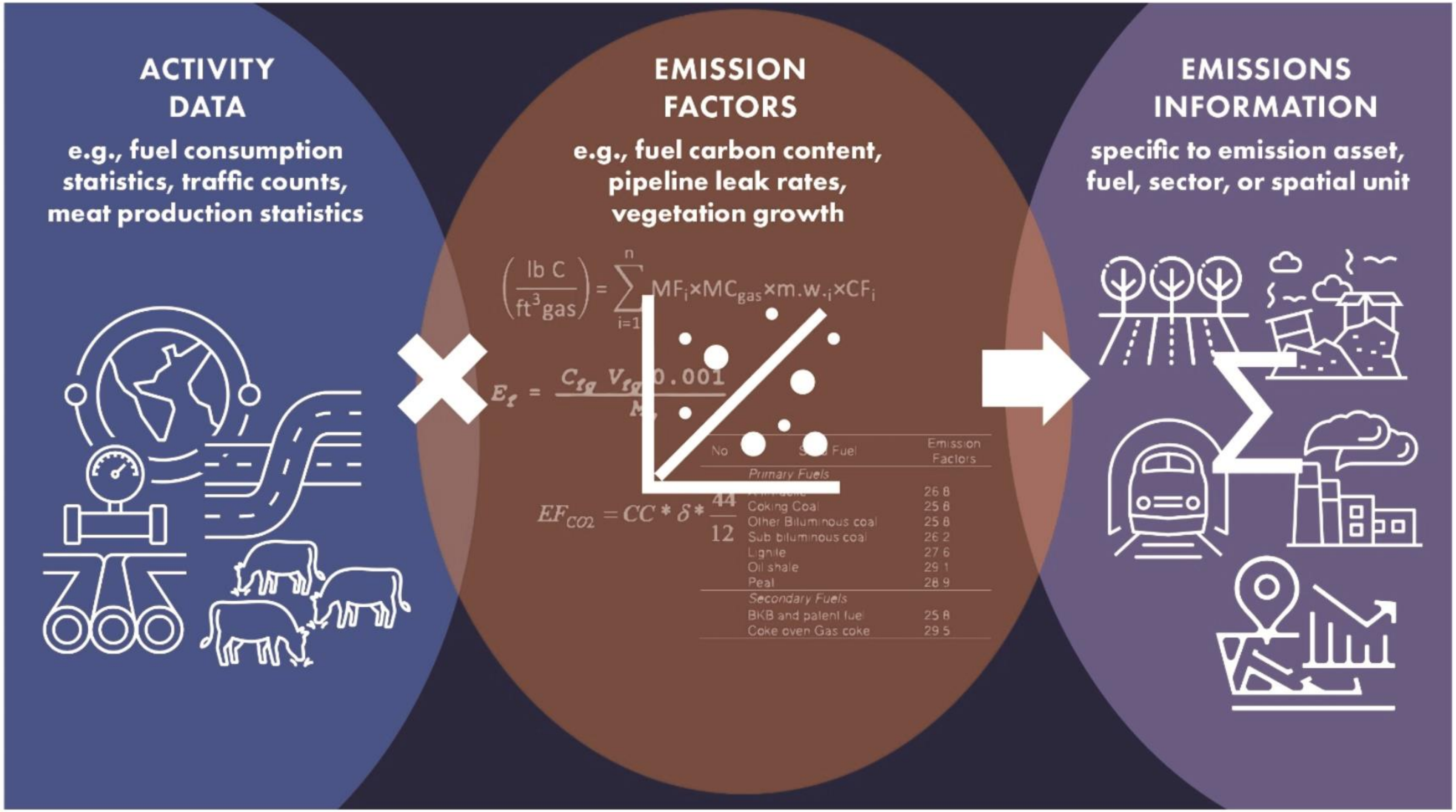
**(Lin et al., BAMS, 2018)**

# Classification of Urban GHG Emissions

EPA Guidance on Scope 1, 2 and Scope 3



# Bottom-Up Estimation of Urban Emissions

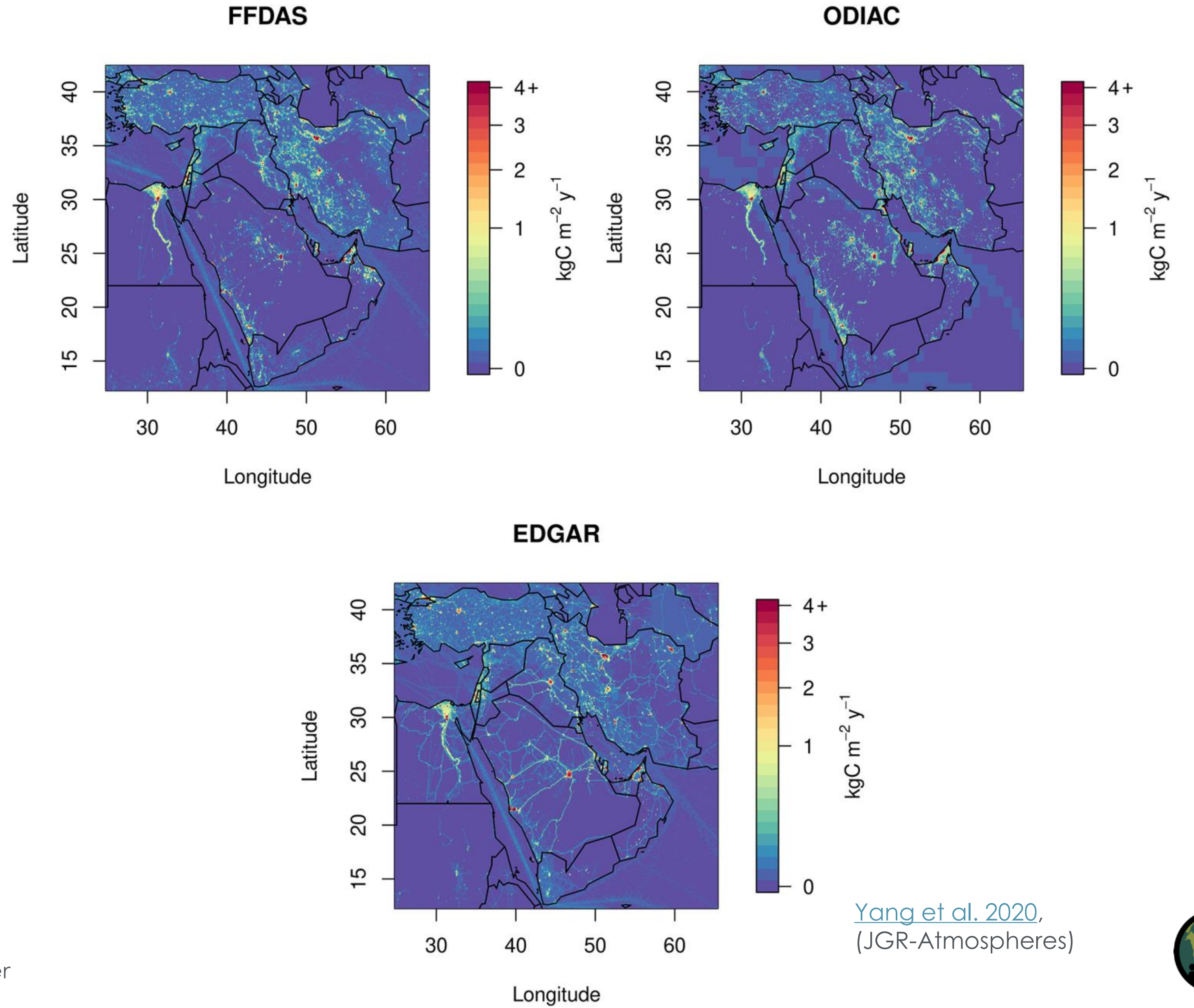



Activity-based approaches **multiply activity data** (representative indicators or drivers of greenhouse gas [GHG] emissions, such as fuel consumption statistics, population, equipment count, traffic counts) **by an emission factor** (a coefficient that represents the emission or removal of a GHG per unit of activity) **to produce GHG emission totals** or emissions by sector.

Greenhouse Gas Emissions Information for Decision Making, NAS 2022

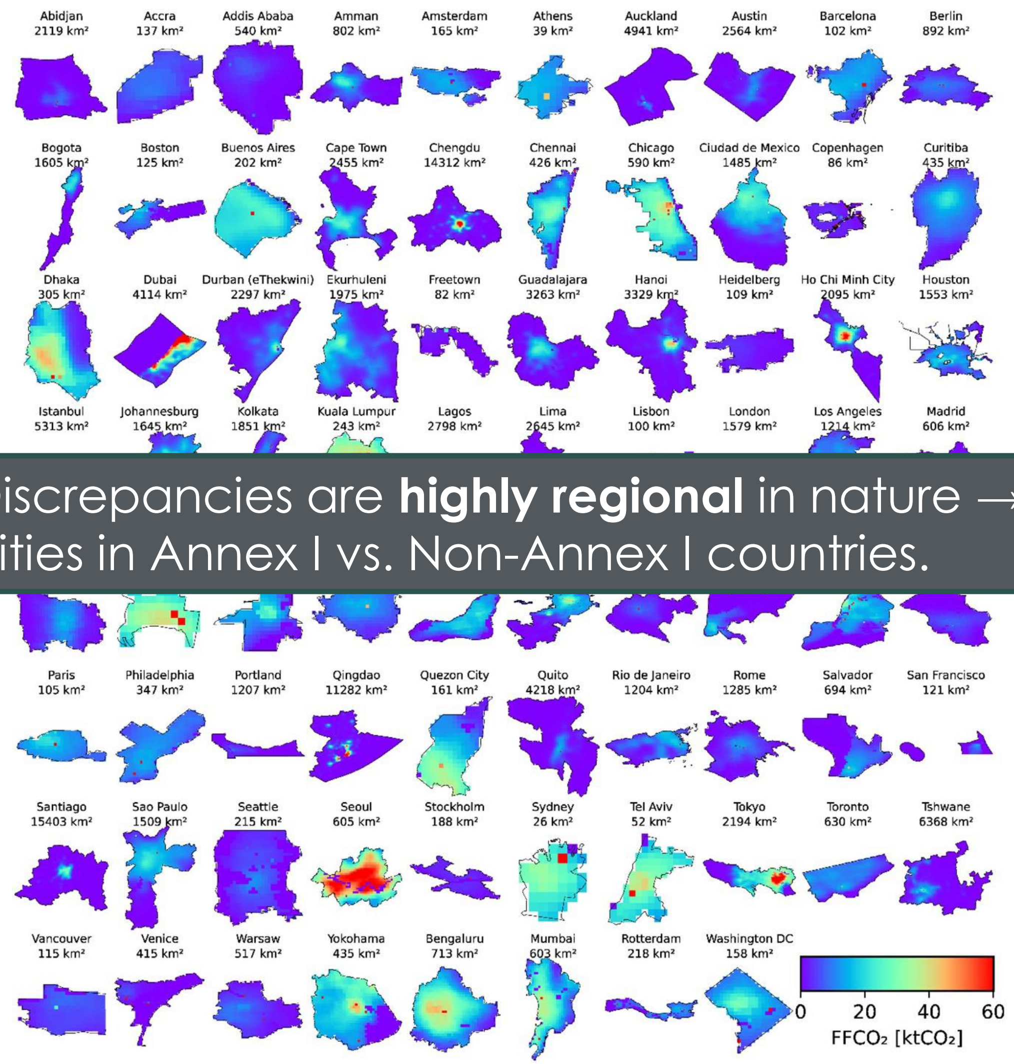
# Bottom-Up Estimation of Urban Emissions – Example

- Comparison of global fossil fuel $CO_2$ emissions inventory representations of the Middle East, shown with square root scale: FFDAS, ODIAC, and EDGAR.
- The three representations differ in both spatial distribution and magnitude of emissions.
- Note that all inventories are shown at their native resolutions.



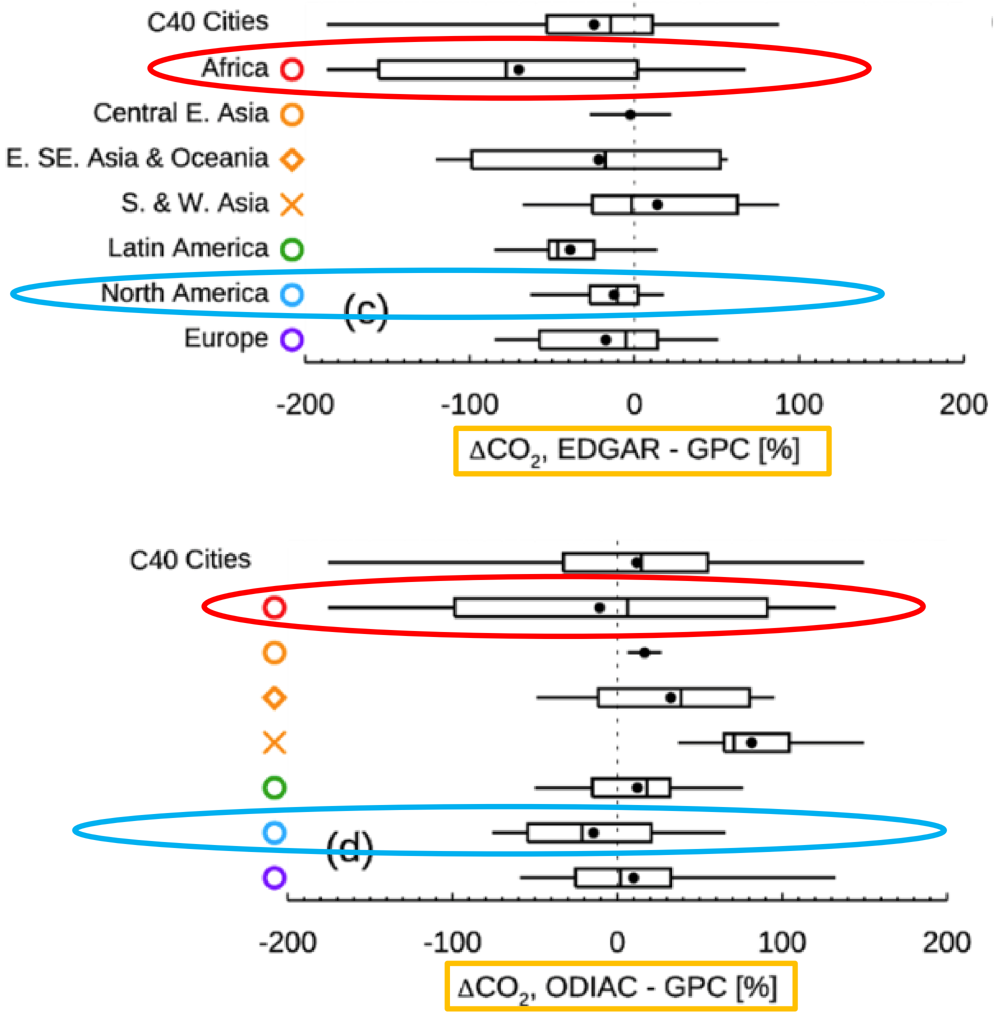

Yang et al. 2020, (JGR-Atmospheres)

# Bottom-up emission inventories are improving, but differences persist.



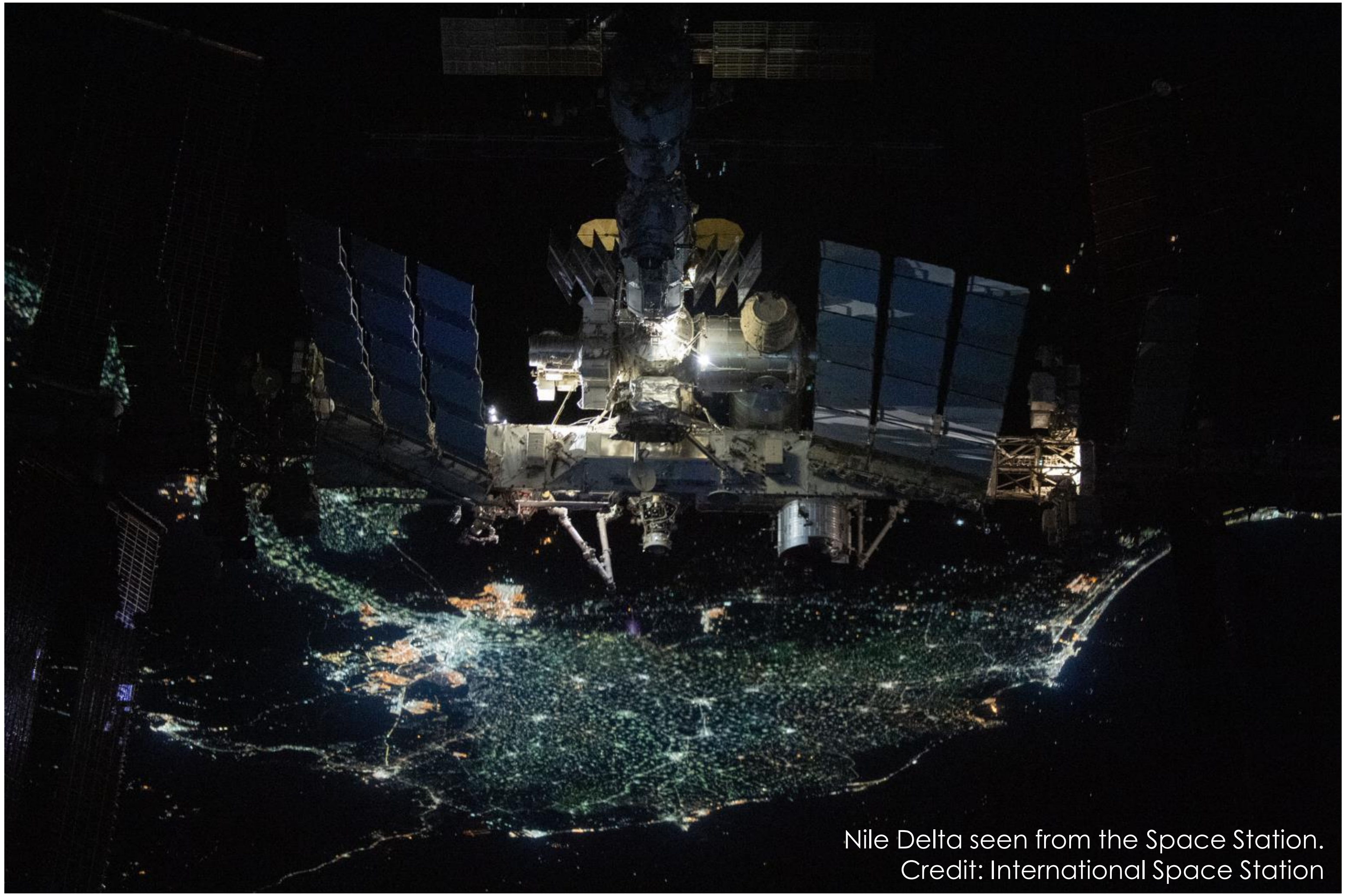

Discrepancies are **highly regional** in nature → cities in Annex I vs. Non-Annex I countries.

**Figure 1.** Overview of the 78 C40 cities analyzed in this study. The area size for each city is shown. Color scales show ODIAC's fossil fuel $CO_2$ emissions (unit: $ktCO_2\ km^{-2}\ yr^{-1}$, year 2015).

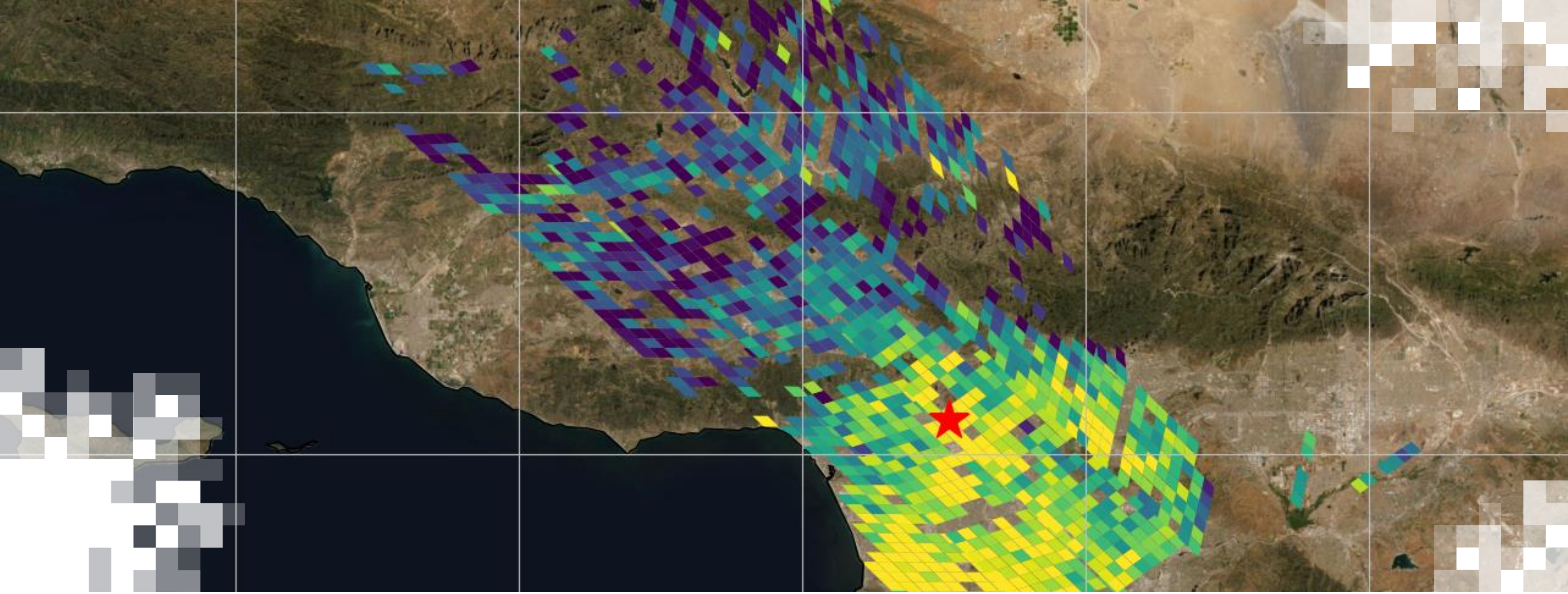



Ahn et al., 2023, *Environ. Res. Lett.*

# Can space-based data provide a check on estimates derived from bottom-up inventories, book-keeping, and modeling studies?



Nile Delta seen from the Space Station.
Credit: International Space Station

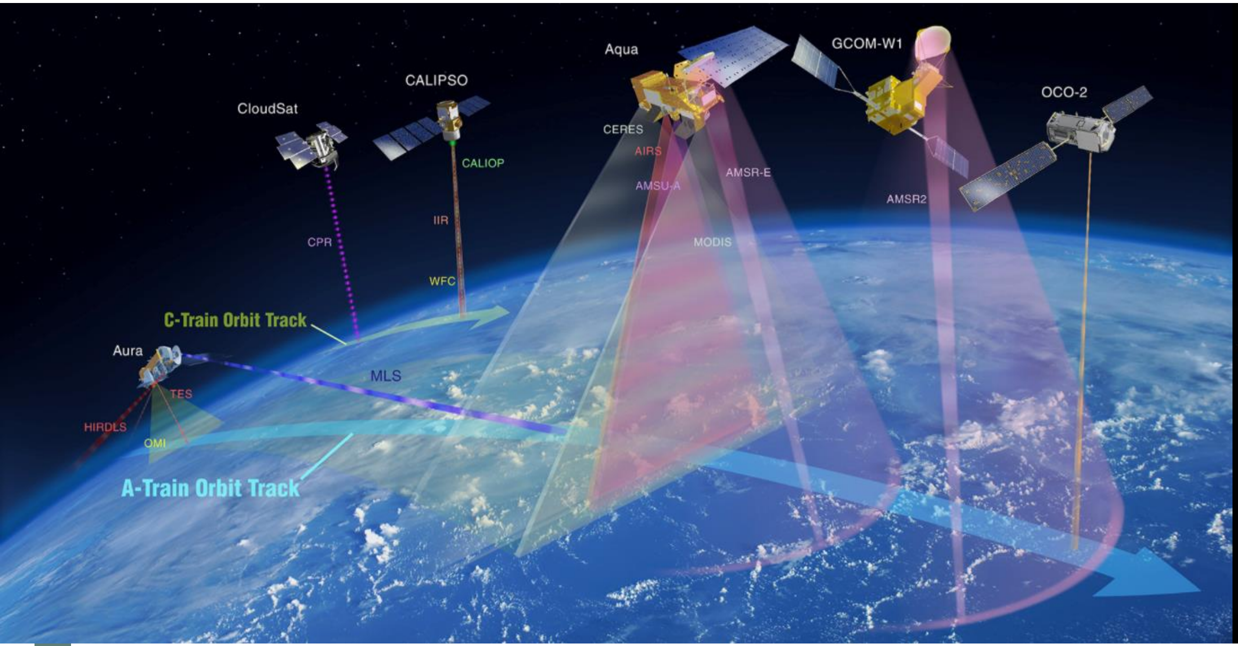


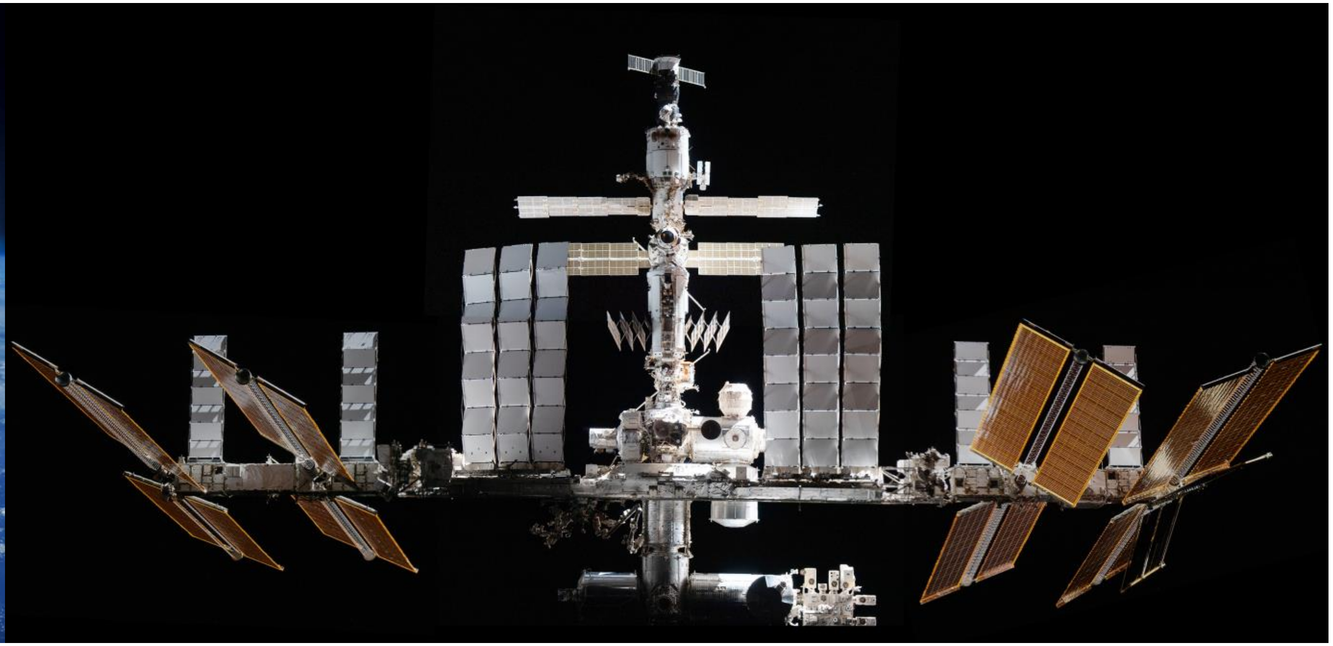
Part 3:

## Section 2: OCO-3 Snapshot Area Mapping (SAM) Mode Observations

# Recap from Part 1 – OCO-2 and OCO-3

- **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)



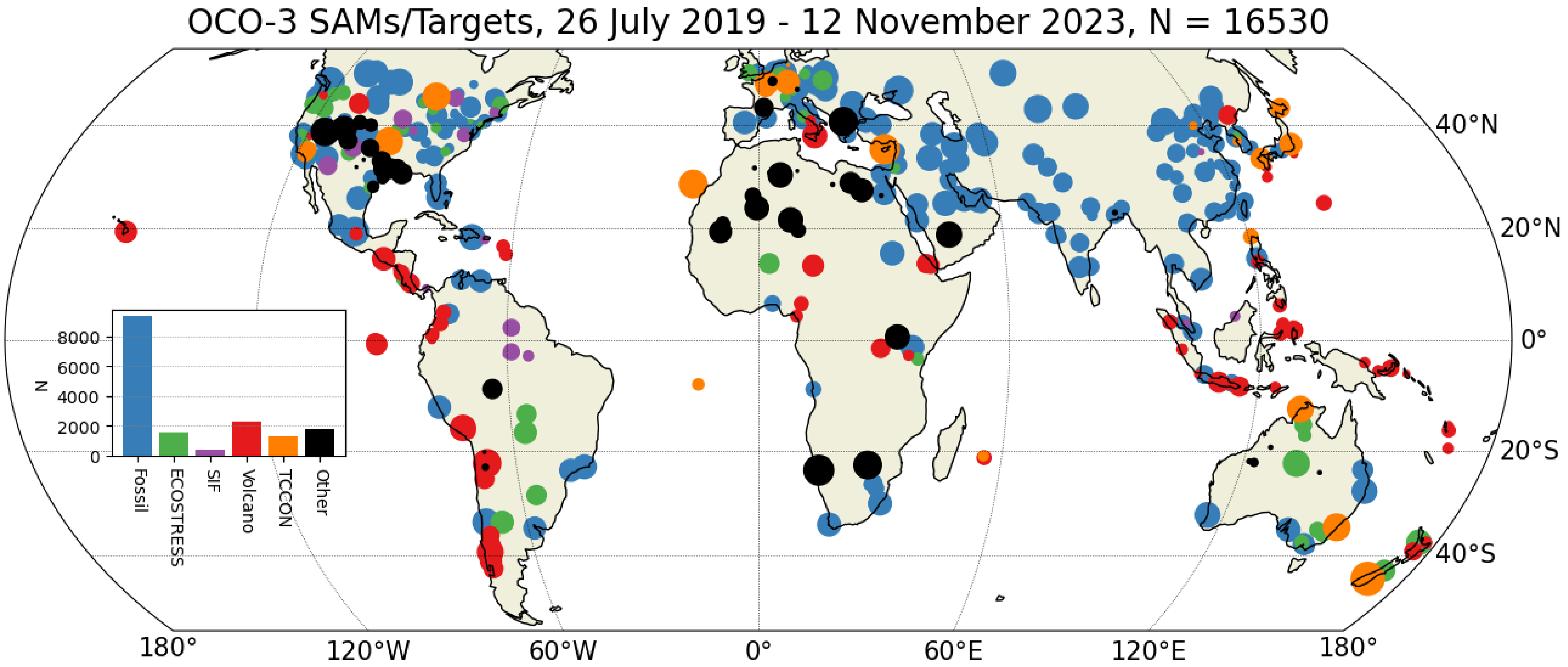
# OCO-3's Unique Fourth Observing Mode – SAM Mode

**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 ~80 km × 80 km area in 2 minutes
- Complements the near-global nadir & glint measurements from routine operations

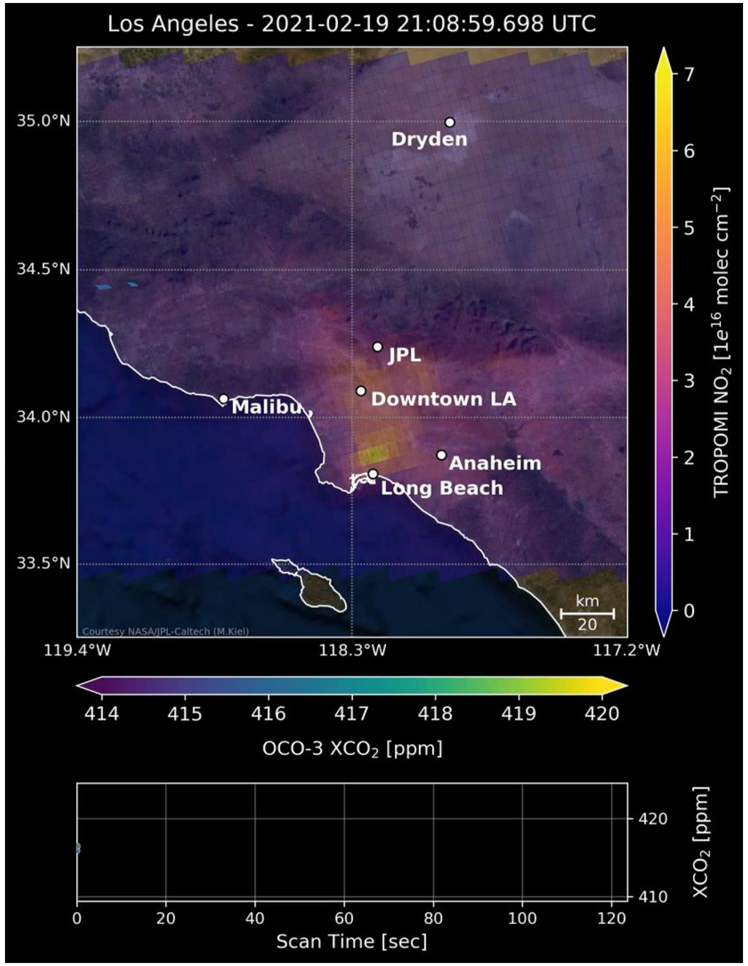
**Video**: Animation showing SAM operation mode over a point source; in this example, we see $XCO_2$ measurements over the Bełchatów power plant (Poland) from three ISS overpasses.

# Location of OCO-3 SAMs Across the Globe




All the blue dots on the map are emission hotspots – either urban areas/megacities, power plants, or other super-emitters. See [OCO-3 SAM webpage](#).

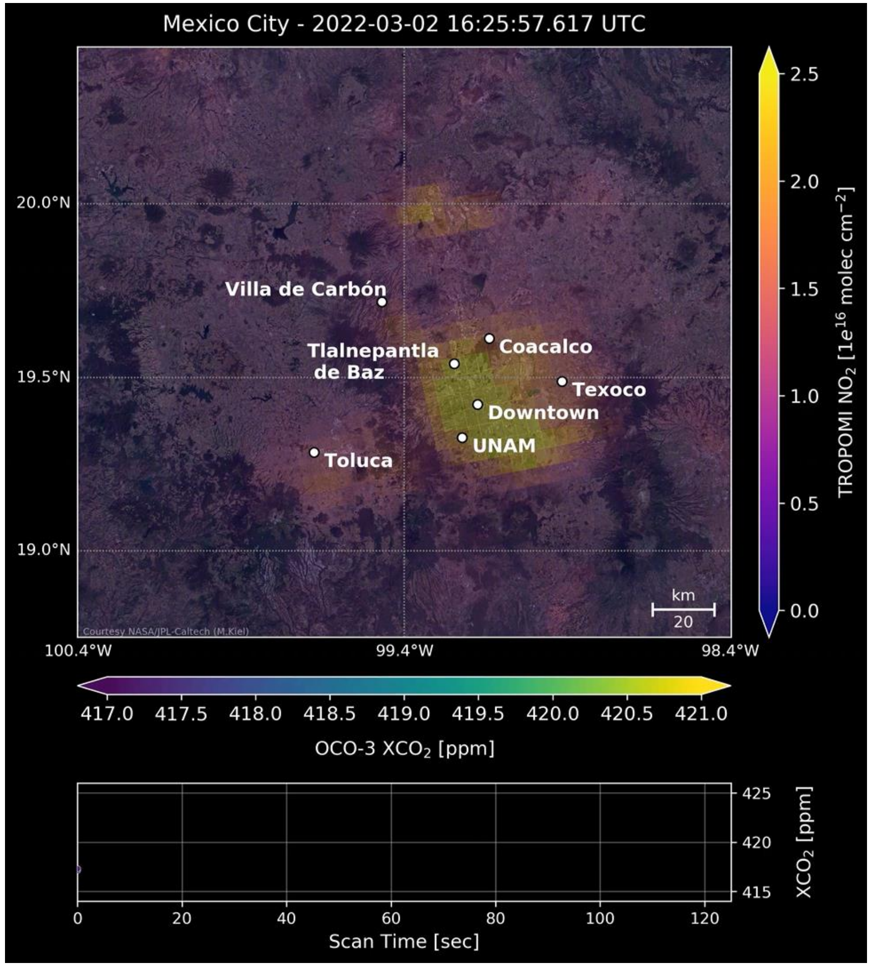
# OCO-3 SAM Observations Over Urban Areas – 2 Examples




Los Angeles

Mexico City

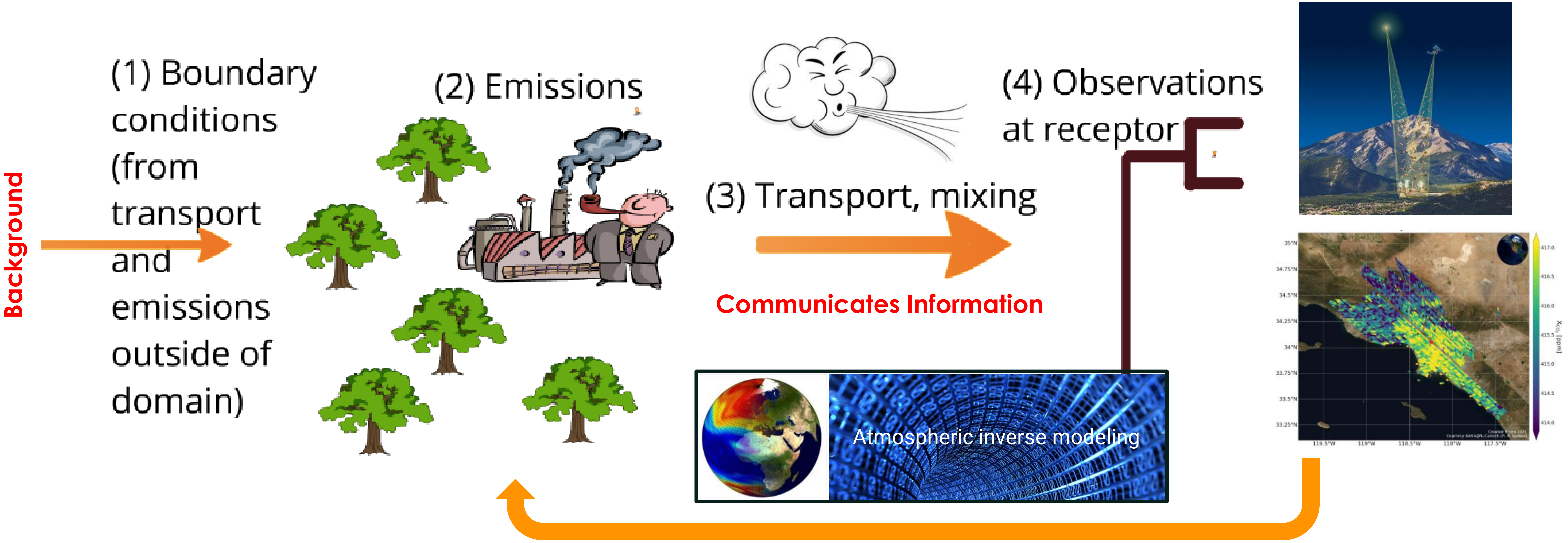
- Similar OCO-3 SAM observations made over other urban areas have been used to estimate urban $CO_2$ emissions.
- While several studies are now available, some key studies have been highlighted in the list below. 👇




**Key References:** Kiel et al. 2021 (RSE); Wu et al. 2022 (ACP); Lei et al. 2022 (RSE); MacDonald et al. 2022 (ACP); Yang et al. 2023 (JGR-Atmospheres); Roten et al. 2023 (GRL); Fonseca and Francis 2024 (Front. Environ. Sci.), Che et al. 2024 (JGR-Atmospheres)

# Top-Down Approach for Estimating Urban Emissions

OCO-3 observations carry **information** about emissions and processes in the upwind source region.




**But** the atmosphere is an **imperfect** communication channel (loss of information through mixing);
**And** our ability to decode the information through atmospheric inverse modeling is subject to uncertainties, a key aspect being the "background."

# Determining the Background $CO_2$ Concentrations

- Background = Atmospheric $XCO_2$ that is not "contaminated" by emissions from or within the urban area of interest.
- Definitions of "background" vary among studies with different applications. For example, studies have used –
  - **Geographic definitions** (Kort et al., 2012; Schneising et al., 2013) or **statistical estimates** (Hakkarainen et al., 2016; Silva and Arellano, 2017) to select upwind measurements for deriving background values,
  - Total column **measurements made upwind** (Kiel et al., 2021),
  - **Trajectory-endpoint method** (Lin et al., 2017) that establishes the background based on $CO_2$ extracted at endpoints of back trajectories from modeled regional/global concentration fields, and…
  - **Overpass-specific method** (Wu et al., 2018) that requires a model-defined urban plume and measurements outside the plume is examined.
- **Note:** For the exercise later, we are going to use the simplest approach and choose a constant, random background value of 410 ppm for visualization and illustration purposes only. For scientific research, one should use the techniques mentioned above.

# Uncertainties in Urban Emissions Estimates

## Top-Down Approach

- Grid resolution used to estimate emissions – limited spatial and temporal definition
- Can only provide Scope 1 emissions estimates
- Errors due to wind, meteorology, and determining background conditions
- Influence of urban biosphere that can confound the observed signal in observations

**But…**

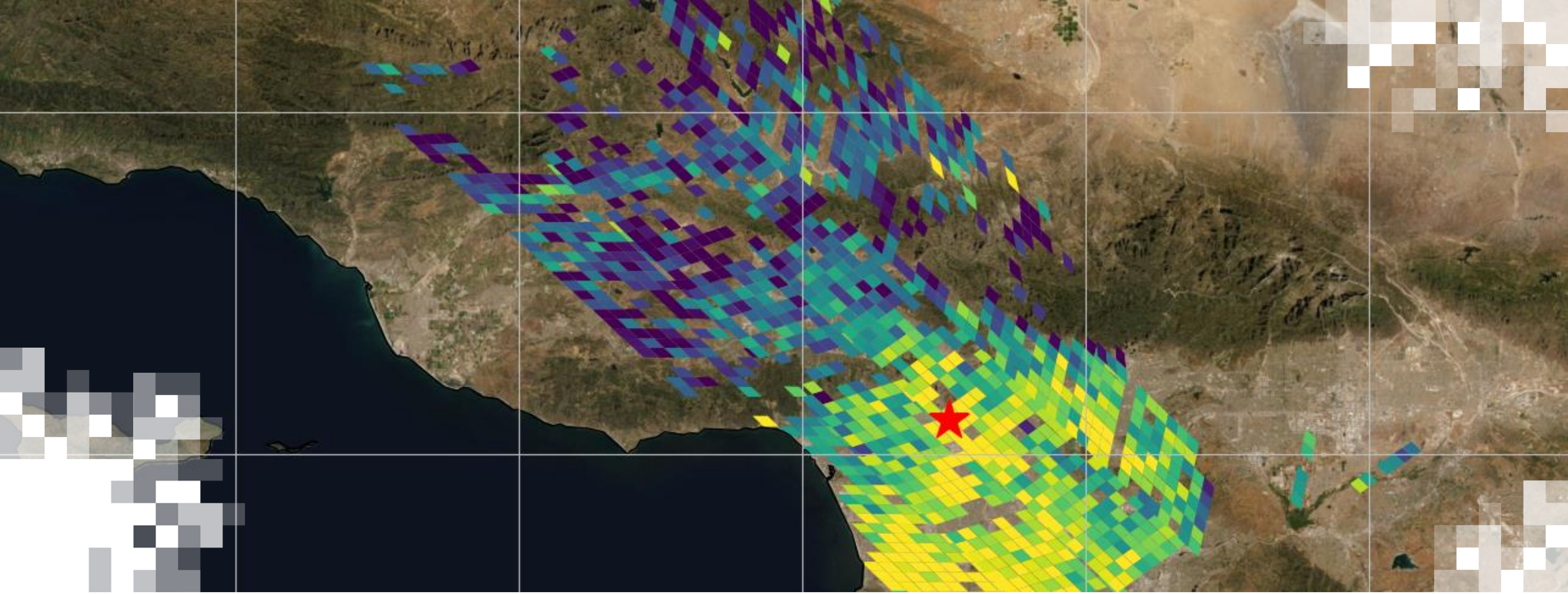
- Considers **real-world** atmospheric observations
- Provides an important sanity check on bottom-up emission estimates

## Bottom-Up Approach

- Relies on self-reported economy/energy activity data across socioeconomic sectors
- May miss specific sectors and have under-reporting of emission estimates
- Can temporally lag by multiple years due to the large scope of input data required
- Sensitive to the construction methodology used

**But…**

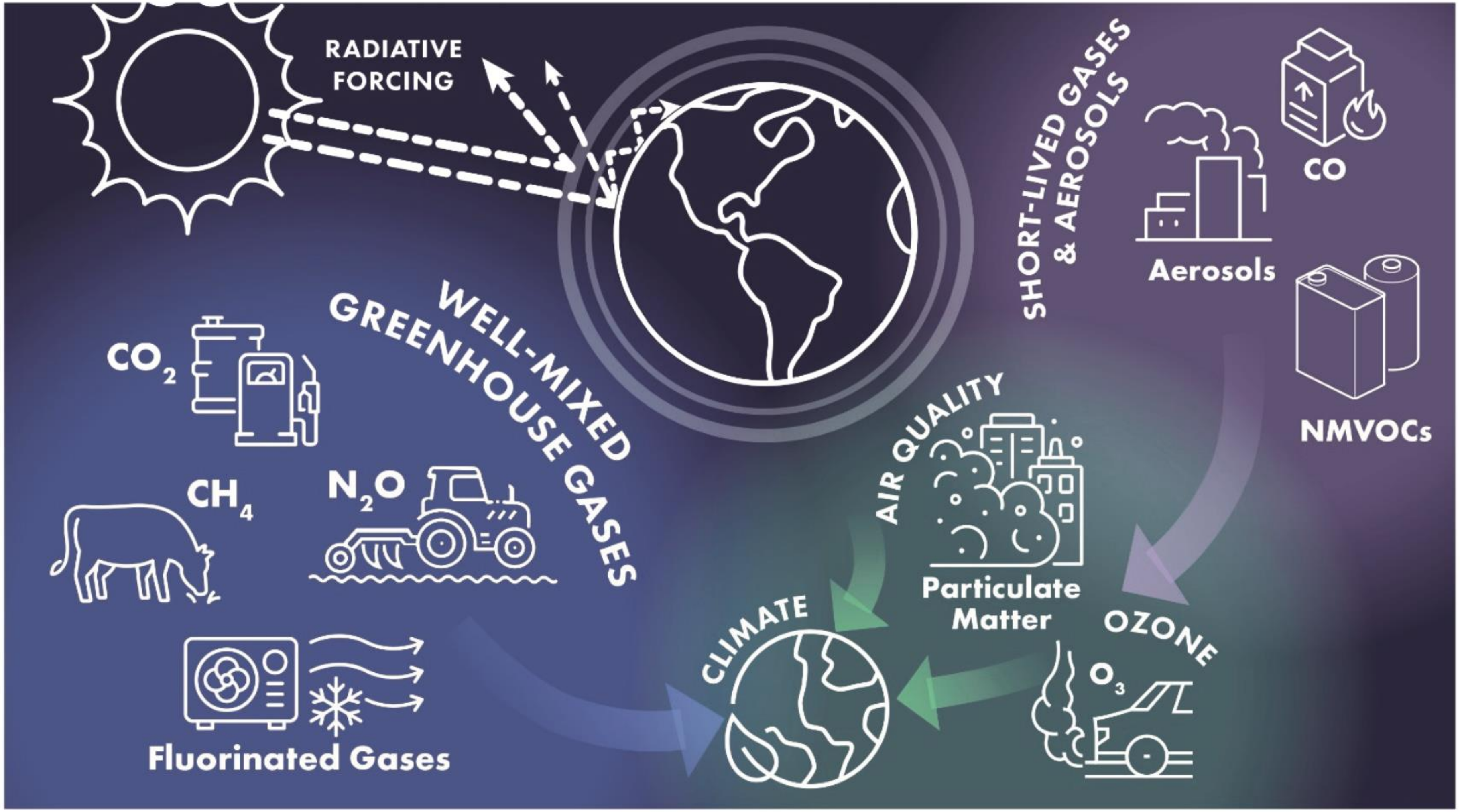
- Can be generated at high spatial and temporal resolutions
- Provides **Scope 1+2+3** emission estimates



Part 3:

## Section 3: Pairing OCO-3 $CO_2$ Observations with Measurements of Co-Emitted Species

# Co-Emitted GHGs and Other Species from Urban Areas



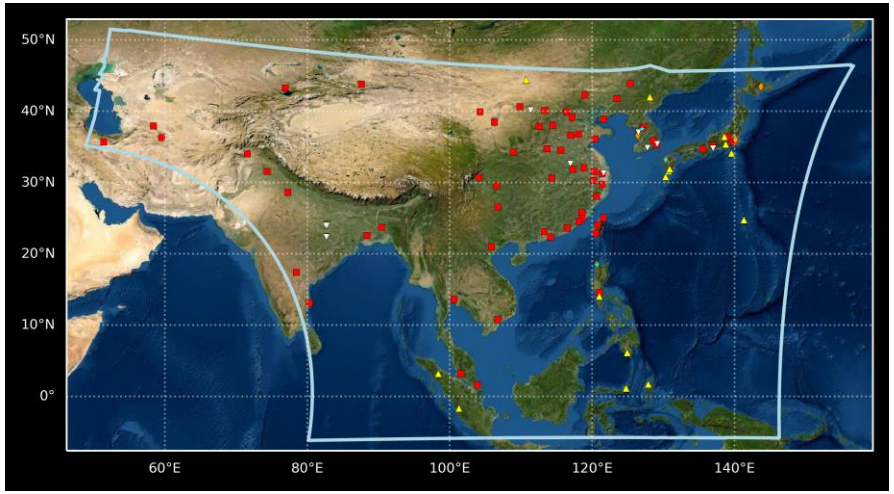

- Well-mixed greenhouse gases (left) and shorter-lived gases and aerosols (top right) impact climate, ozone, and air quality. Greenhouse gases and aerosols impact radiative forcing and changes in global temperature.

Greenhouse Gas Emissions Information for Decision Making, NAS 2022

# Why Use Co-Emitted Species Alongside $CO_2$?

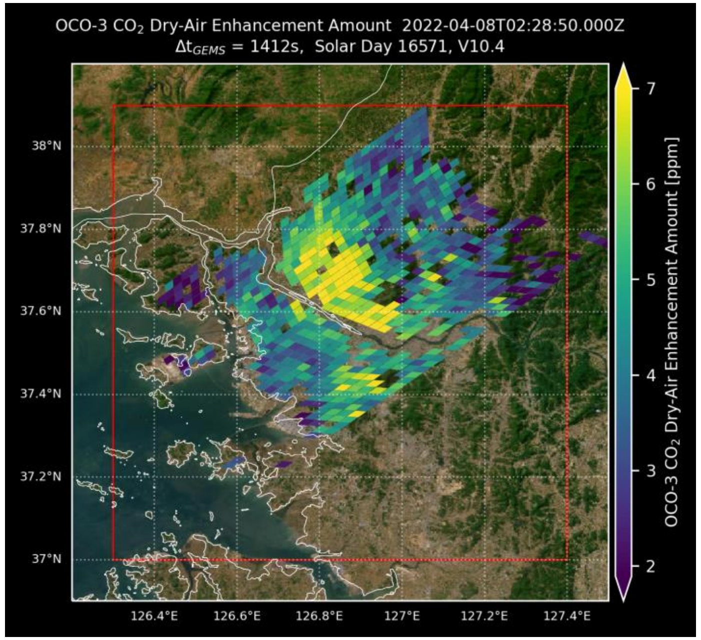
- $CO_2$ by itself is a great tracer for net emissions (for whole-city, total area) but because it has a long lifetime (ranging from years to millennia) and large fluxes of natural origin → $CO_2$ enhancements due to urban emissions are often swamped by its own background values and changes due to natural variability.
- Co-emitted species – for example, $NO_2$, $CH_4$, CO – can help with both sectoral attribution and more robust total emission estimates.
- For example:
  - Nitric oxide (NO) is co-emitted with $CO_2$ during the combustion of fossil fuels. It rapidly reacts with ozone ($O_3$) to form nitrogen dioxide ($NO_2$). $NO_2$ vertical column densities in plumes released from fossil fuel combustion exceed background values and sensor noise, typically by orders of magnitude. This makes $NO_2$ a suitable tracer for recently emitted $CO_2$ . Reference: See Yang et al. 2023 (JGR-Atmospheres).
  - Carbon monoxide (CO) is a valuable tracer for combustion, has a longer lifetime than NO/$NO_2$ and can help pinpoint hotspots with poor combustion efficiency, which can inform sub-city emission/pollution control efforts. Reference: See Wu et al. 2022 (Atmos. Chem. Phys.).

# $CO_2$ and $NO_2$ Coincident Examples from OCO-3 and GEMS

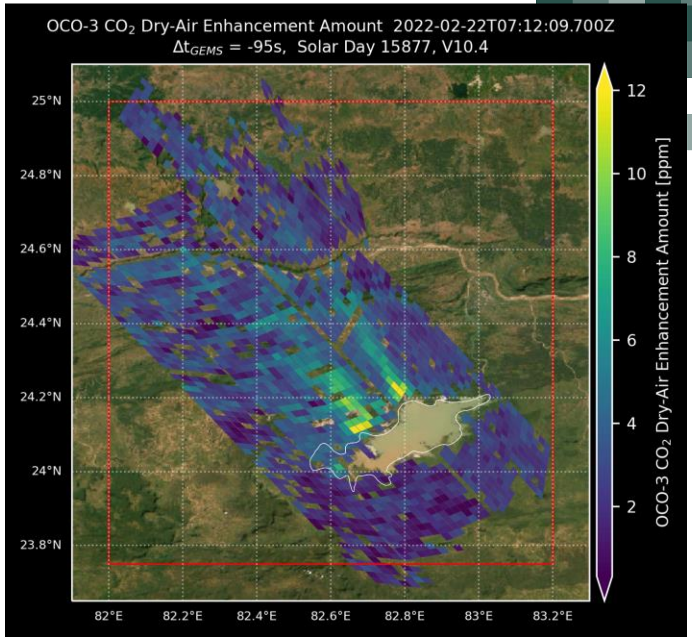


GEMS – Geostationary Environmental Monitoring Spectrometer (Air Quality)

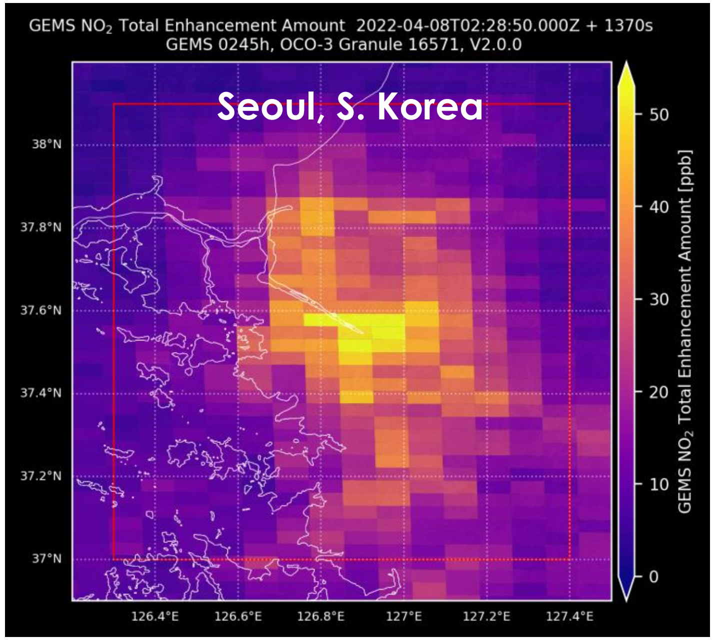
2022-04-08 02:29 UTC



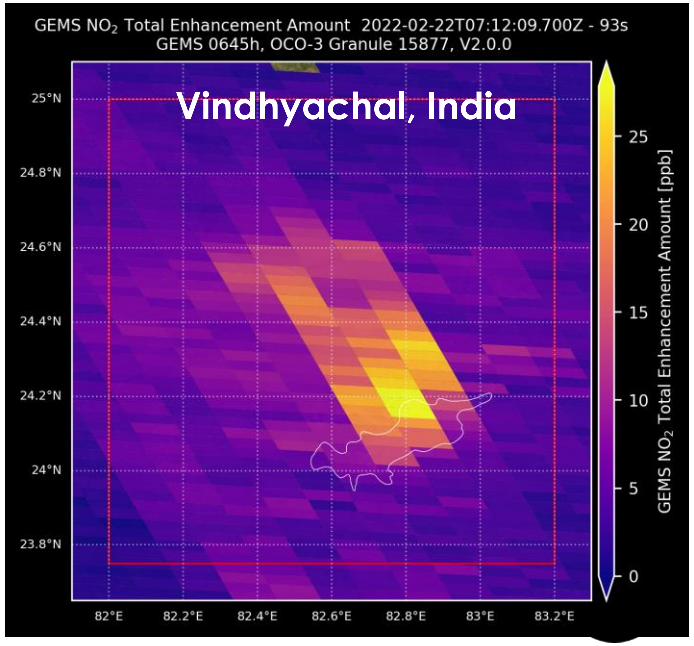

2022-02-22 07:12 UTC



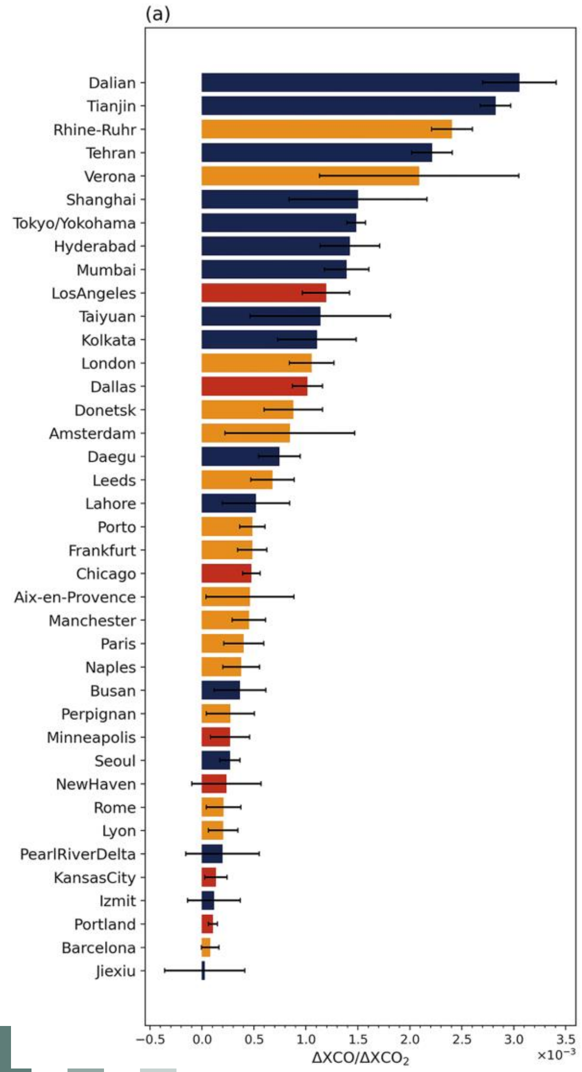

2022-04-08 02:29 UTC + 1370 s

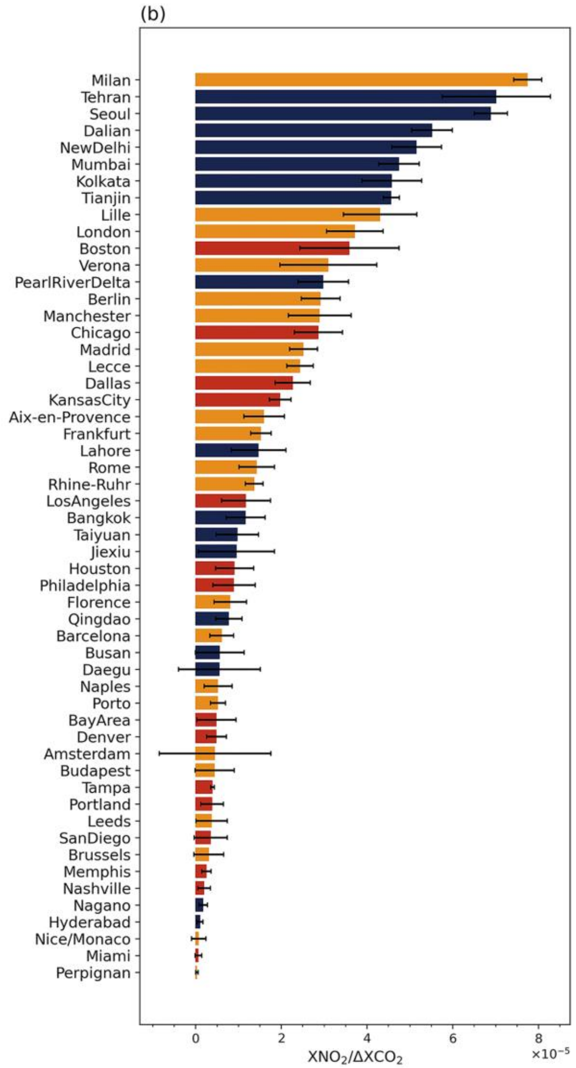


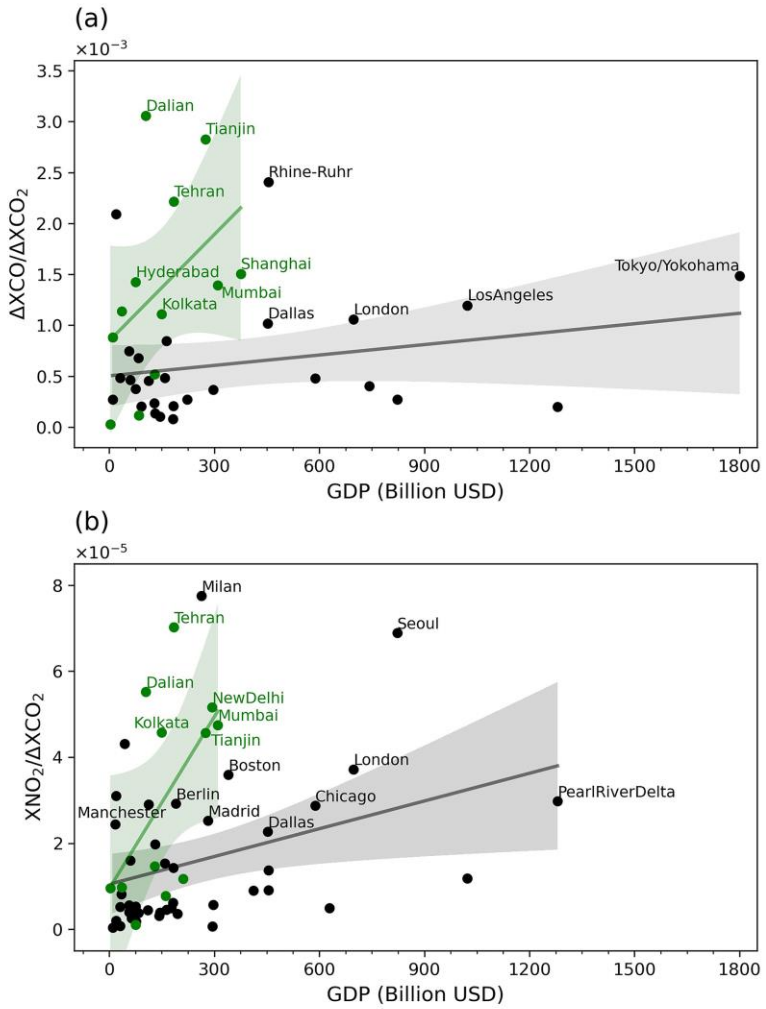

2022-02-22 07:12 UTC – 93s



# $CO_2$, $NO_2$ and CO Utilized from Space-Based Measurements





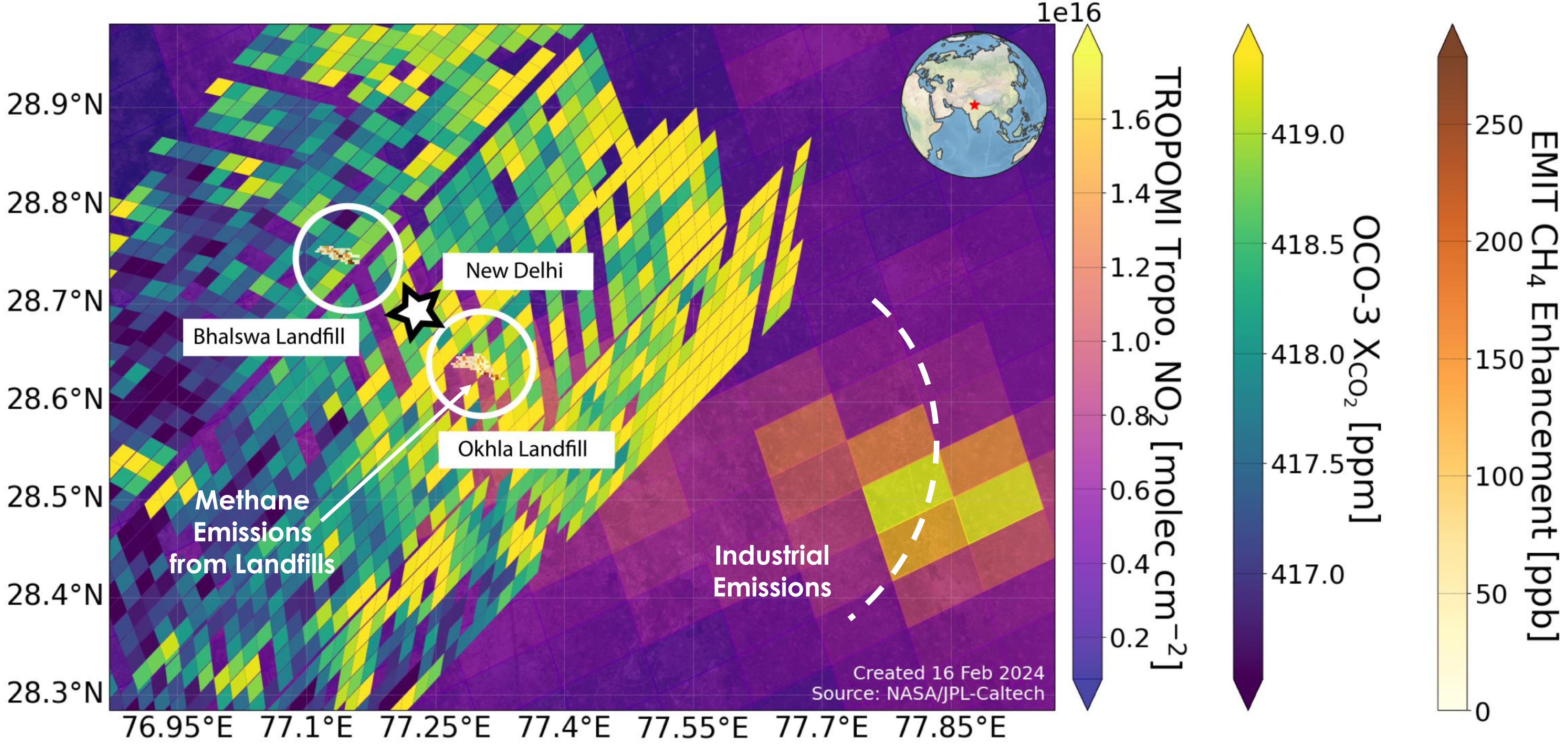


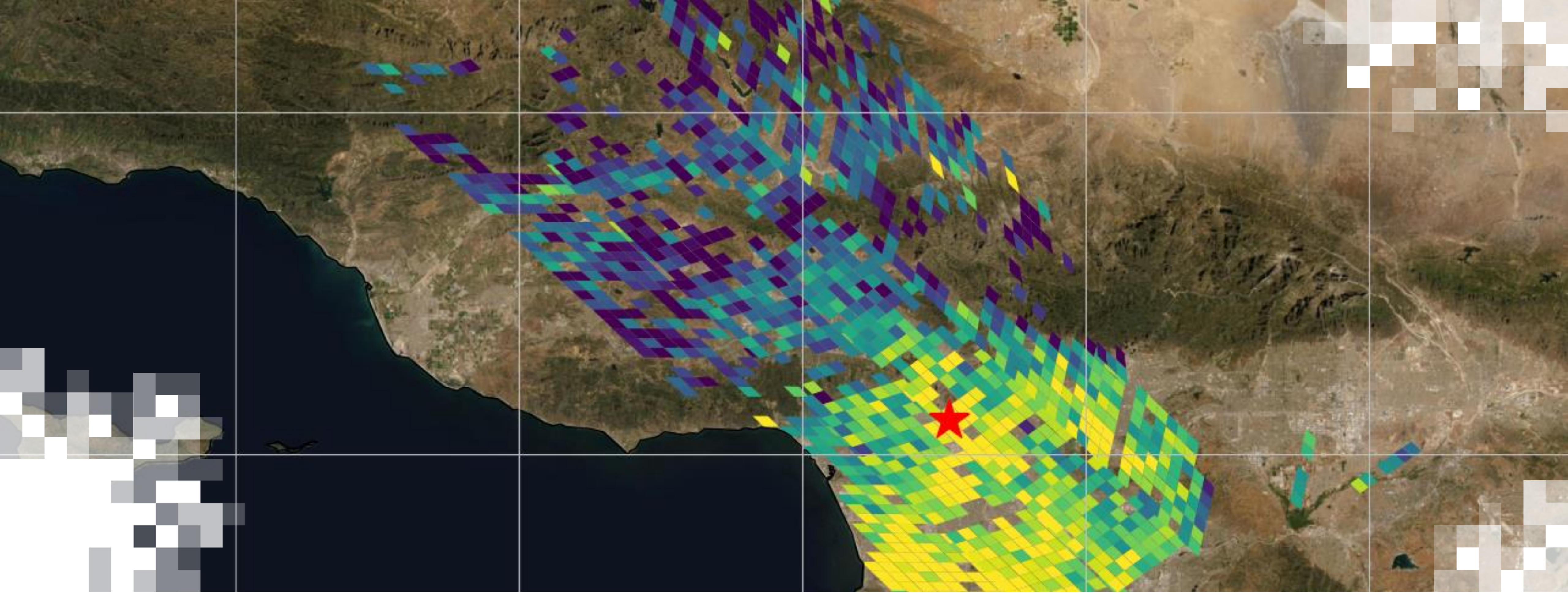
- Synergy between OCO-2 and TROPOMI allows assessment of urban emissions from space.
- Ratios of $CO/CO_2$ and $NO_2/CO_2$ can characterize emission patterns of cities.
- Positive relationship of emission ratios with city population and GDP identified.
- Developing cities have higher incline of emission ratio per GDP than developed cities.



Park et al., 2021 (Remote Sens. Environ.)

# $CO_2$, $NO_2$, and $CH_4$ from NASA's OCO-3, EMIT, and ESA's S5P TROPOMI – A Trio of Sensors!

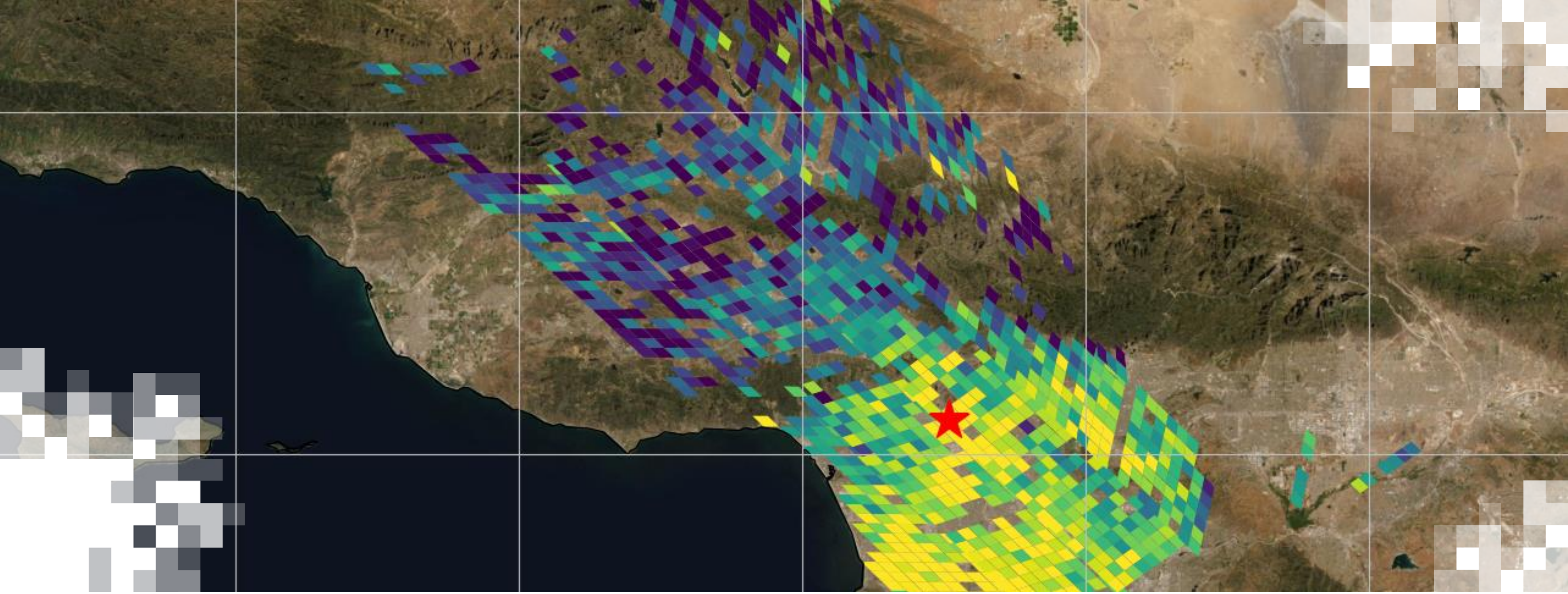




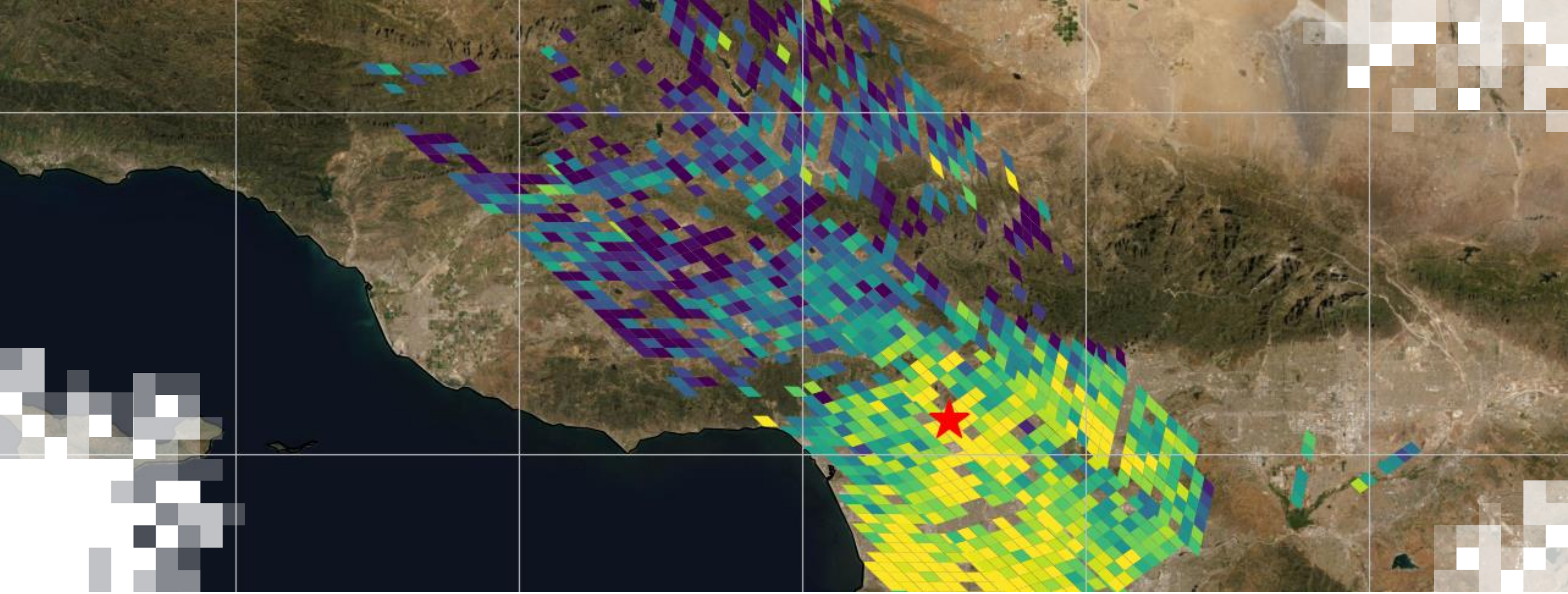
Part 3:
**Section 4: Summary**

# Summary

- There is now rapidly increasing demand from a range of users (public, private, and government entities) for trusted information about greenhouse gas (GHG) emissions over urban areas and megacities.
- OCO-3 SAM observations have **advanced our scientific understanding of urban $CO_2$ emissions, helped develop new top-down approaches to address increasing demand,** and **demonstrated that space-based $CO_2$ measurements -**
  - Have the information content and the ability to quantify emissions changes happening across urban areas
  - In conjunction with co-emitted species (such as $NO_2$, CO) improve sectoral attribution
  - Track socioeconomic/regional characteristics in global cities' emissions
  - And finally, provide a check on bottom-up emissions estimates, helps boost transparency in carbon accounting, and assists with decision-making processes



Part 3:
**Demonstration**



# Applications of Carbon Dioxide Measurements for Climate-Related Studies

**Summary**

# Training Summary

- OCO-2 has a 10-year record with a temporal resolution of 16 days. It overflies the equator at 1:30 pm local time.
- OCO-3 has a 5-year acquisition record. The sensor is on the International Space Station and the coverage is limited to ±52° latitude. Its observations cover all hours of the day.
- Both sensors make acquisitions in Nadir, Glint and Target modes. OCO-3 also makes acquisitions in the SAM mode.
- The XCO2 data from these missions is the column average volume mixing ratio of CO2 in the atmosphere.
- The data between OCO-2 and OCO-3 are consistent over time and are complementary.
- It is recommended that you use the Level-2 Lite XCO2 data - which have been filtered and corrected for bias. They are openly available through GES DISC.
- Surface carbon fluxes are related to the biosphere and oceans.
- The global average atmospheric CO2 concentration is the integration of all surface carbon fluxes.

# Training Summary

- The temporal change of local and regional $CO_2$ concentrations is related to surface carbon fluxes and lateral transport or background values.
- Surface carbon fluxes are linked to atmospheric concentrations by means of atmospheric transport models.
- The process to calculate carbon fluxes from atmospheric $CO_2$ concentrations is called atmospheric $CO_2$ flux inversion.
- SAM acquisitions:
  - are useful for quantifying changes in emissions occurring in urban areas.
  - together with co-emitted species, such as $NO_2$ or CO, they can aid in sectoral attribution,
  - have the potential to monitor the socioeconomic/regional characteristics of global urban emissions,
  - help increase transparency in carbon accounting and aid in the decision-making process.

# Homework and Certificates

- **Homework:**
  - One homework assignment
  - Opens on Jul. 16, 2024
  - Access from the training webpage
  - Answers must be submitted via Google Forms
  - **Due by Aug. 14, 2024**

- **Certificate of Completion:**
  - Attend all three live webinars (attendance is recorded automatically)
  - Complete the homework assignment by the deadline

You will receive a certificate via email approximately two months after completion of the course.

# Contact Information

Invited Instructors:

- Abhishek Chatterjee
  - abhishek.chatterjee@jpl.nasa.gov
- David Moroni
  - david.f.moroni@jpl.nasa.gov
- Karen Yuen
  - karen.yuen@jpl.nasa.gov
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