Satellite-based Analysis of CO_2 Emissions from Global Cities: Regional, Economic, and Demographic Attributes

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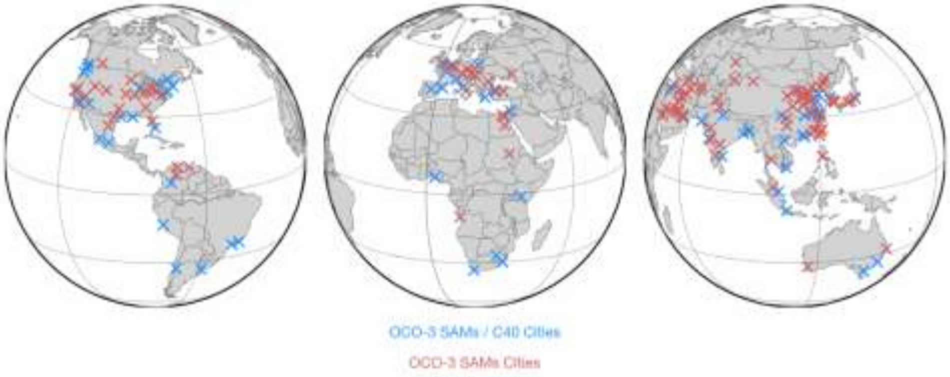
C40 Cities and NASA OCO-3 SAM

C40 Cities Climate Leadership Group

- 96 Cities, 582 million residents, 20% of the global GDP
- C40 cities have been using self-reported GHG emission inventory (GPC) to track their mitigation progress toward net-zero by 2050
- GPC Provides the principles for calculating emissions, but it does not require specific methodologies
- Global South cities tend to show larger variability in emission estimates among GPC, EDGAR, and ODIAC (Ahn et al., 2023)
- Global South cities tend to use more outdated/lower quality emission factors (Ahn et al., 2023)

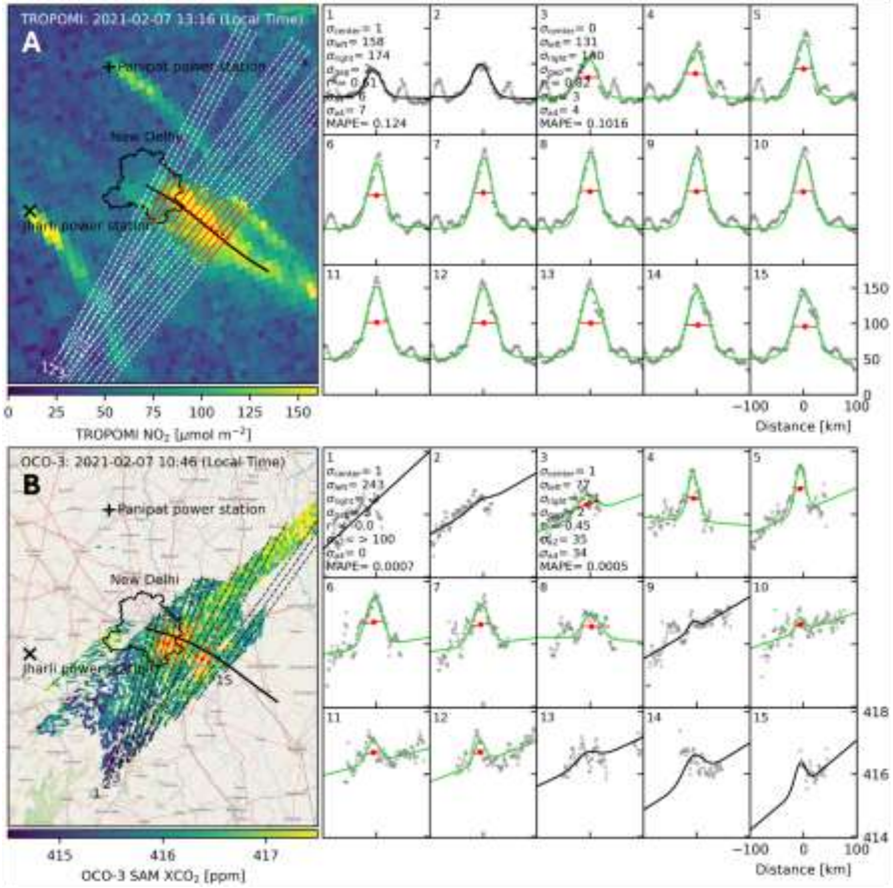
NASA's OCO-3 Scanning Area Mapping (SAM)

- Same instrument as OCO-2: Footprint ~3km^2 & Precision < 1 ppm
- Launched in May 2019, installed on ISS
- Pointing Mirror Assembly (PMA): multi-swath scans of 80 x 80 km^2
- version 11r (B11072Ar) used in this study



Can we use the unique vantage point of OCO-3 SAM XCO_2 observations to provide policy-relevant information for global C40 cities?

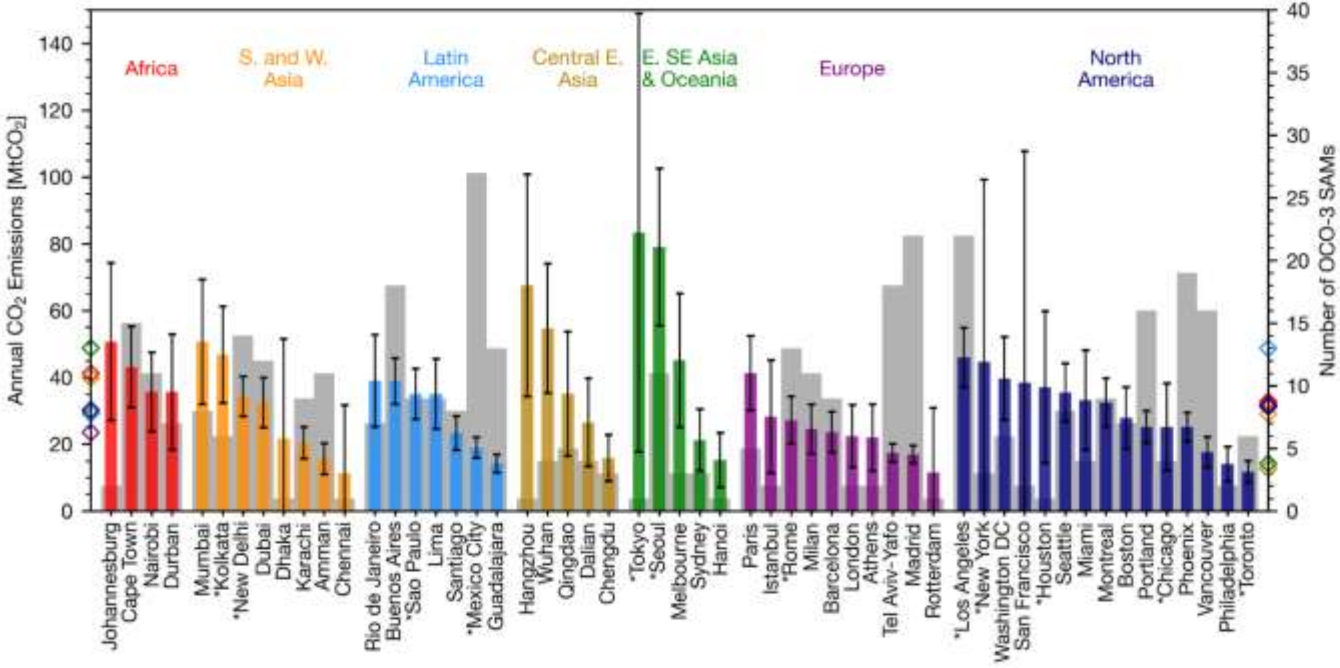
OCO-3/TROPOMI Cross-Sectional Flux Method



- We developed a computationally efficient, low latency Cross-Sectional Flux (CSF) approach for OCO-3 XCO_2 and TROPOMI NO_2 observations.
- Urban CO_2 plume shapes are constrained using co-located TROPMI NO_2 and HYSPLIT trajectories.
- To ensure the quality of Gaussian fits for CO_2 plumes, we apply a goodness-of-fit test based on twelve mutually inclusive goodness-of-fit metrics
- As a result of this filtering process, 2,381 Gaussian curves pass the goodness-of-fit test, representing 7% of all Gaussian curves fitted to XCO_2 measurements.

Ahn et al. (In review)

Satellite-based CO_2 Emissions for Global C40 Cities



- Annual CO_2 emissions for 54 cities were estimated using OCO-3 SAMs collected during Sep. 2019 ~ Nov. 2023.
- Estimated emissions range from 11 $MtCO_2$ for Rotterdam (pop: 2M) to 83 $MtCO_2$ for Tokyo (pop: 22M).
- The 1σ uncertainty range from 15% for Madrid (# SAMs: 22) to 181% for San Francisco (# SAMs: 2), with a median uncertainty of 31% for Washington DC (# SAMs: 6).
- On average, 9 SAMs are used to estimate annual CO_2 emissions.

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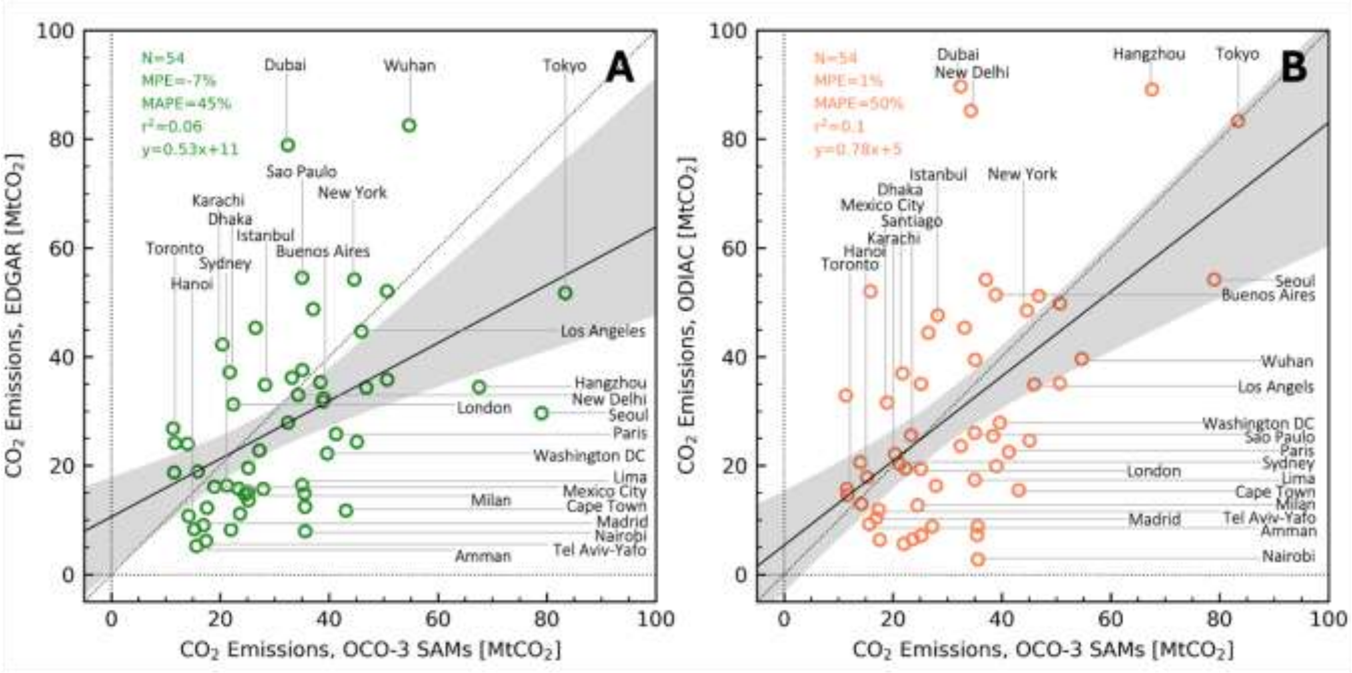
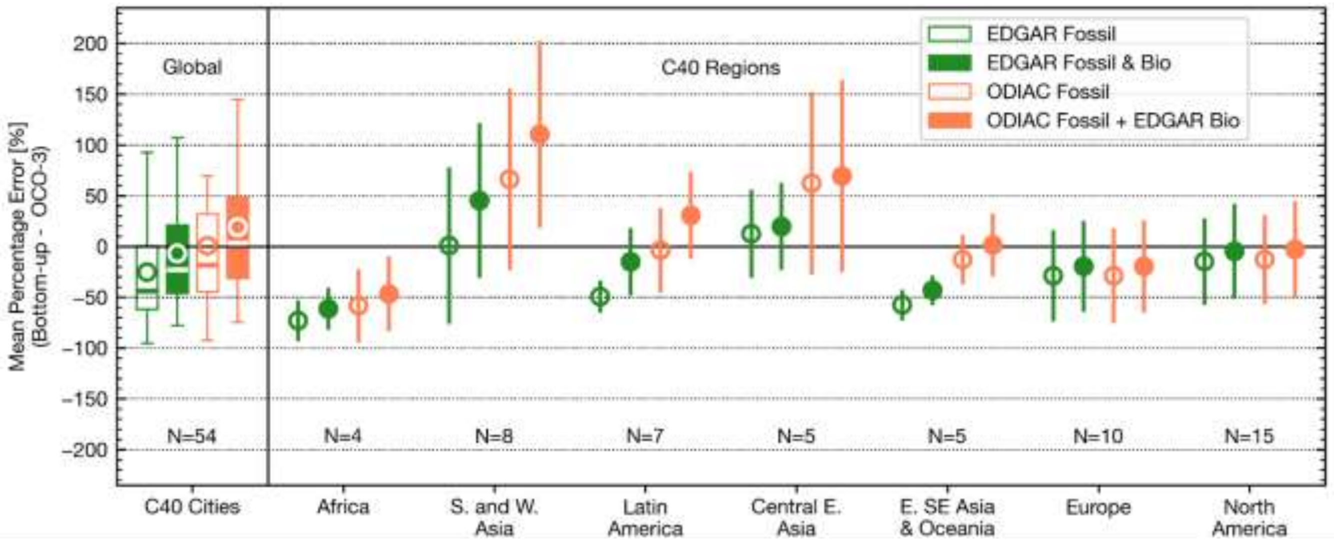
Global comparison of Bottom-up and Satellite-based Emission Estimates



- Globally, EDGAR and ODIAC agrees with satellite-based emission estimates within 7%.
- Such agreement results from the cancellation of large errors in opposite directions at the individual city level.
- Among the 54 cities, EDGAR estimates fall within the 1σ range of our OCO-3 estimates for 25 cities, and ODIAC estimates fall within this 1σ range for 22 cities.
- While individual city estimates should be interpreted with caution, there is less uncertainty when emissions are aggregated regionally or globally.

Ahn et al. (In review)

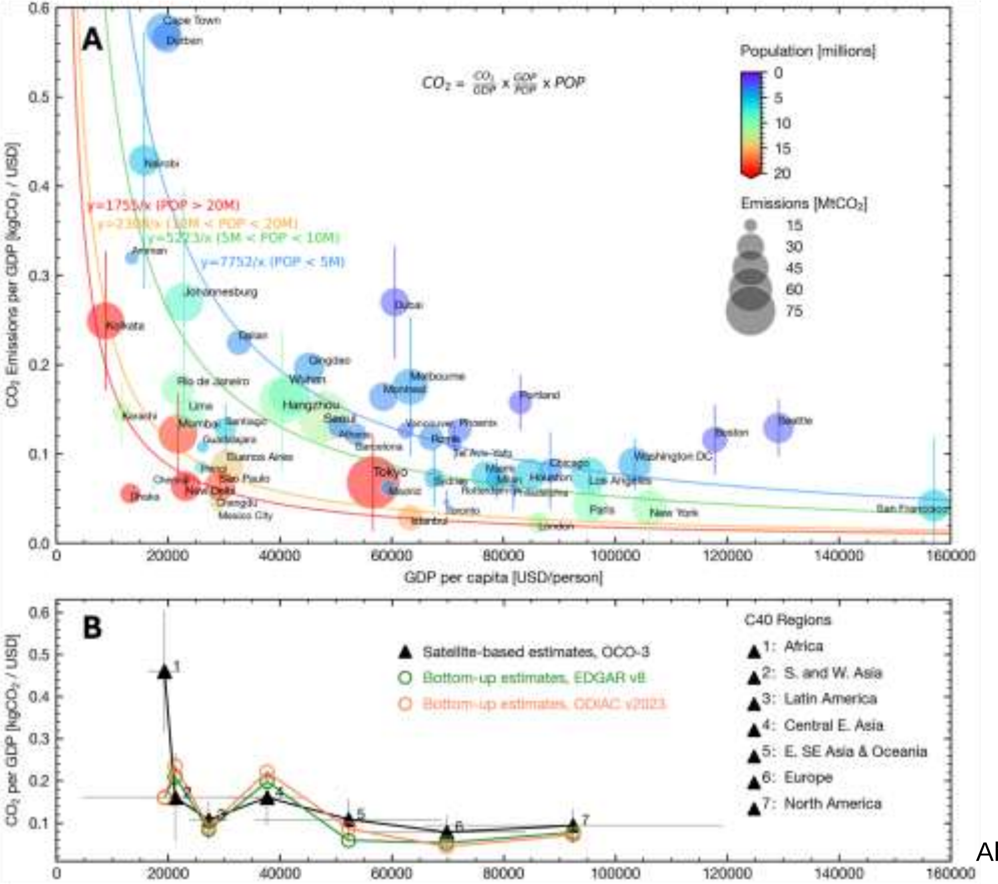
Regional comparison of Bottom-up and Satellite-based Emission Estimates



- Cities in N. America showed the best agreement between bottom-up and satellite-based estimates, with MPE ranging from −15 ± 41% for EDGAR fossil to −3 ± 46% for ODIAC total emissions.
- For cities in Africa, both EDGAR and ODIAC significantly underestimated emissions compared to satellite-based estimates. Africa is the only region where satellite-based estimates fall outside the 1 sigma range of all four bottom-up emission estimates.

Ahn et al. (In review)

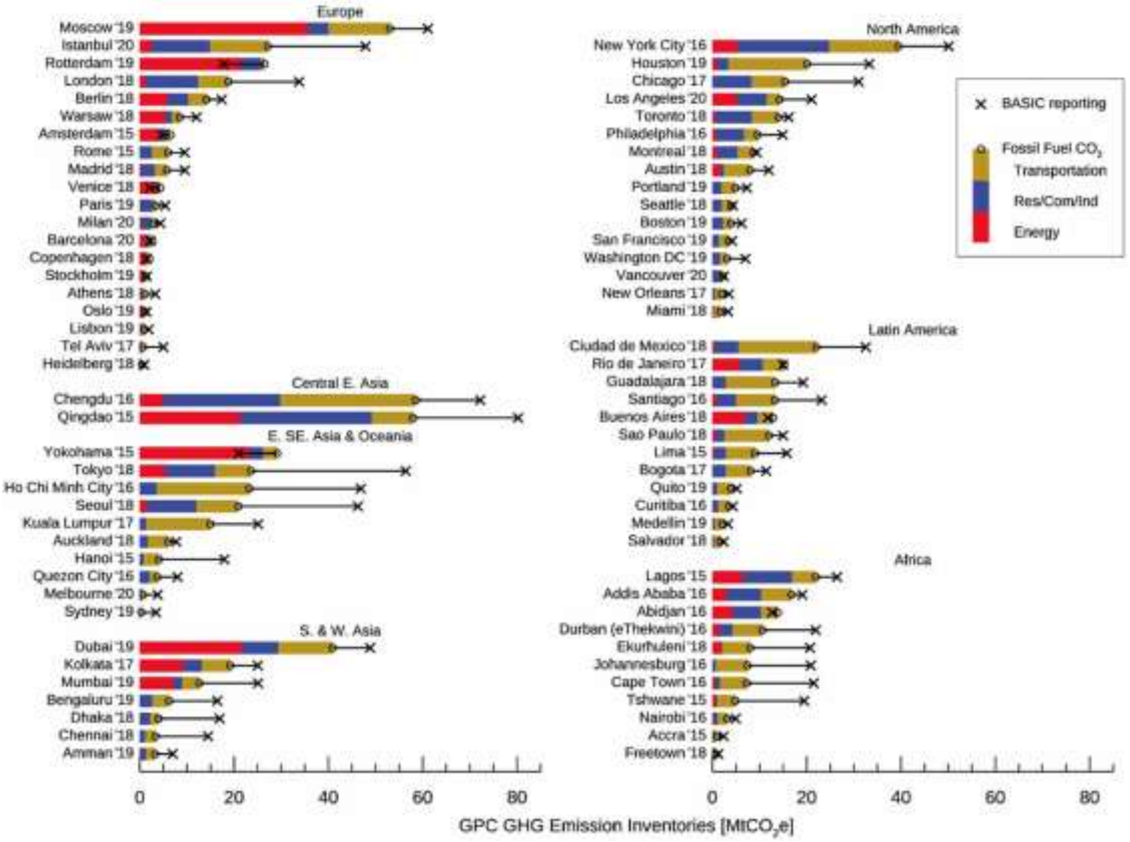
Satellite-based Kaya Identity Analysis of Global Cities' CO_2 Emissions



- We applied a modified Kaya Identity to decompose our satellite-based emission estimates for the 54 C40 cities: $CO_2 = CO_2/GDP \times GDP/Population \times Population$
- High-income cities tend to have less carbon-intensive economies: North American cities emit 0.1 ± 0.04 kg CO_2 per USD of economic output , while African cities emit 0.5 ± 0.14 kg CO_2 per USD
- A similar inverse relationship —the decoupling of CO_2 emissions from economic growth— is observed when cities are grouped into global regions.
- Per capita emissions decrease with increasing population size, from 7.7 tCO_2/person for cities under 5M residents to 1.8 tCO_2/person for cities over 20M residents.

Ahn et al. (In review)

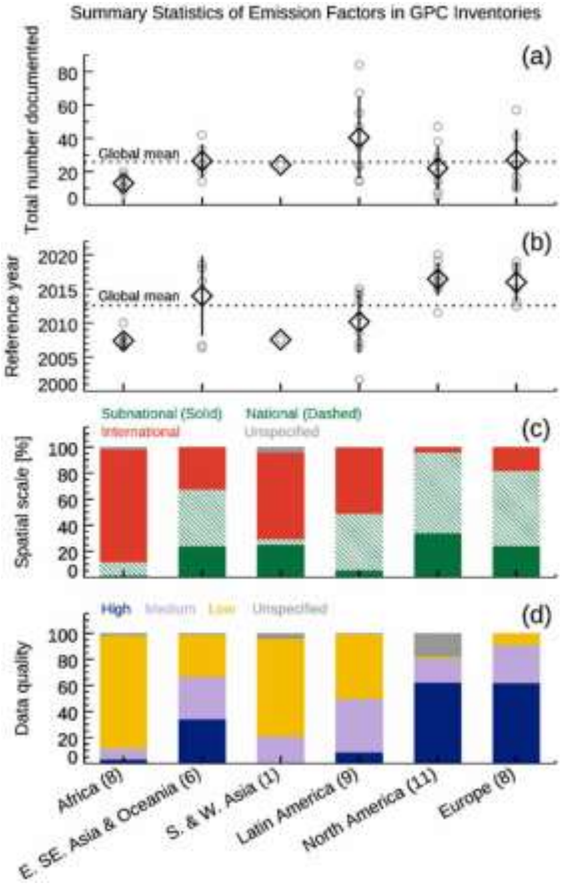
Policy Implications of Satellite-based CO_2 Emission Estimates



Ahn et al. (2023)

- Satellite-based emission estimates cover emissions within a city' geographical domain (Scope 1).
- The GPC emissions inventory—the standard emission tracking method for C40 Cities— also covers emissions occurring outside of the city's geographical domain (Scope 2+3, also called BASIC reporting).
- According to GPC inventory, Latin American cities have the highest Scope 1 CO_2 percentage (78%), followed by North America (72%), Europe (62%), South & West Asia (52%), Africa (48%), East, Southeast Asia & Oceania (32%), with a global mean of 61%.

Policy Implications of Satellite-based CO_2 Emission Estimates



Ahn et al. (2023)

- The data quality of emission factors (EFs) used in GPC inventories vary regionally: the highest quality for European and North American and the lowest for African and Latin American cities.

→ Satellite-based dataset can provide an independent check for C40 cities, especially for Africa, Latin America, and S. & W. Asia

- A major challenge for the GCoM (Global Covenant of Mayors) is assisting cities with limited resources or capacity to build their own emissions inventory.

→ Satellite-based emission dataset can offer an initial estimate to support these cities

Summary

- We developed a *computationally-efficient* CSF approach for estimating CO_2 emissions for 54 cities using OCO-3 SAMs data. The CSF approach detect urban plume pixels using TROPOMI NO_2 and HYSPLIT trajectory, without relying on prior emission inventories.

- By comparing our satellite-based emissions estimates with two of the most widely used bottom-up datasets —EDGAR and ODIAC— we found that bottom-up datasets tend to overestimate CO_2 emissions for cities in Central East Asia and South and West Asia, while underestimating for cities in Africa, East and Southeast Asia & Oceania, Europe, and North America.

- The application of the Kaya Identity reveals the decoupling of economic growth and carbon-intensive sectors across global cities. Also, the satellite analysis captured that per capita CO_2 emissions tend to decrease as a city's population size grows.

Ongoing and Next Steps

- **Expanding city coverage:** increasing from 54 to 175 cities
- **Integration with air quality data**: linking CO_2 emissions with NO_X and PM2.5
- **Temporal analysis**: Tracking emission changes over time
- **Operationalization**: Enabling near-real-time updates on an open-access platform

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