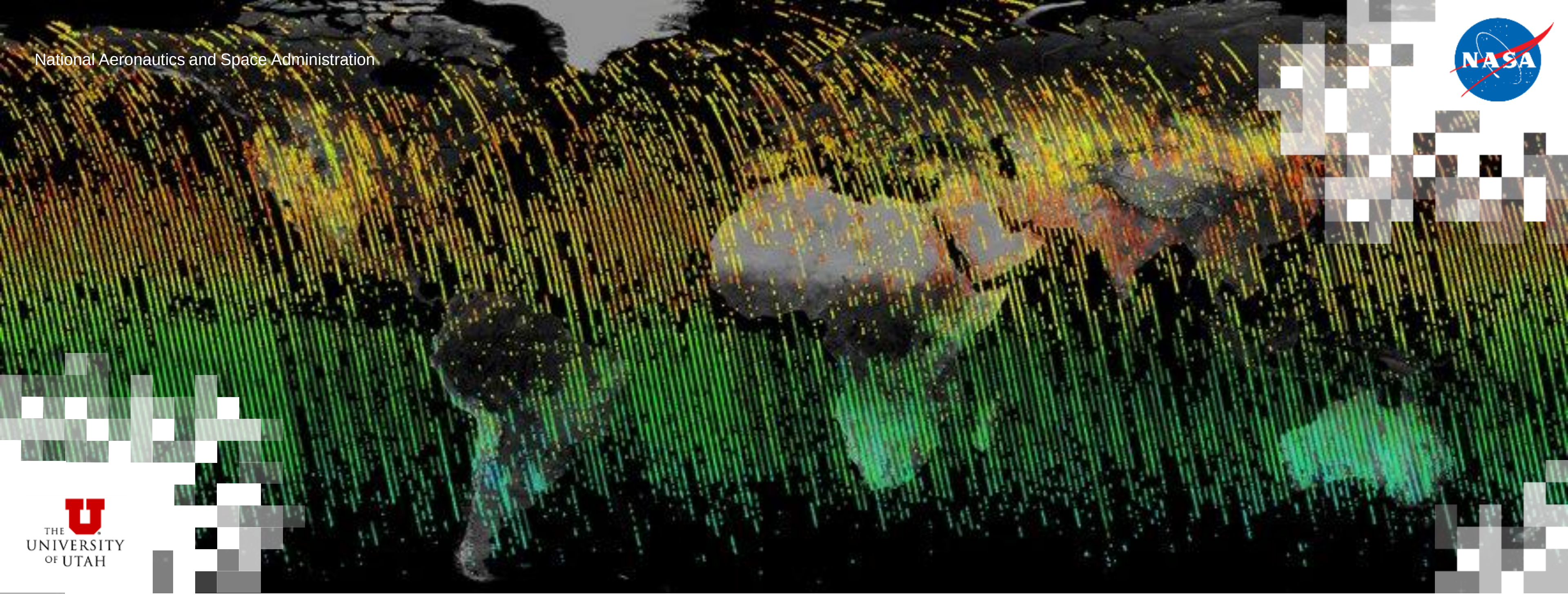
National Aeronautics and Space Administration



Understanding Urban Carbon Emissions with Space-Based Carbon Dioxide Observations

John C. Lin, Professor, Dept. of Atmospheric Sciences, University of Utah. John.Lin@utah.edu

June 2, 2022

Webinar Agenda

Part 1: An Introduction to XCO_2 with OCO-2 and OCO-3

- EDT (UTC-4:00)
- Tuesday, May 24, 2022
- Trainers: Vivienne Payne (JPL)
- Background of the XCO2 measurement and how it is measured
- Description of the OCO-2/OCO-3 sensors
- Characteristics, limitations and validation of the measurement
- Q&A

Part 2: A Demonstration on how to Access and Visualize OCO-2/OCO-3 Data

- EDT (UTC-4:00)
- Thursday, May 26, 2022
- Trainers: Karen Yuen (JPL)
- Use of Jupyter Notebook to access, search, filter and display XCO_2 data
- Q&A

Part 3: XCO_2 in Support of Global and Regional Climate-Related Studies

- EDT (UTC-4:00)
- Tuesday, May 31, 2022
- Trainers: Abhishek Chatterjee (JPL)
- Global and regional carbon flux estimation, and carbon cycle response to climate variability and changes in anthropogenic emissions
- Q&A

Part 4: XCO_2 in Support of Local and Regional Climate-Related Studies

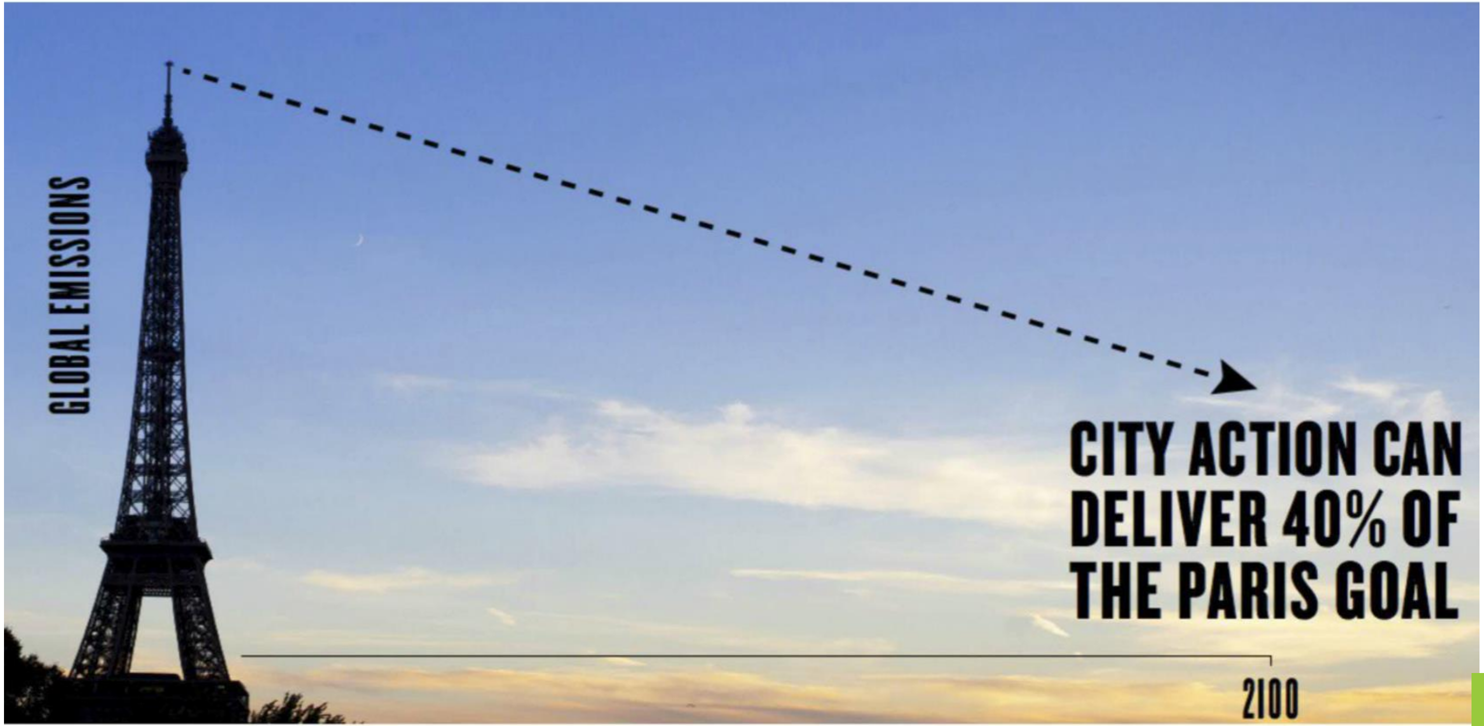
- EDT (UTC-4:00)
- Thursday, June 2, 2022
- Trainers: John Lin (University of Utah)
- Climate impacts from localized emissions, air quality, and urban density
- Q&A

URBAN areas, where **more than HALF of the global population** resides, are responsible for **significant emissions of CO_2.**

Air Quality issues are also magnified in cities, where pollutant emissions are concentrated and where exposure of large populations crammed into small areas are found.

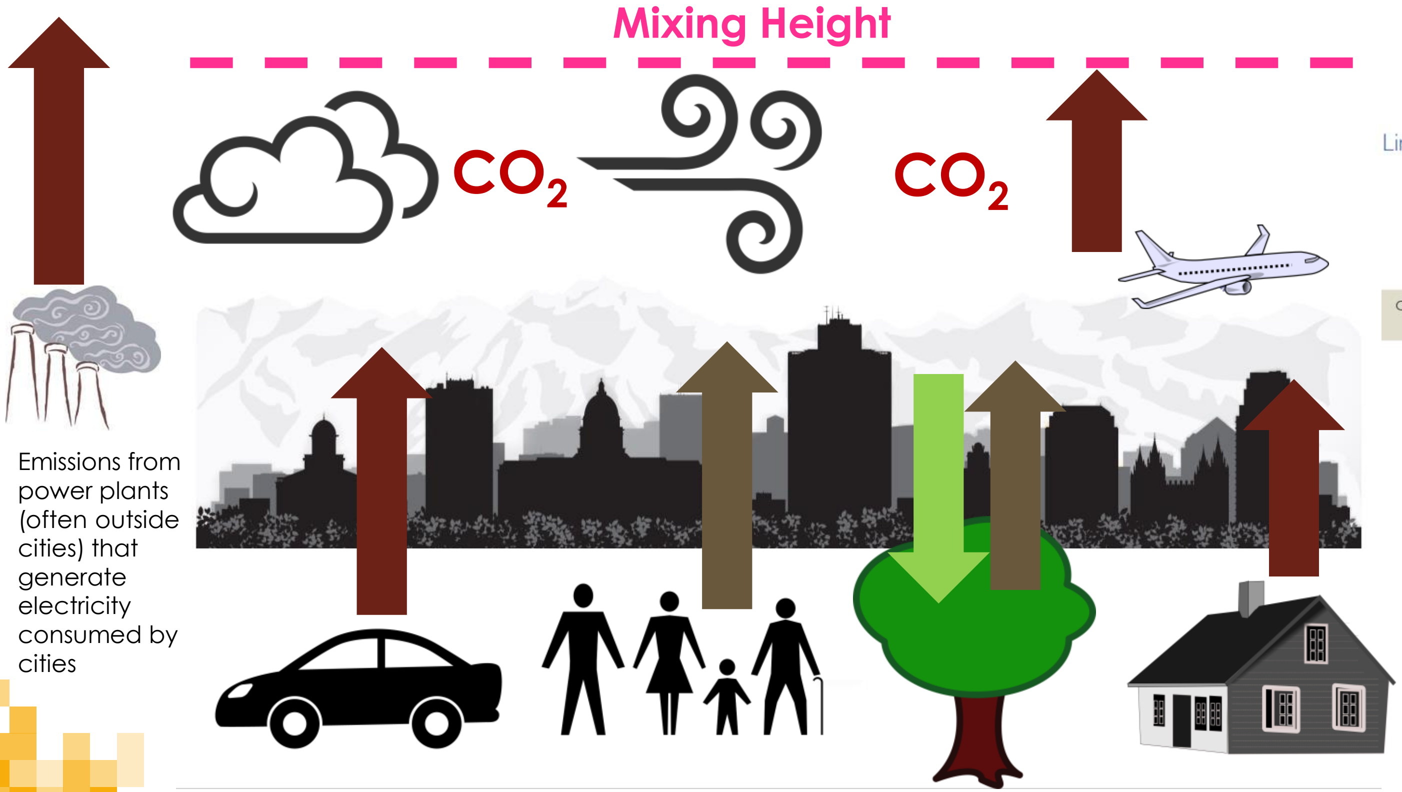
http://visibleearth.nasa.gov/view.php?id=55167

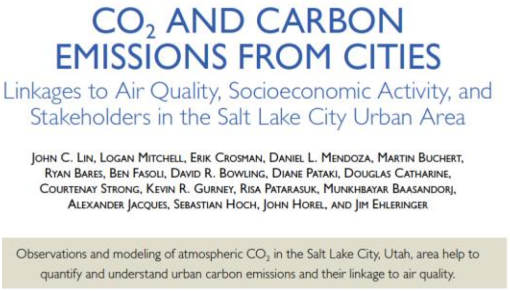
Significance of Urban Emissions



http://www.c40.org/c40_research

Sources of Carbon Emissions in Cities




CO_2 AND CARBON EMISSIONS FROM CITIES

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

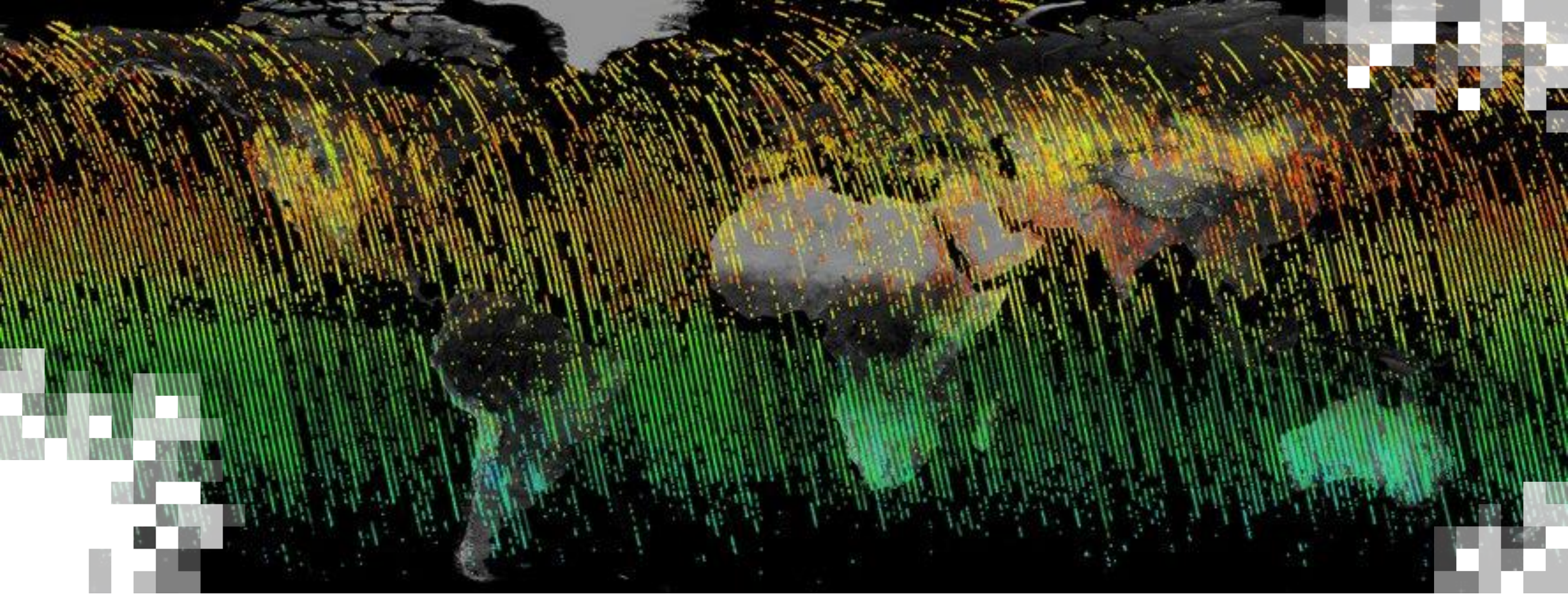
John C. Lin, Logan Mitchell, Erik Crosman, Daniel L. Mendoza, Martin Buchert, Ryan Bares, Ben Fasoli, David R. Bowling, Diane Pataki, Douglas Catharine, Courtenay Strong, Kevin R. Gurney, Risa Patarasuk, Munkhbayar Baasandorj, Alexander Jacques, Sebastian Hoch, John Horel, and Jim Ehleringer

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)

Key Scientific Questions

- How can atmospheric CO_2 be used to understand urban carbon emissions?
- How do carbon emissions vary between different cities?
- How can co-benefits be realized in reducing carbon emissions and improving air quality?



Part 1: Examples of Studies from Salt Lake City, Utah

Credit: NASA Earth Observatory/NOAA NGDC

Credit: NASA Earth Observatory/NOAA NGDC

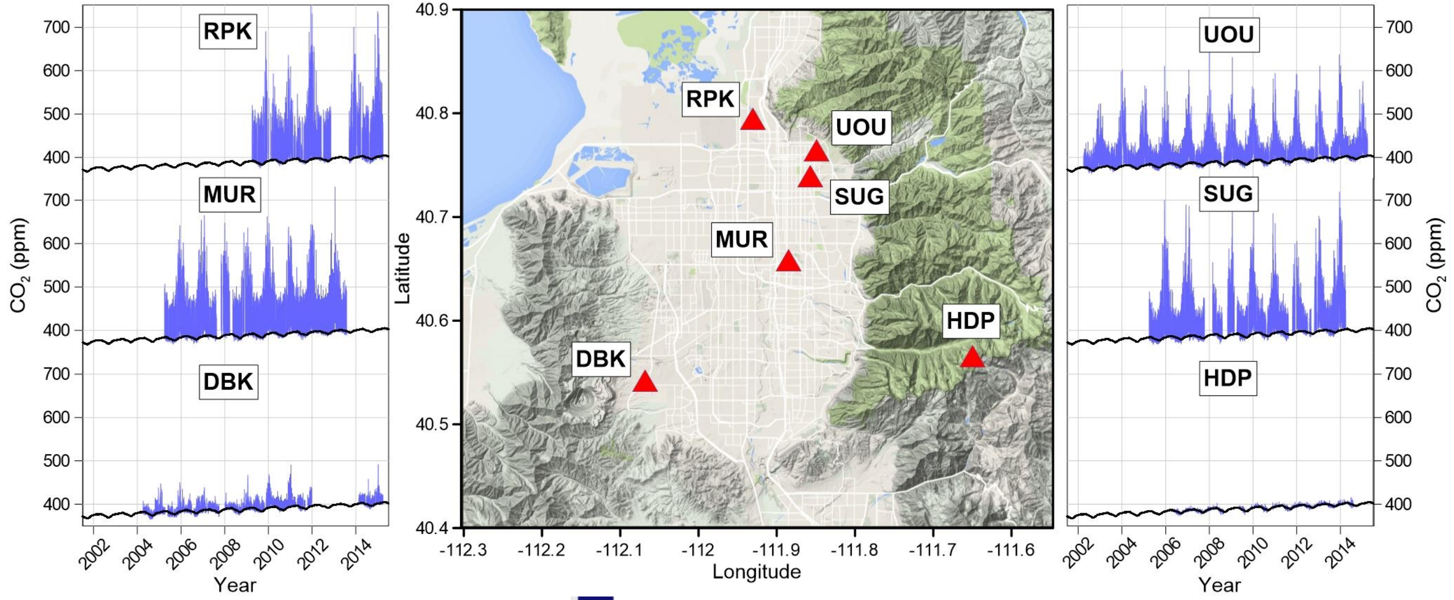
Credit: NASA Earth Observatory/NOAA NGDC

Salt Lake Valley CO_2 Observational Network
(Among the longest-running urban CO_2 networks in the world)

https://air.utah.edu/

"If you can't measure it, you can't improve it."
- Peter Drucker

Salt Lake City – CO_2 Long-Term Trends at various sites (3-letter site codes below)



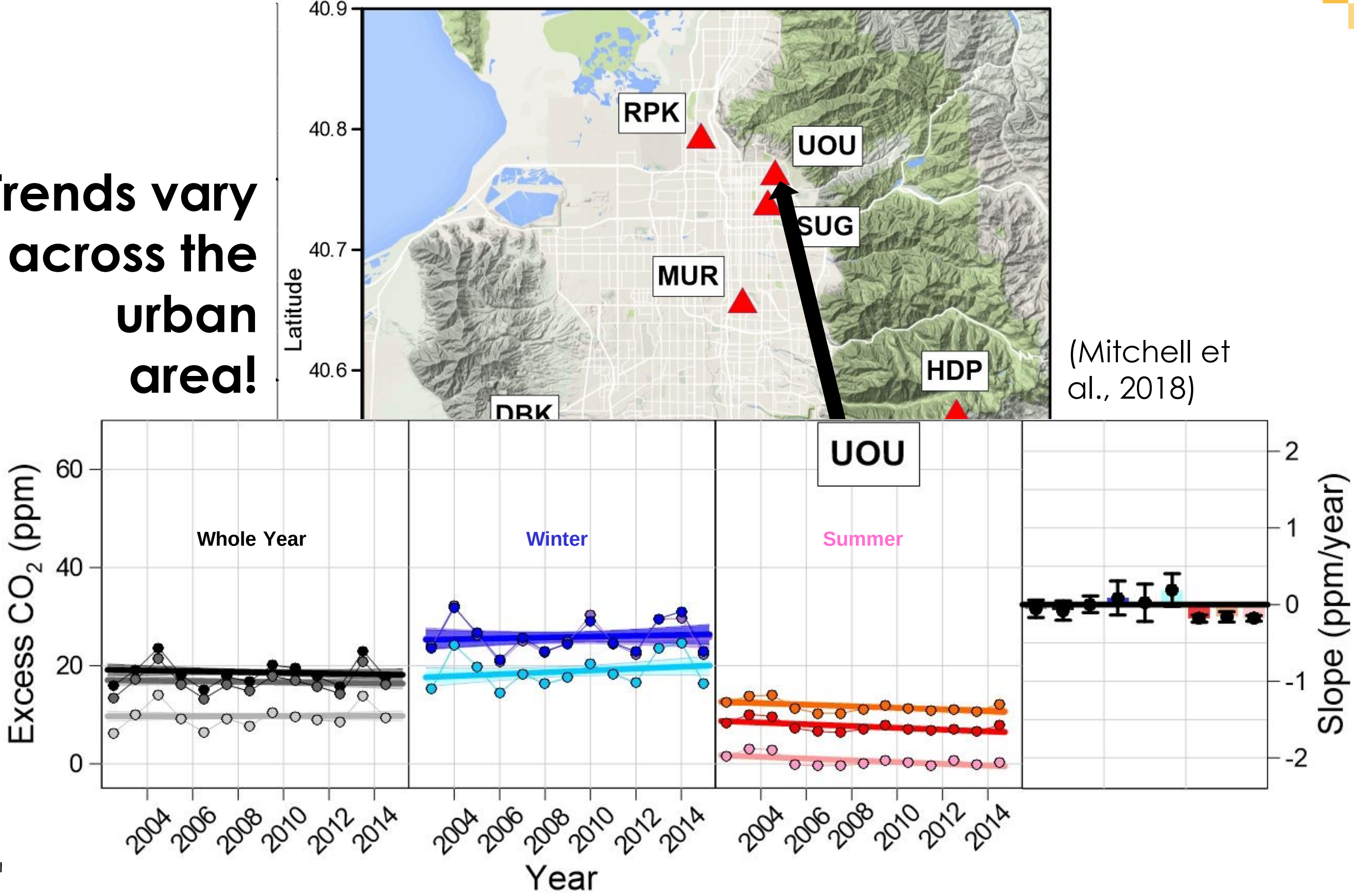
Long-term urban carbon dioxide observations reveal spatial and temporal dynamics related to urban characteristics and growth

Logan E. Mitchell[a,1], John C. Lin[a], David R. Bowling[b], Diane E. Pataki[b], Courtenay Strong[a], Andrew J. Schauer[c], Ryan Bares[a], Susan E. Bush[b], Britton B. Stephens[d], Daniel Mendoza[a], Derek Mallia[a], Lacey Holland[a,e], Kevin R. Gurney[f], and James R. Ehleringer[b]

[a]Department of Atmospheric Sciences, University of Utah, Salt Lake City, UT 84112; [b]Department of Biology, University of Utah, Salt Lake City, UT 84112; [c]Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195; [d]National Center for Atmospheric Research, Boulder, CO 80307; [e]Department of Atmospheric Sciences, University of Hawaii at Manoa, Honolulu, HI 96822; and [f]School of Life Sciences, Arizona State University, Tempe, AZ 85287

Salt Lake City – CO_2 Long-Term Trends

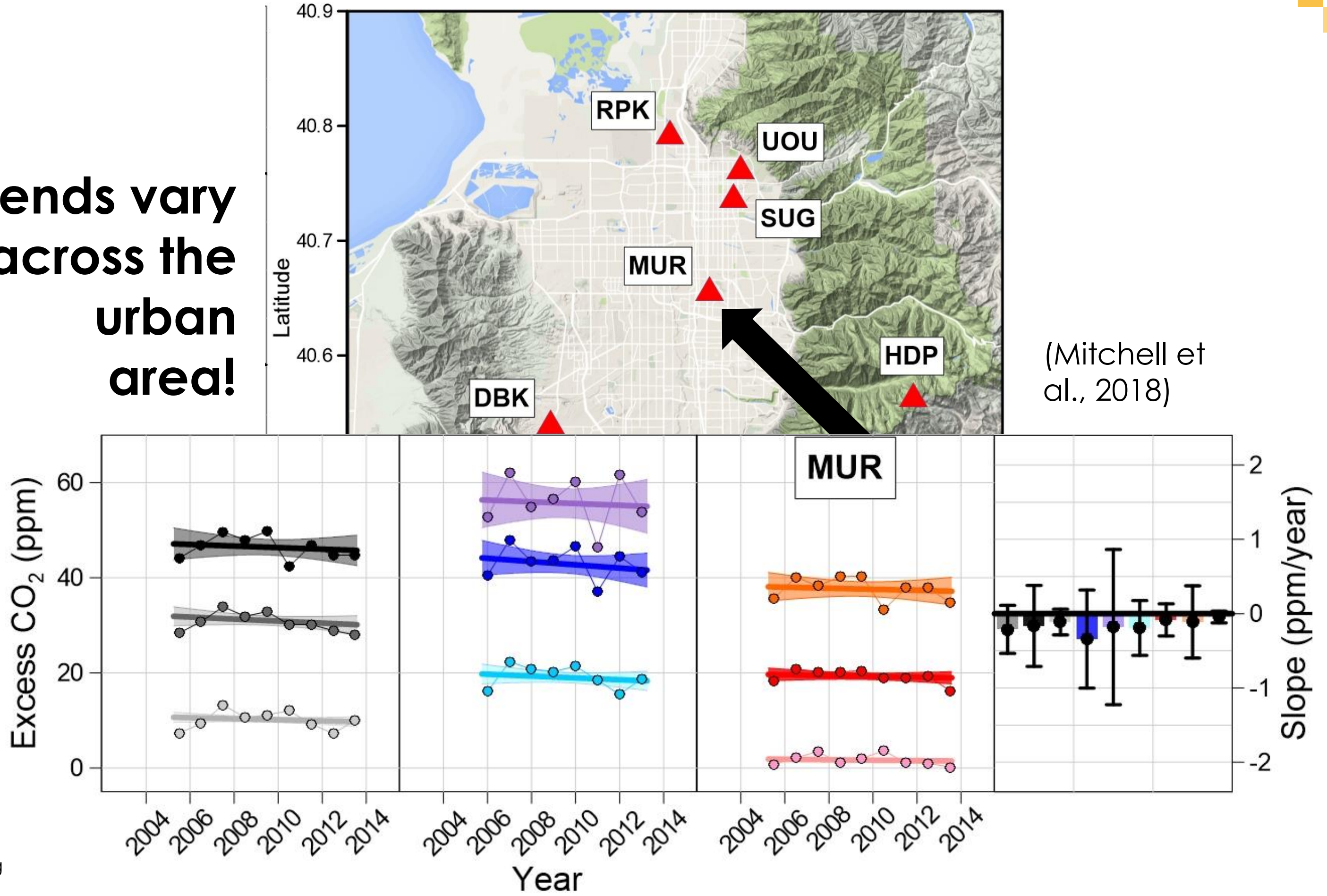
Trends vary across the urban area!



(Mitchell et al., 2018)

Salt Lake City – CO_2 Long-Term Trends

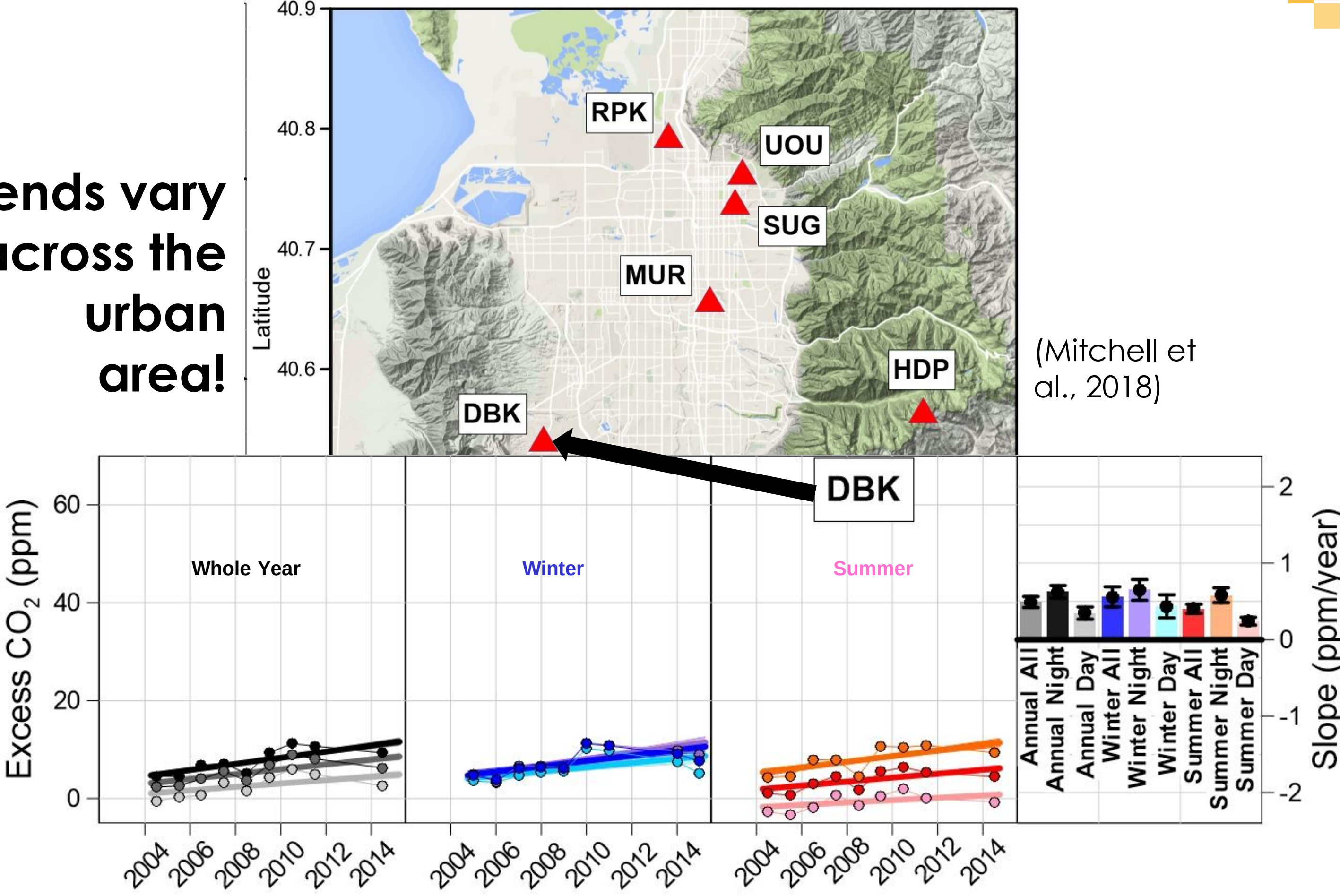
Trends vary across the urban area!



(Mitchell et al., 2018)

Salt Lake City – CO_2 Long-Term Trends

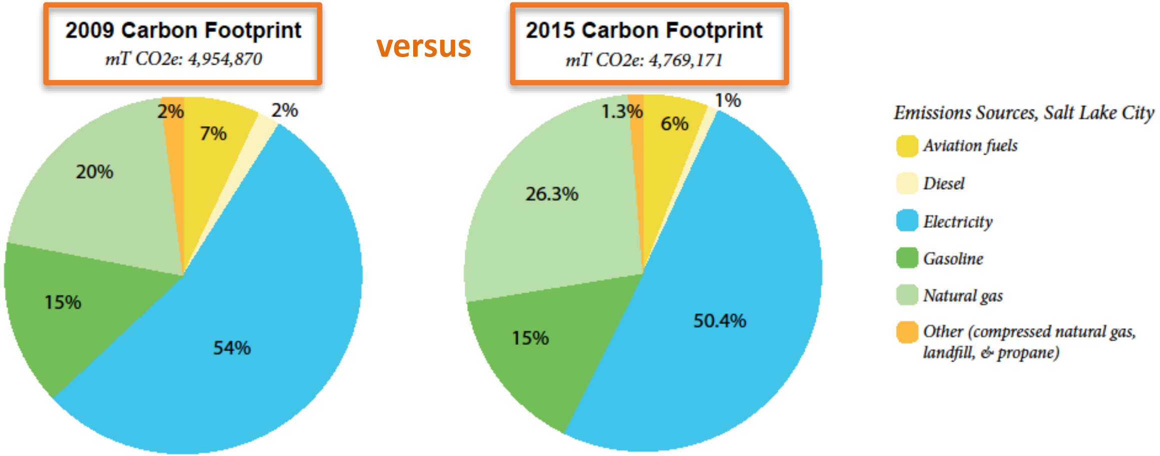
Trends vary across the urban area!



(Mitchell et al., 2018)

Comparison Against Salt Lake City Government's Estimates of Carbon Emissions

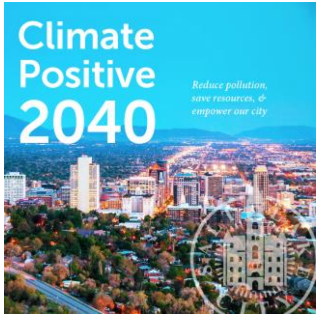
The following pie charts represent most Scope I and Scope II emissions for the Salt Lake City community. The charts include fuels combusted locally, as well as upstream emissions associated with electricity generation. Scope III emissions such as those associated with the production of food and goods consumed locally are important contributors to climate change, but are not quantified in this report.



2009: mT CO_2e: ~5 million

2015: mT CO_2e: ~4.8 million

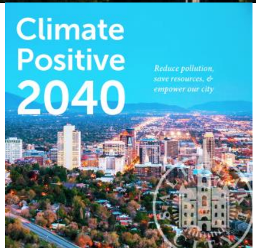
Consistent with observed flat trends in atmospheric CO_2 in Salt Lake City



Salt Lake City's Climate Commitment (Climate Positive 2040)

"Our city. . . is committed to powering 50% of municipal operations with renewables by 2020. We have set another goal of transitioning the entire community's electricity supply to 100 percent clean energy by 2032, followed by an overall reduction of community greenhouse gas emissions 80% by 2040."

-Jackie Biskupski, Former Mayor of Salt Lake City



Seen as Nature Lovers' Paradise, Utah Struggles With Air Quality

Scott G. Winterton/Deseret News

Along the Wasatch Front, the corridor where most Utahans live, weather and geography often help trap bad air.

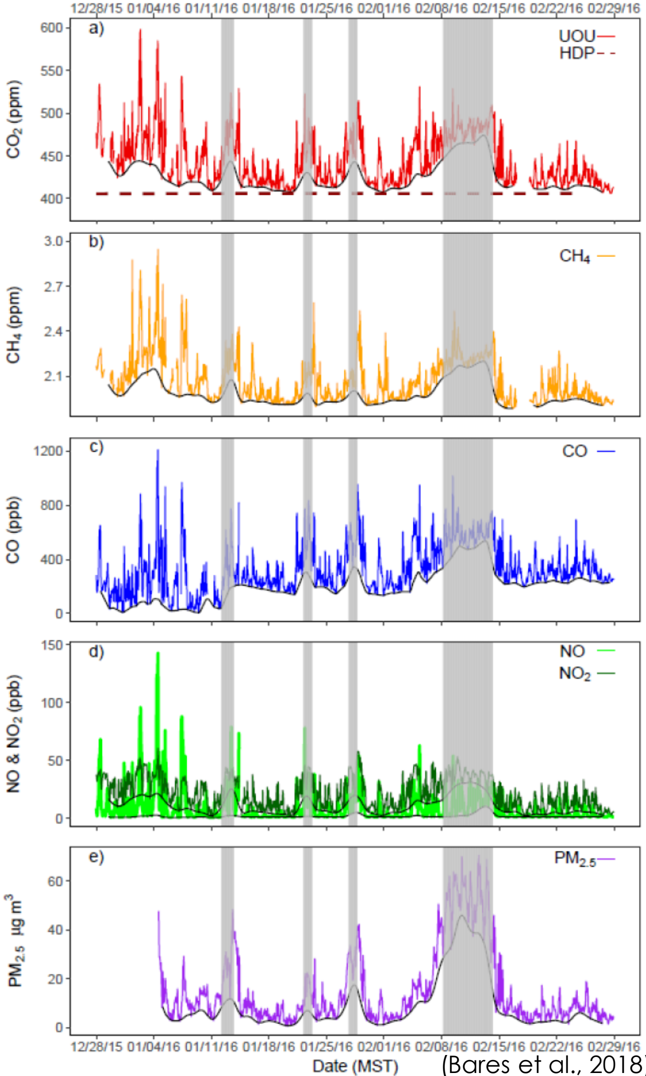
By DAN FROSCH

Published: February 23, 2013 New York Times

https://www.nytimes.com/2013/02/24/us/utah-a-nature-lovers-haven-is-plagued-by-dirty-air.html

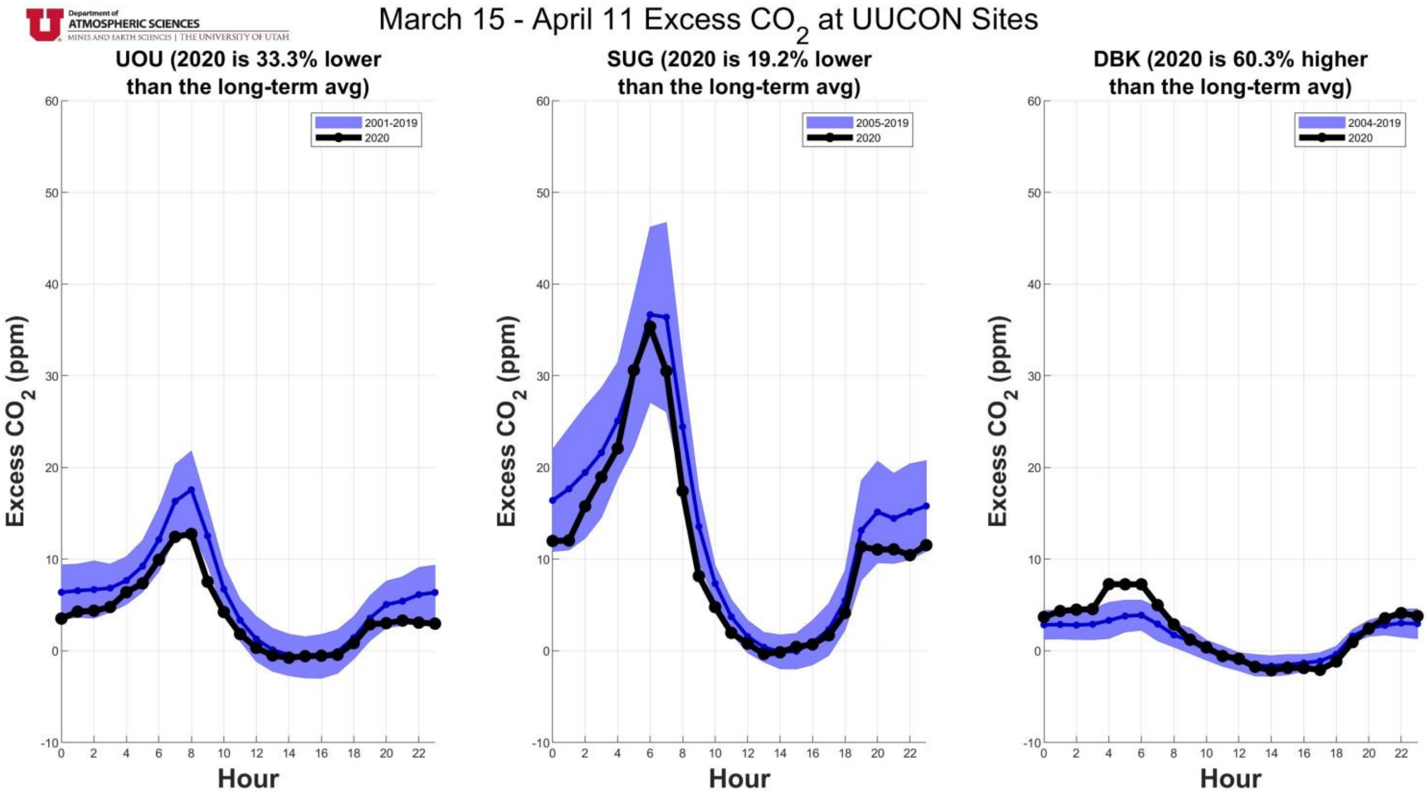
Observations on Univ. of Utah Campus of Greenhouse Gases and Criteria Pollutants

Utah Trace Gas & Air Quality (U-ATAQ) Lab



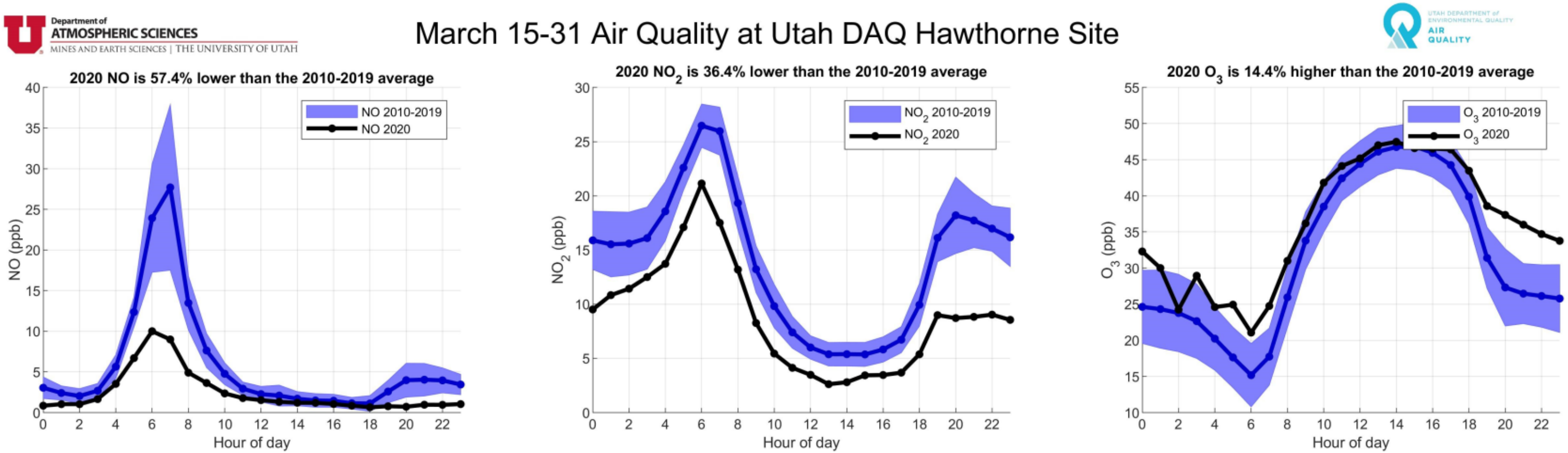
(Bares et al., 2018)

COVID Shutdown Signal

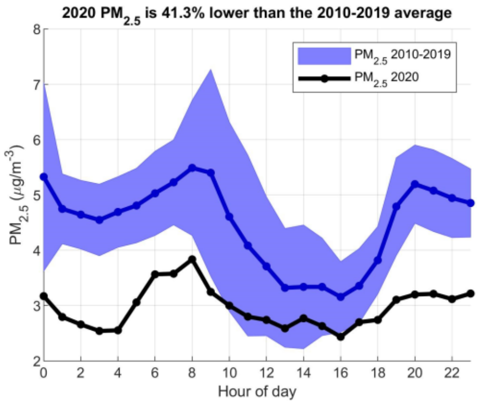


L. Mitchell, Unpublished: https://atmos.utah.edu/air-quality/covid-19_air_quality.php

COVID Shutdown Signal



L. Mitchell, Unpublished: https://atmos.utah.edu/air-quality/covid-19_air_quality.php



TRAX Monitoring of Air Quality and Greenhouse Gases in the Salt Lake Valley

UTA TRAX

THE UNIVERSITY OF UTAH

UTAH DEPARTMENT of ENVIRONMENTAL QUALITY
AIR QUALITY

Atmospheric Environment 187 (2018) 9–23

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

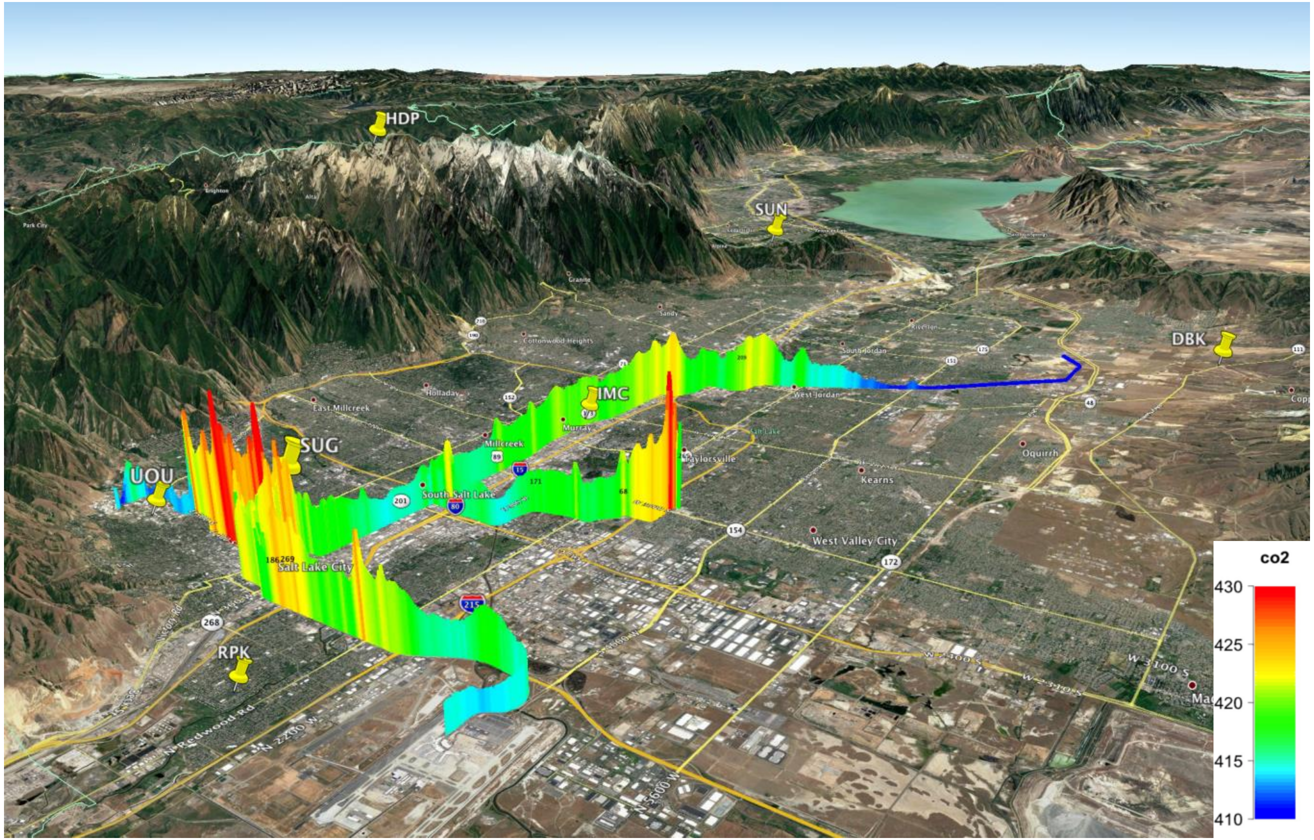
ELSEVIER

Monitoring of greenhouse gases and pollutants across an urban area using a light-rail public transit platform

Logan E. Mitchell[a,*], Erik T. Crosman[a], Alexander A. Jacques[a], Benjamin Fasoli[a], Luke Leclair-Marzolf[a], John Horel[a], David R. Bowling[b], James R. Ehleringer[b], John C. Lin[a]

[a] Department of Atmospheric Sciences, University of Utah, Salt Lake City, UT, United States
[b] Department of Biology, University of Utah, Salt Lake City, UT, United States

Spatial Distribution of CO_2 as Observed on Light Rail Routes (July and August 2015)

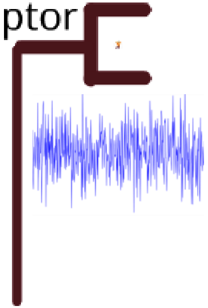


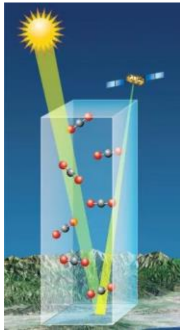
(Lin et al., BAMS, 2018)

Information in Atmospheric CO2 Observations

Atmospheric Measurement Carries **INFORMATION** About **EMISSIONS** & **PROCESSES** in Upwind Source Region

(4) Observations at receptor

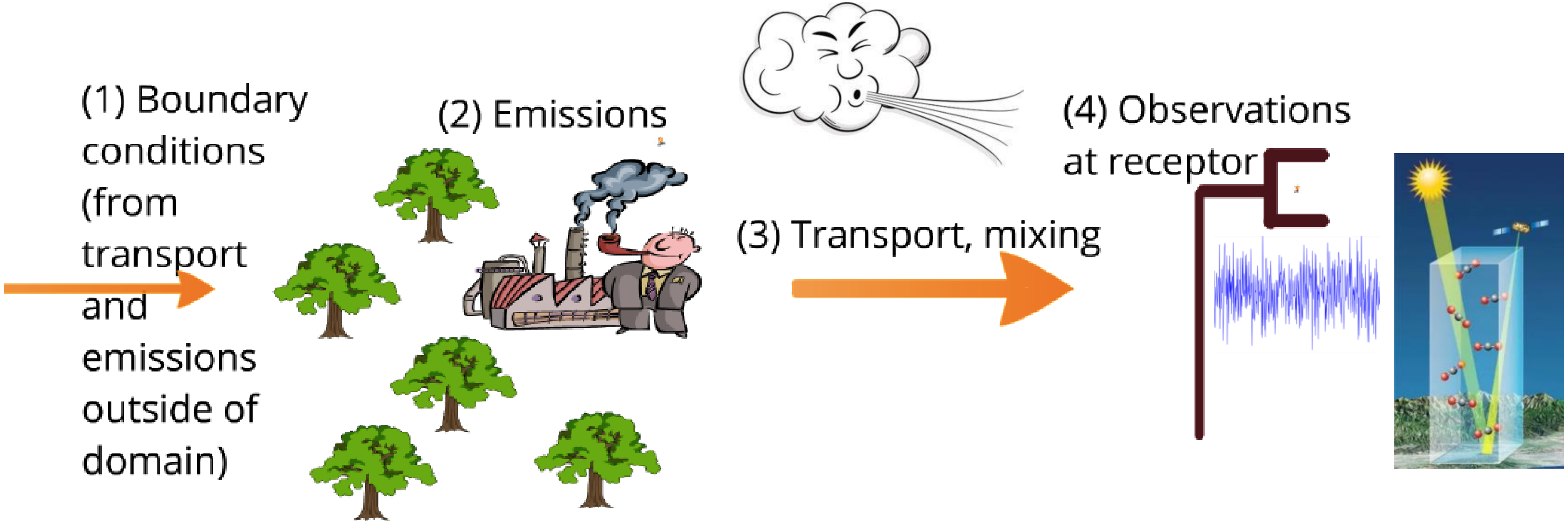




For Example, CO_2

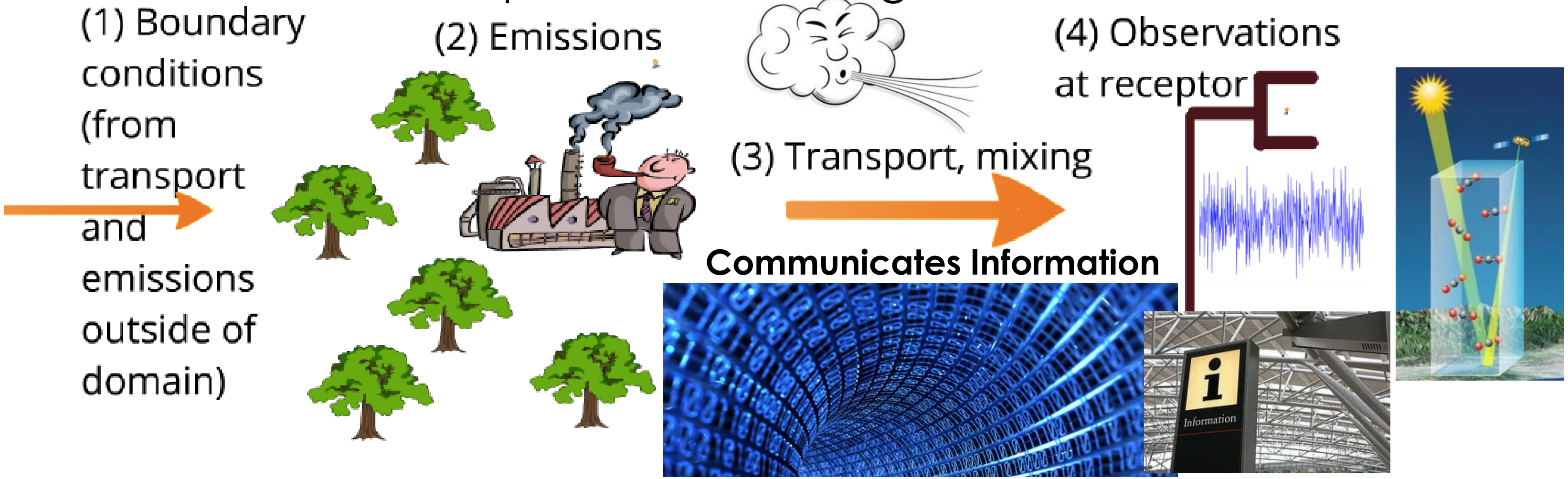
Information in Atmospheric CO_2 Observations

Atmospheric Measurement Carries **INFORMATION** About **EMISSIONS** & **PROCESSES** in Upwind Source Region



Information in Atmospheric CO_2 Observations

Atmospheric Measurement Carries **INFORMATION** About **EMISSIONS** & **PROCESSES** in Upwind Source Region



Information on:

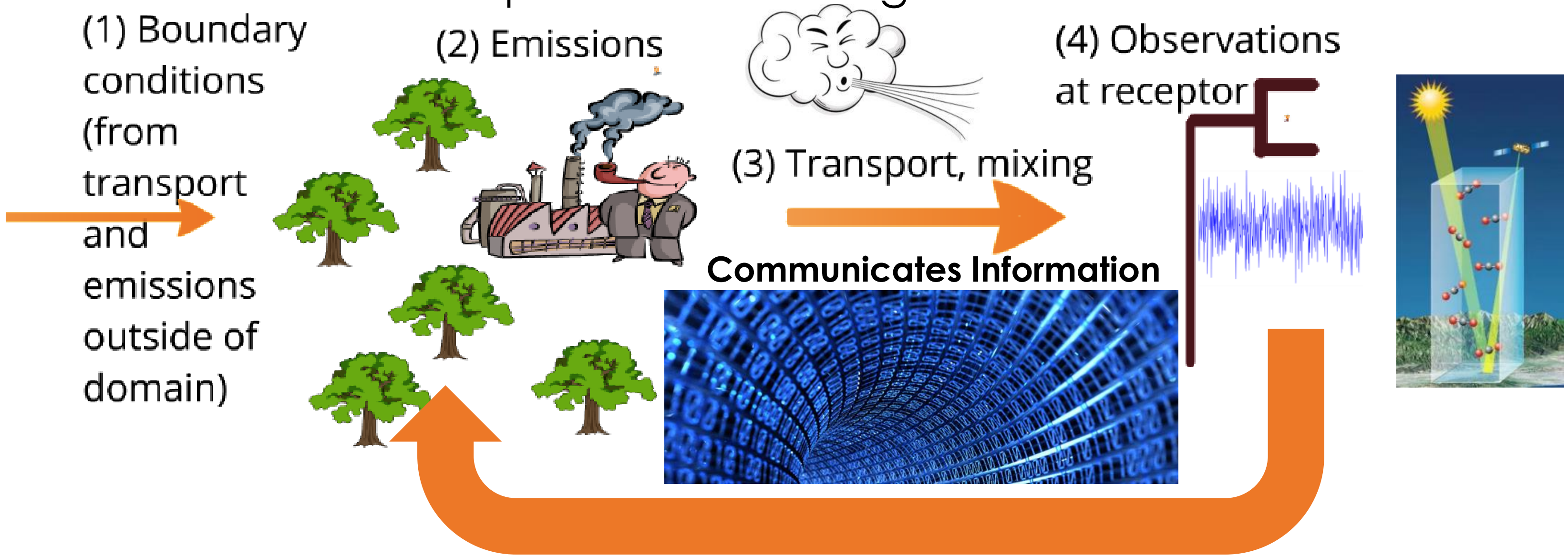
- Carbon emissions, fluxes
- Ecosystem stress
- Pollution, air quality
- Hydrology
- Etc.

The atmospheric observations can be:

- CO_2, CH_4
- CO, $PM_{2.5}$, NOx
- H_2O, D_2O, $H_2{}^{18}O$
- And many others…

Information in Atmospheric CO_2 Observations

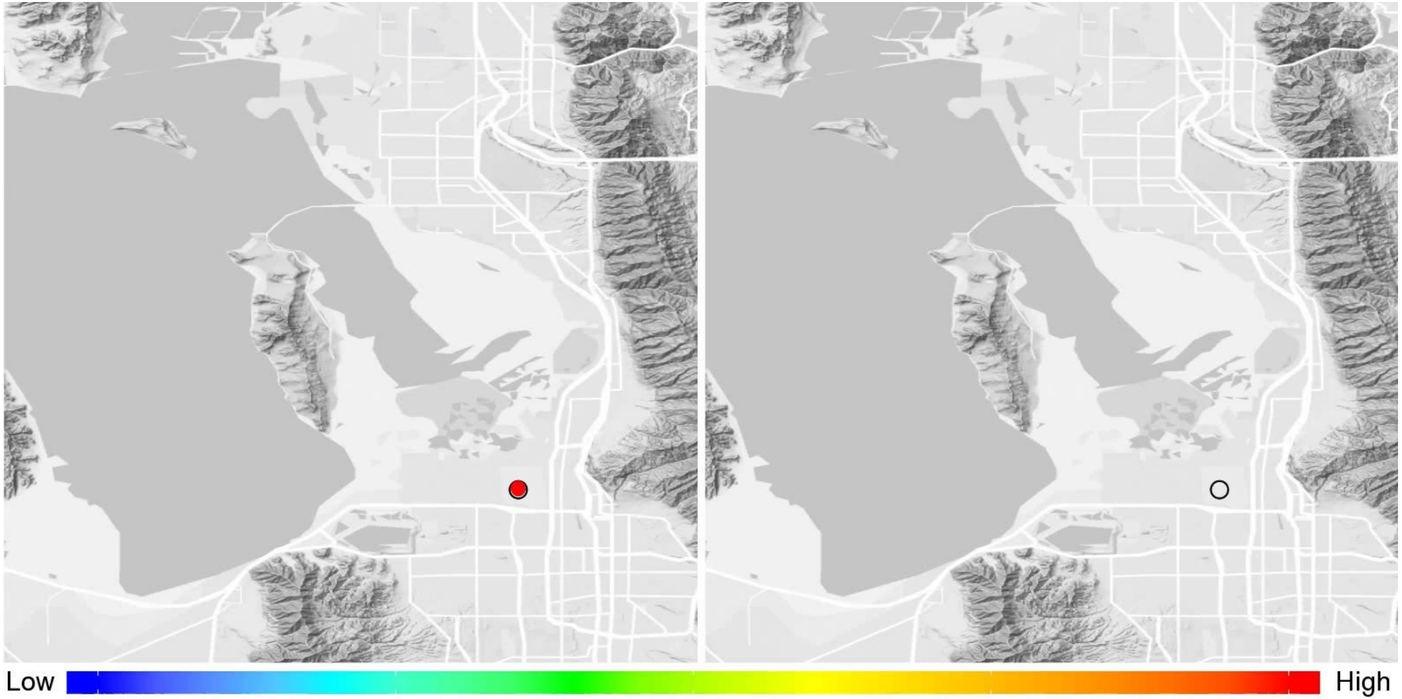
Atmospheric Measurement Carries **INFORMATION** About **EMISSIONS** & **PROCESSES** in Upwind Source Region



BUT the atmosphere is an **IMPERFECT** communication channel (loss of info through mixing); **AND** our ability to decode the information through atmosphere modeling is subject to uncertainties.

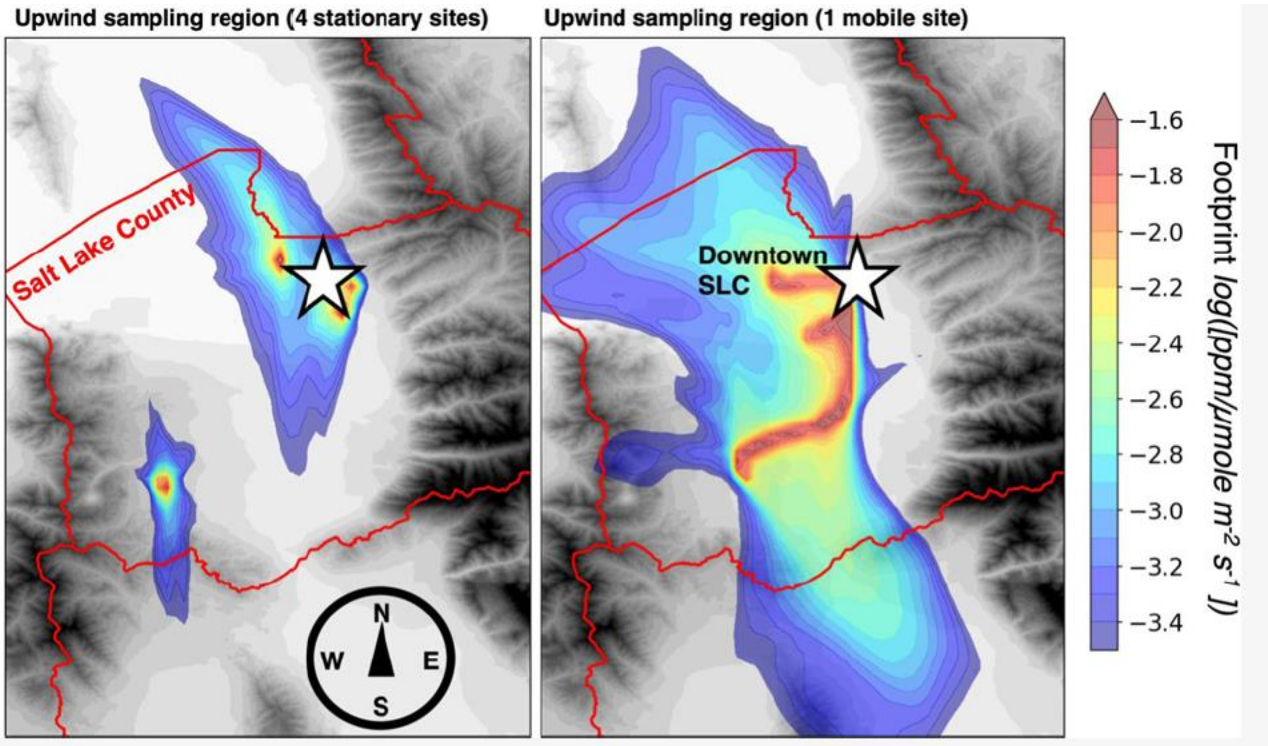
Stochastic Time-Inverted Lagrangian Transport (STILT) Model Simulation:

Determining Source Region



https://uataq.github.io/stilt

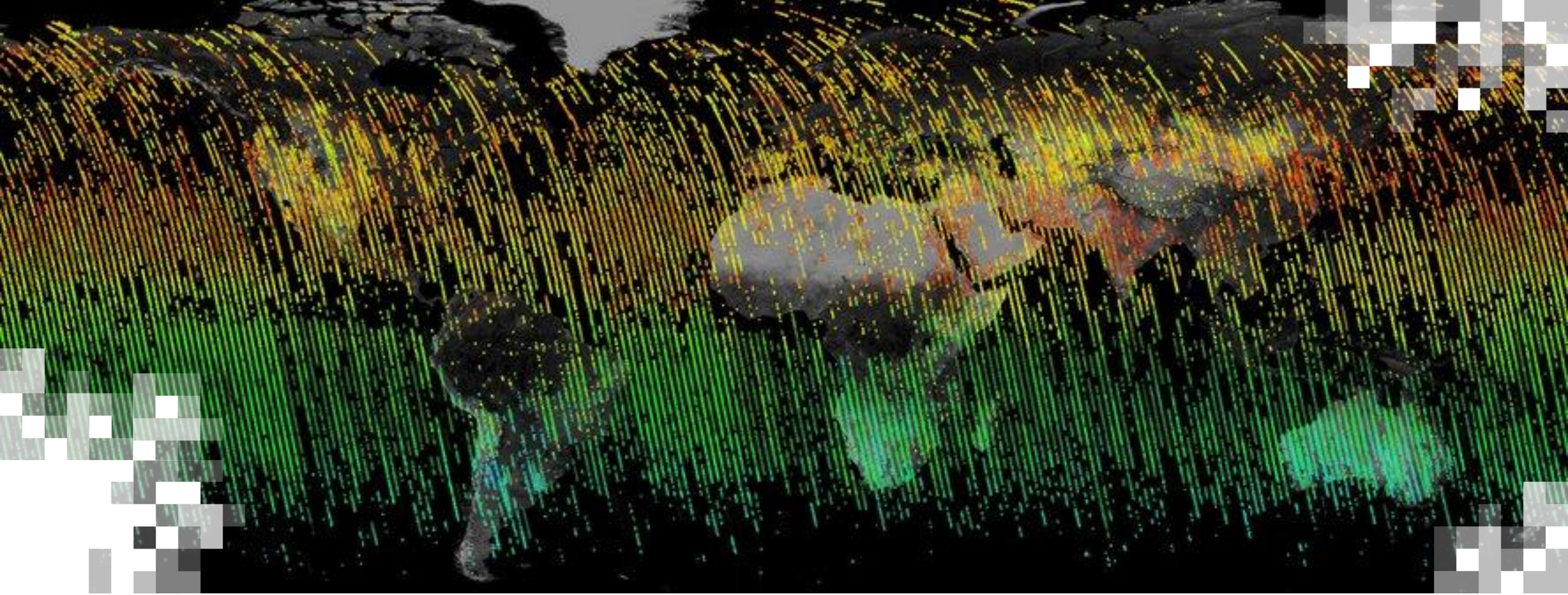
STILT-Simulated Atmospheric Footprints of Observations



Environmental Science & Technology
pubs.acs.org/est

Constraining Urban CO_2 Emissions Using Mobile Observations from a Light Rail Public Transit Platform

Derek V. Mallia,* Logan E. Mitchell, Lewis Kunik, Ben Fasoli, Ryan Bares, Kevin R. Gurney, Daniel L. Mendoza, and John C. Lin



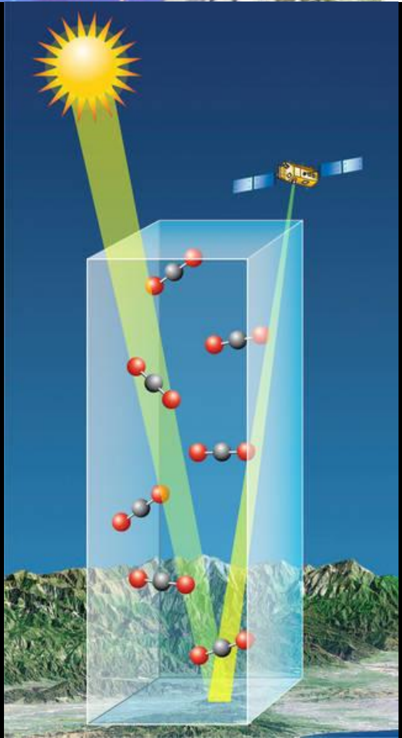
Part 2: Understanding Carbon Emissions from Cities Around the World

Credit: NASA Earth Observatory/NOAA NGDC

Credit: NASA Earth Observatory/NOAA NGDC

Problem: Lack of High-Precision CO_2 Measurements in Most Cities Around the World!

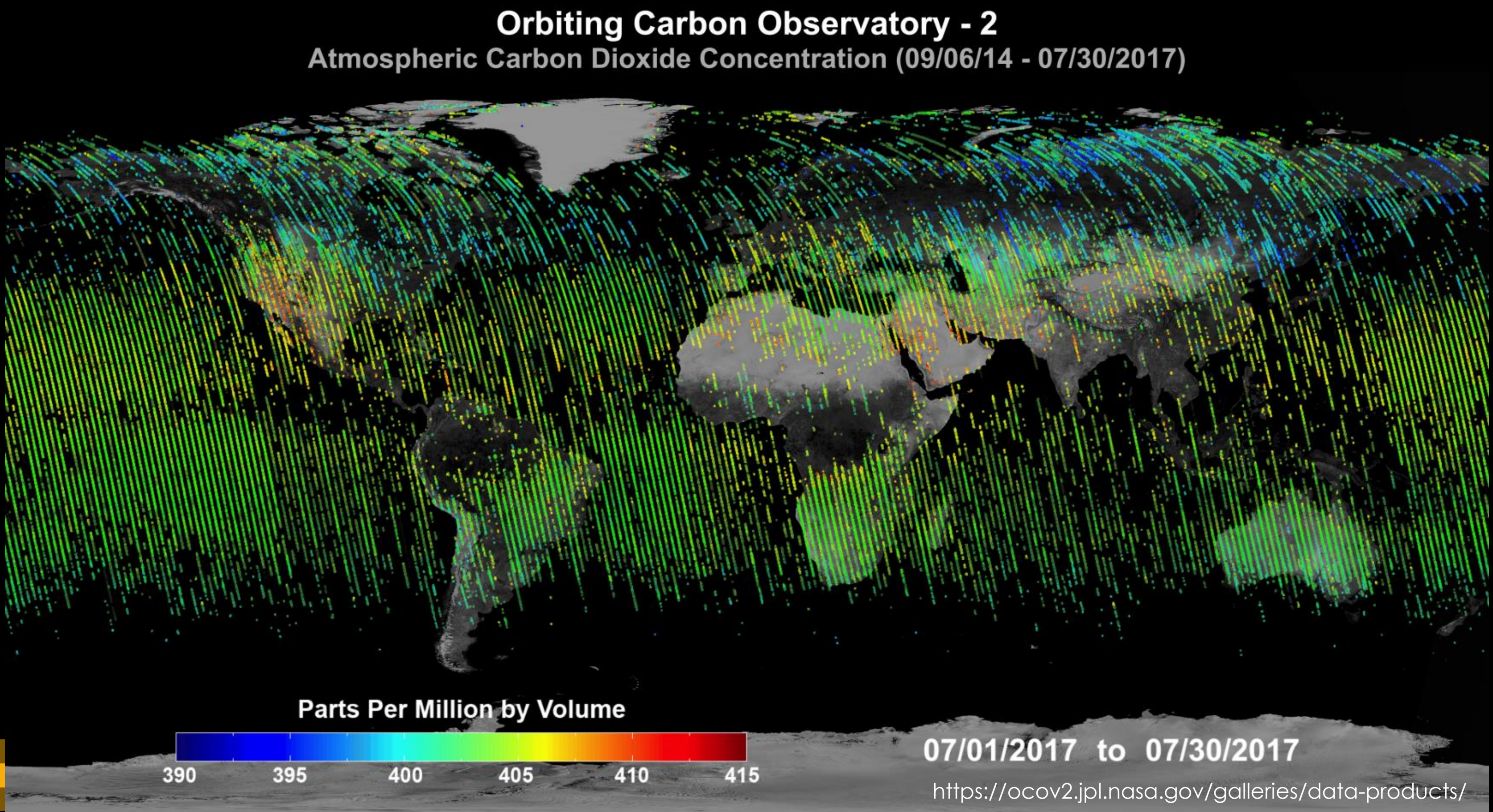
Satellites to the Rescue



Launched on July 1st, 2014

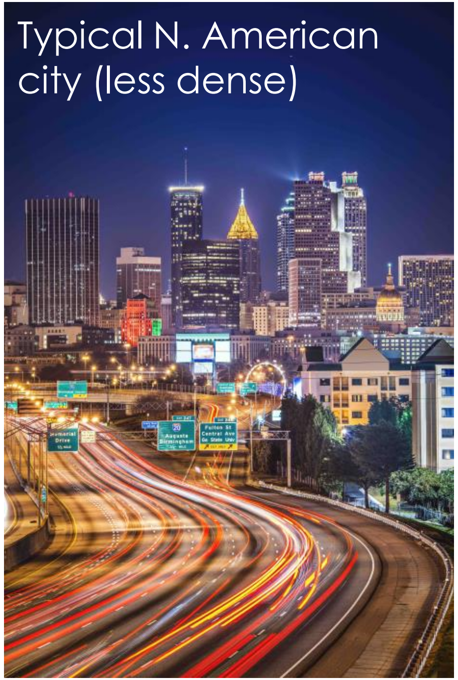
Credits: NASA-JPL/Caltech

Global Coverage from Space-Based CO_2 Measurements



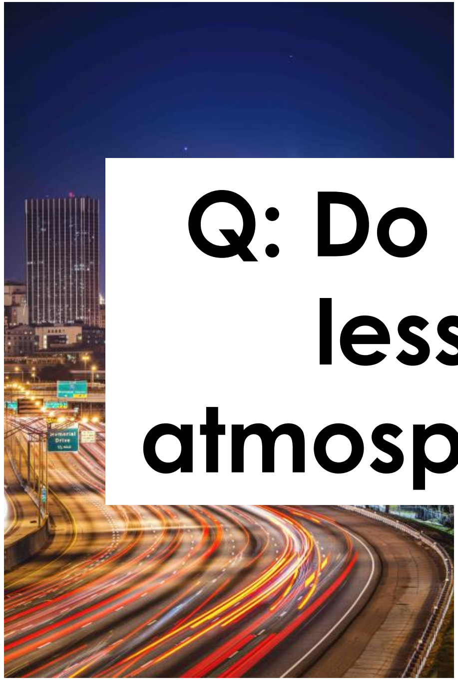
https://ocov2.jpl.nasa.gov/galleries/data-products/

How Do Emissions Vary Between:



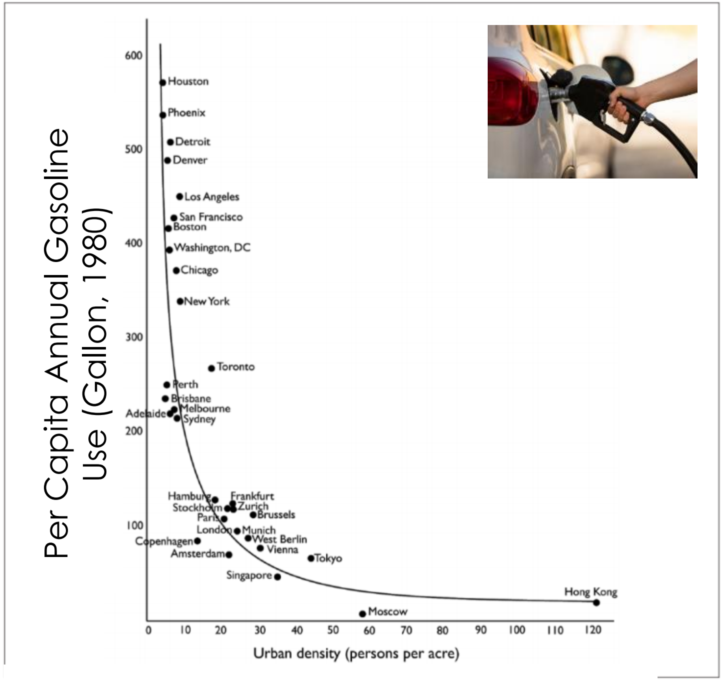
versus

How Do Emissions Vary Between:



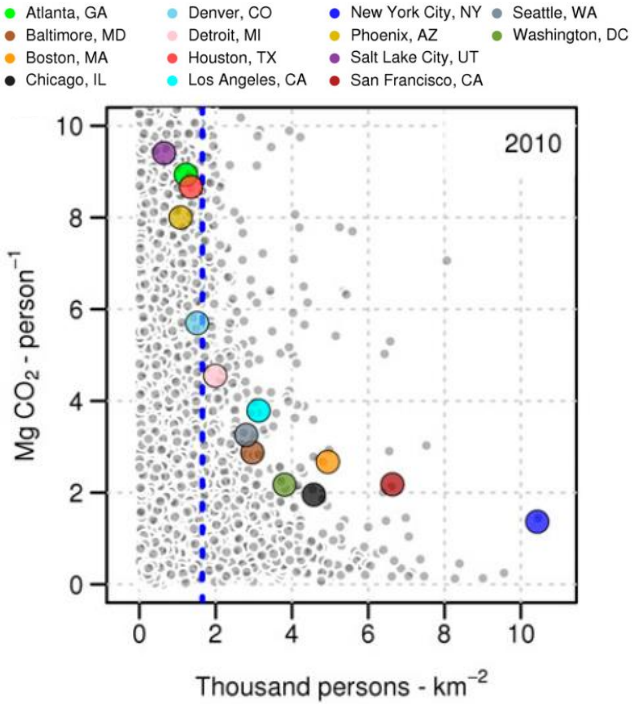
Q: Do denser cities emit less carbon to the atmosphere (per capita)?

Do Denser Cities Emit Less Carbon to the Atmosphere (Per Capita)?



Urban Density (Persons Per Acre)

[*Newman and Kenworthy*, 1989]



[*Gately et al.*, 2015]

Geosci. Model Dev., 11, 4843–4871, 2018
https://doi.org/10.5194/gmd-11-4843-2018

Geoscientific Model Development
Open Access
EGU

A Lagrangian approach towards extracting signals of urban CO_2 emissions from satellite observations of atmospheric column CO_2 (XCO_2): X-Stochastic Time-Inverted Lagrangian Transport model ("X-STILT v1")

Dien Wu[1], John C. Lin[1], Benjamin Fasoli[1], Tomohiro Oda[2], Xinxin Ye[3], Thomas Lauvaux[3], Emily G. Yang[4], and Eric A. Kort[4]

[1]Department of Atmospheric Sciences, University of Utah, Salt Lake City, USA
[2]Goddard Earth Sciences Technology and Research, Universities Space Research Association, Columbia, Maryland/Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[3]Department of Meteorology and Atmospheric Science, Pennsylvania State University, USA
[4]Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, USA

Correspondence: Dien Wu (dien.wu@utah.edu)

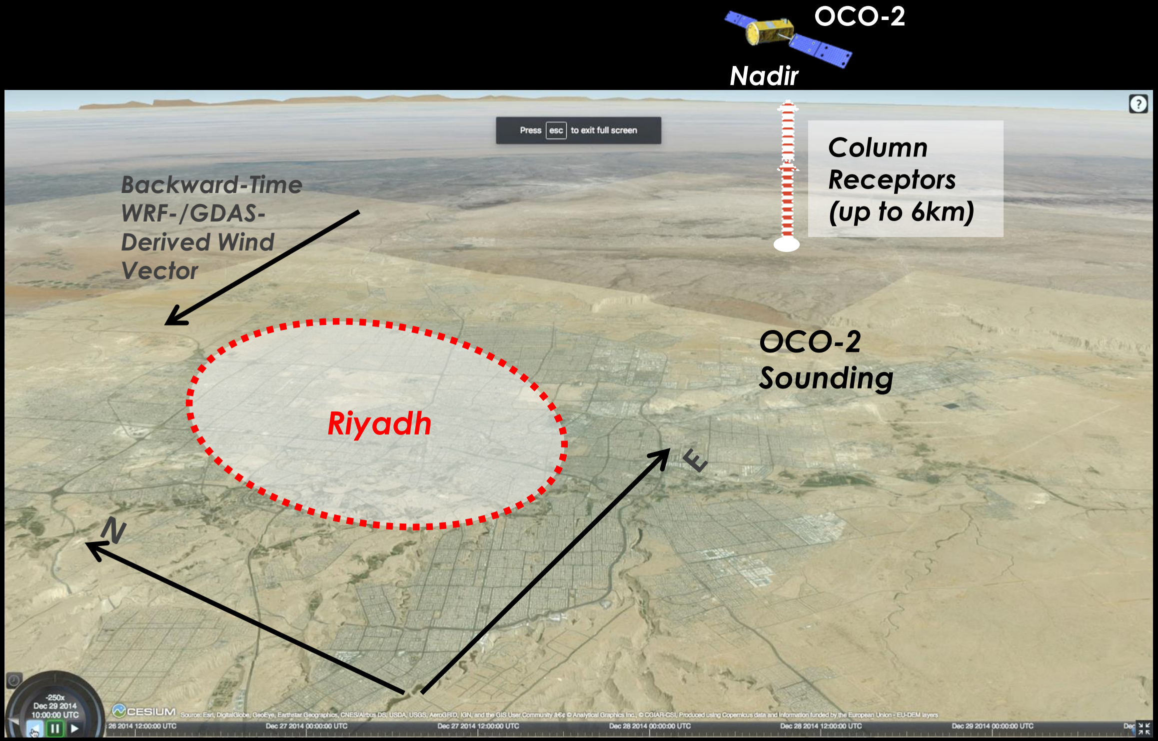
Land-Atmosphere Interactions Research (LAIR) Group
DEPARTMENT OF ATMOSPHERIC SCIENCES | THE UNIVERSITY OF UTAH

NASA Goddard Space Flight Center

PennState College of Earth and Mineral Sciences
Department of Meteorology and Atmospheric Science

CLIMATE AND SPACE SCIENCES AND ENGINEERING
UNIVERSITY OF MICHIGAN

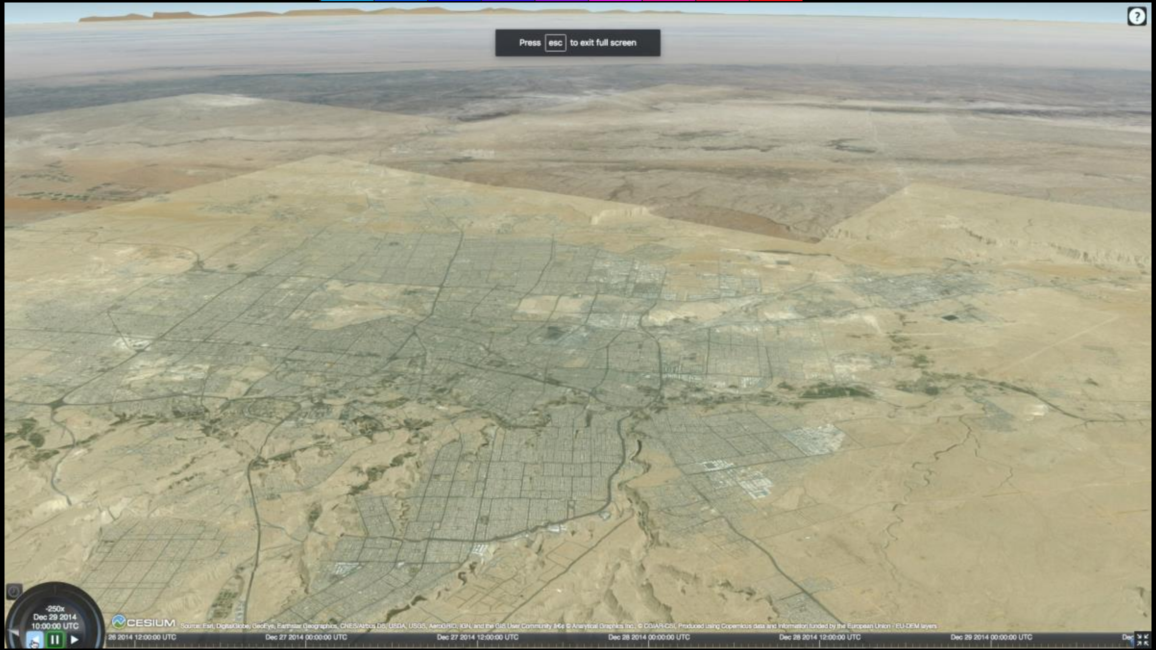
X-STILT to interpret OCO-2



X-STILT to interpret OCO-2

CO_2 enhancement for each air parcel
due to anthropogenic emissions

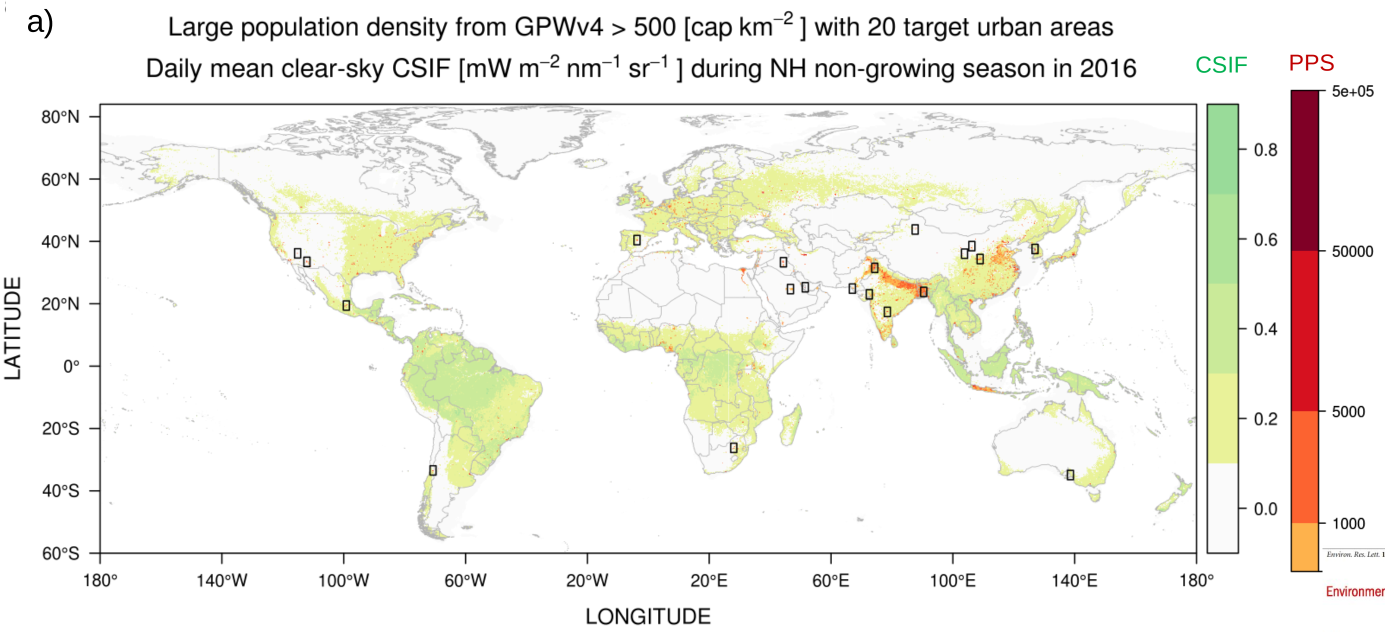
Lower	1	2	3	4	5	6	7	8	9	Higher



Target Cities for Analysis

- ❑ Relatively Large Population density (PPS)
- ❑ Minimal Biospheric Interference
  - Non-Growing season
  - Continuous Solar-Induced Fluorescence (CSIF)

- 20 cities
- 6-9 tracks/city
- 2 by 3 degrees small area



Environ. Res. Lett. **15** (2020) 035004 https://doi.org/10.1088/1748-9326/ab68eb

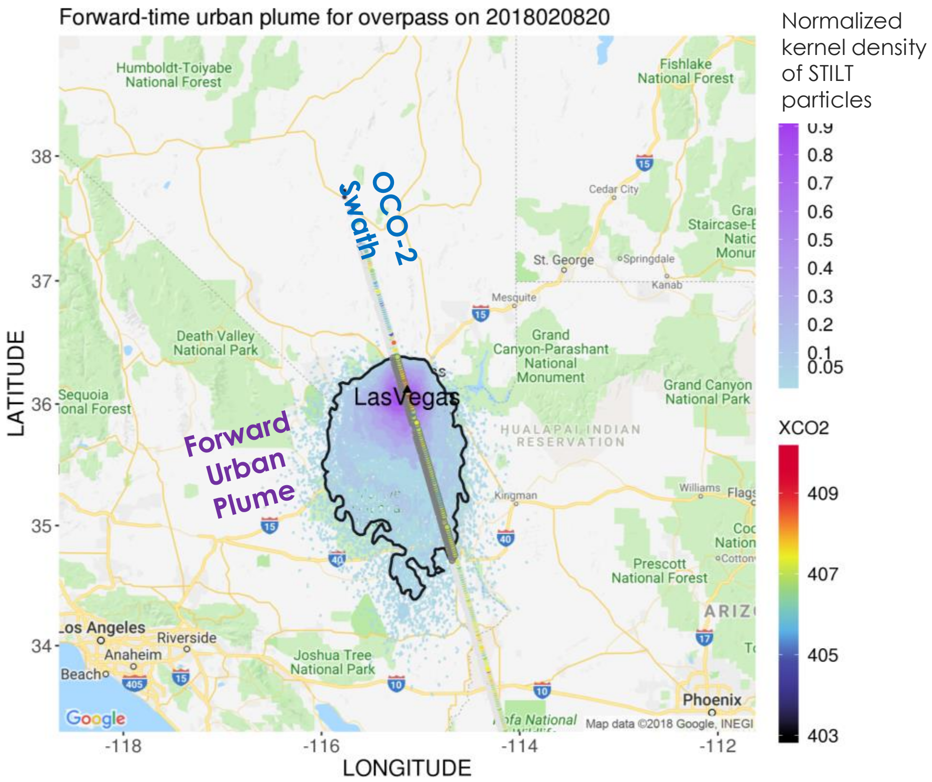
Environmental Research Letters

LETTER

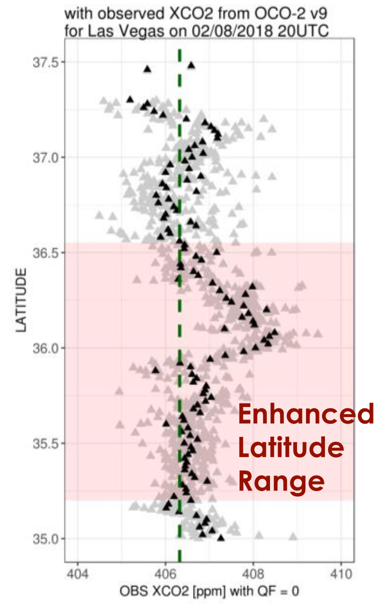
Space-based quantification of per capita CO_2 emissions from cities

Dien Wu[1,5], John C Lin[1], Tomohiro Oda[2,3] and Eric A Kort[4]

Methodology – Estimate Urban Signals



02/08/2018 Las Vegas

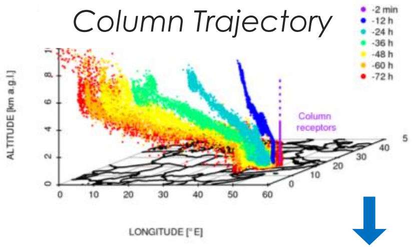


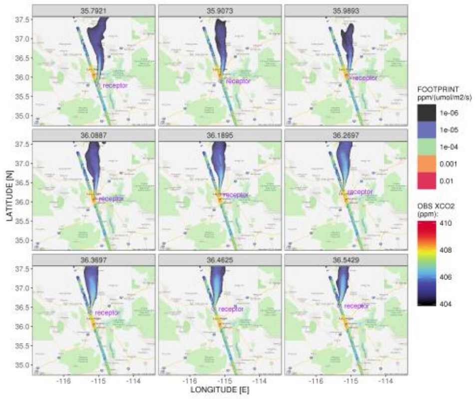
Observed urban signals ($XCO_{2.ff}$ with lat-integration)

$$ppm \cdot degN$$

Methodology – Calculate Carbon Fluxes from XCO_2

Column Trajectory

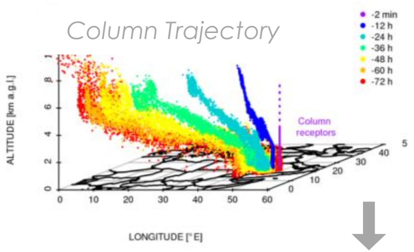




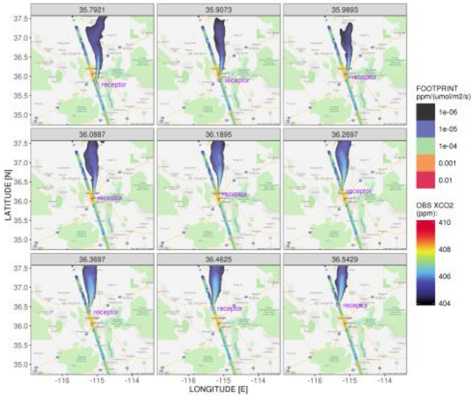
x-footprint/receptor/track

$$\frac{ppm}{\mu mol/m^2/s}$$

Methodology – Calculate Carbon Fluxes from XCO_2

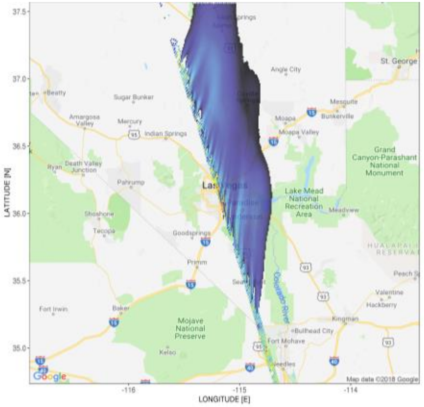


$$xfoot_{int}\,(x,y) = \int_{lat1}^{lat2} xfoot(x,y,lat)\,dlat$$



x-footprint/receptor/track

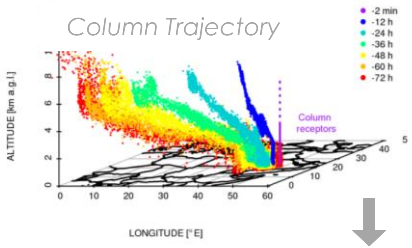
$\frac{ppm}{\mu mol/m^2/s}$

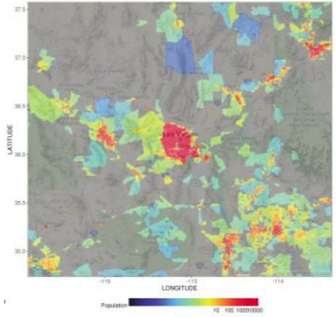


Lat-integrated x-footprint

$\frac{ppm \cdot degN}{\mu mol/m^2/s}$

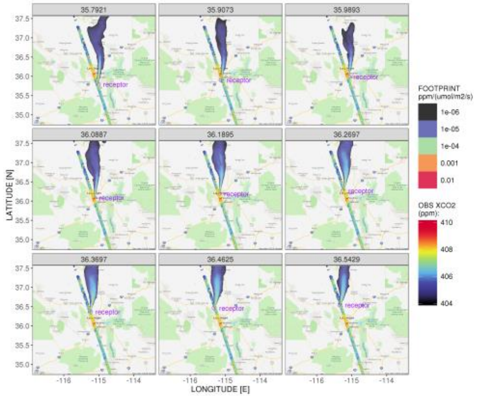
Methodology – Calculate Carbon Fluxes from XCO_2





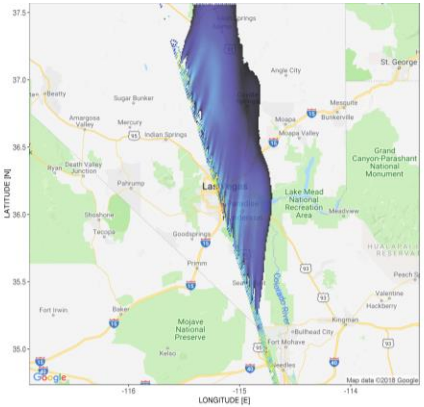
Weight by Gridded Population Density (PPS)

$$\frac{capita}{km^2}$$



x-footprint/receptor/track

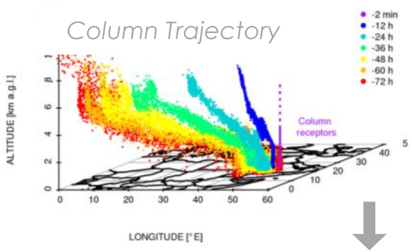
$$\frac{ppm}{\mu mol/m^2/s}$$

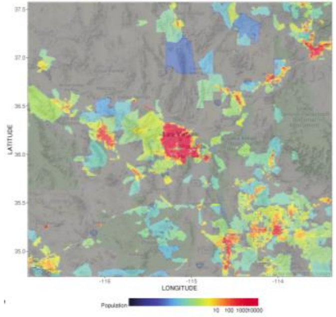


Lat-integrated x-footprint

$$\frac{ppm{\cdot}degN}{\mu mol/m^2/s}$$

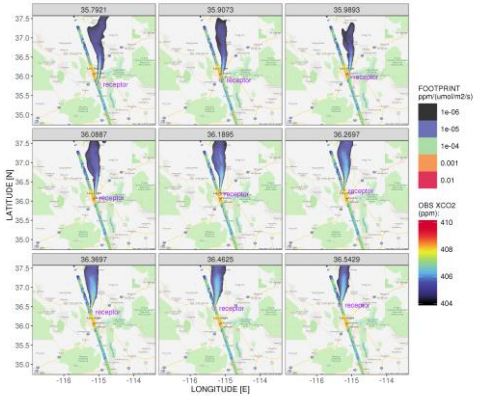
Methodology – Calculate Carbon Fluxes from XCO_2





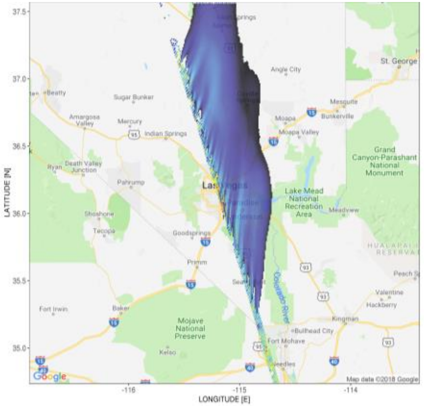
weight xfoot by gridded population density (PPS)

$$\frac{capita}{km^2}$$



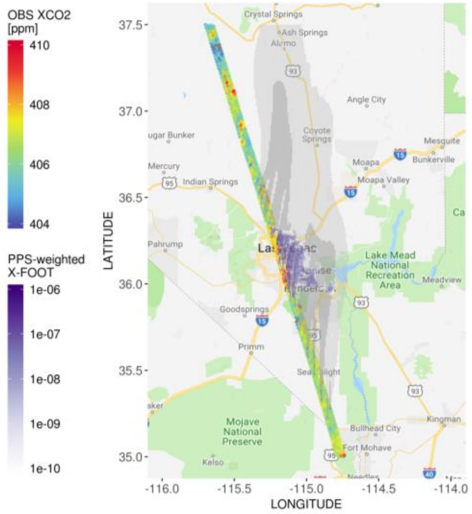
x-footprint/receptor/track

$$\frac{ppm}{\mu mol/m^2/s}$$



Lat-integrated x-footprint

$$\frac{ppm{\cdot}degN}{\mu mol/m^2/s}$$

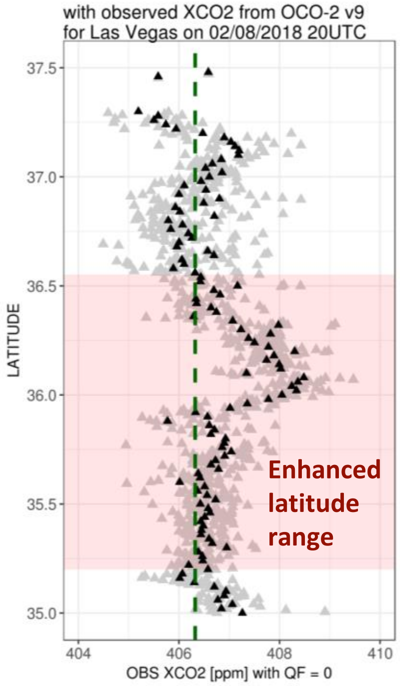


PPS weighted lat-integrated x-footprint (FP)

$$\frac{ppm{\cdot}degN}{\mu mol/capita/s}$$

Methodology – Calculate Carbon Fluxes from XCO_2

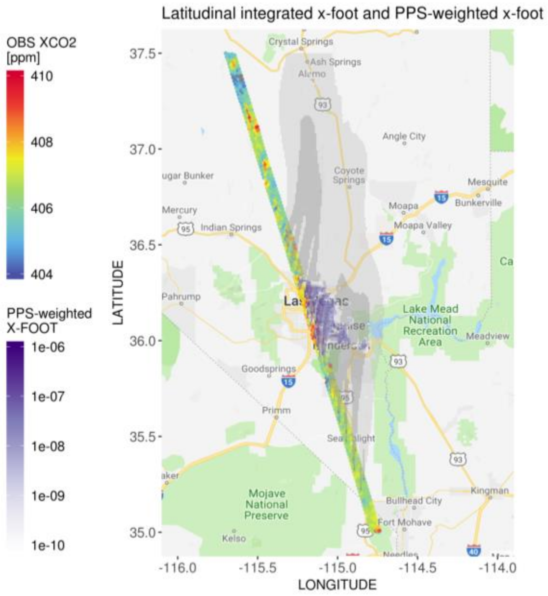
Satellite-observed urban signals in the atmosphere



$ppm \cdot degN$

$\div$

Population-weighted and lat-integrated x-footprint



$$\frac{ppm \cdot degN}{\mu mol/capita/s}$$

Per Capita Emissions

$= \mu mol/capita/s$

Environ. Res. Lett. 15 (2020) 035004 https://doi.org/10.1088/1748-9326/ab68eb

Environmental Research Letters

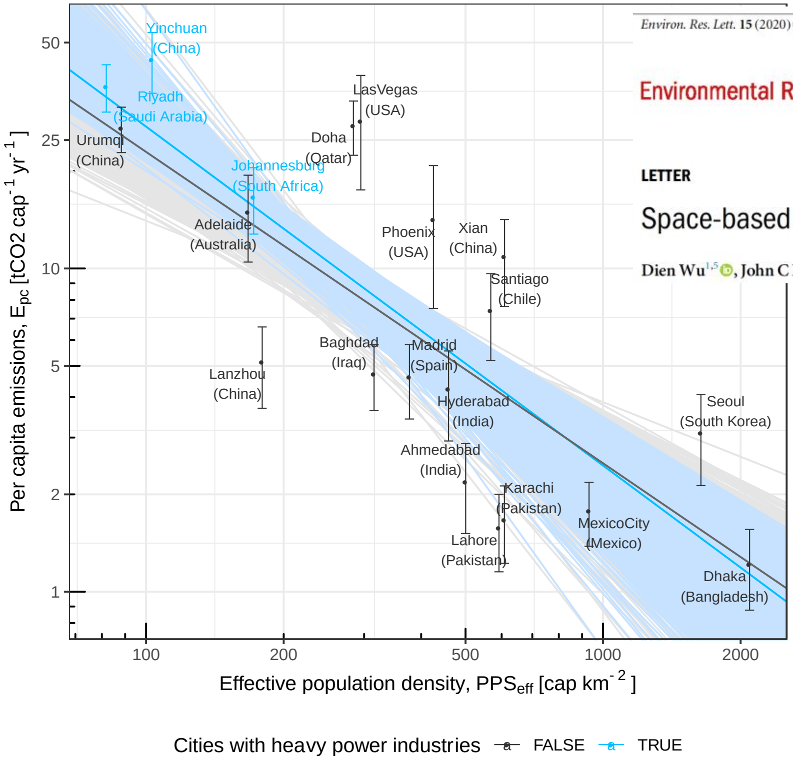
LETTER

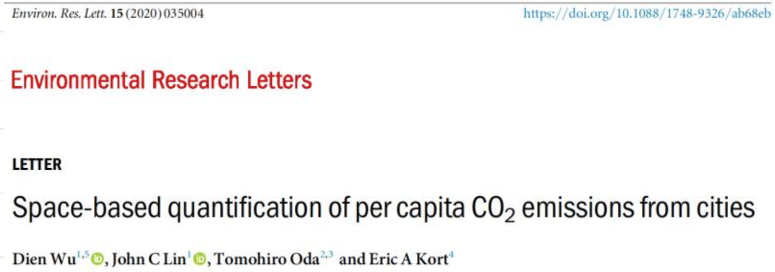
Space-based quantification of per capita CO_2 emissions from cities

Dien Wu[1,2], John C Lin[1], Tomohiro Oda[2,3] and Eric A Kort[4]

Results: Urban Scaling Relations

- *Epc vs. effective PPS (xfoot-weighted PPS, capita km^{-2})*
- *Error bars (observation + simulation errors)*

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Environmental Research Letters

LETTER

Space-based quantification of per capita CO_2 emissions from cities

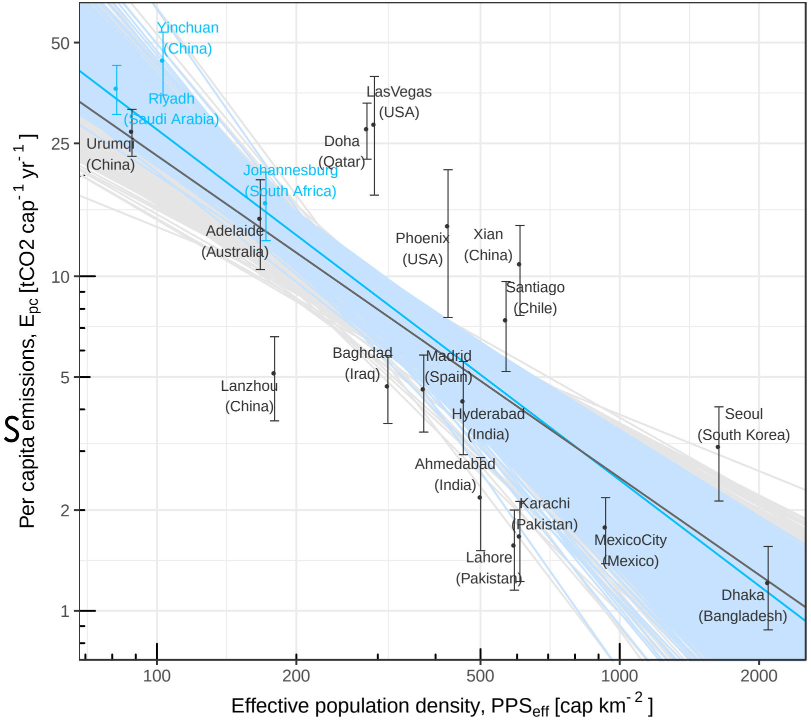
Dien Wu[1,5], John C Lin[1], Tomohiro Oda[2,3] and Eric A Kort[4]

Summary

- **Sub-linear relation between urban emissions & population** derived for the first time from space-based measurements for 20 cities

- Cities with large shares for power industry → higher per capita emissions

- **Denser cities indeed appear to emit less CO_2 to the atmosphere!**



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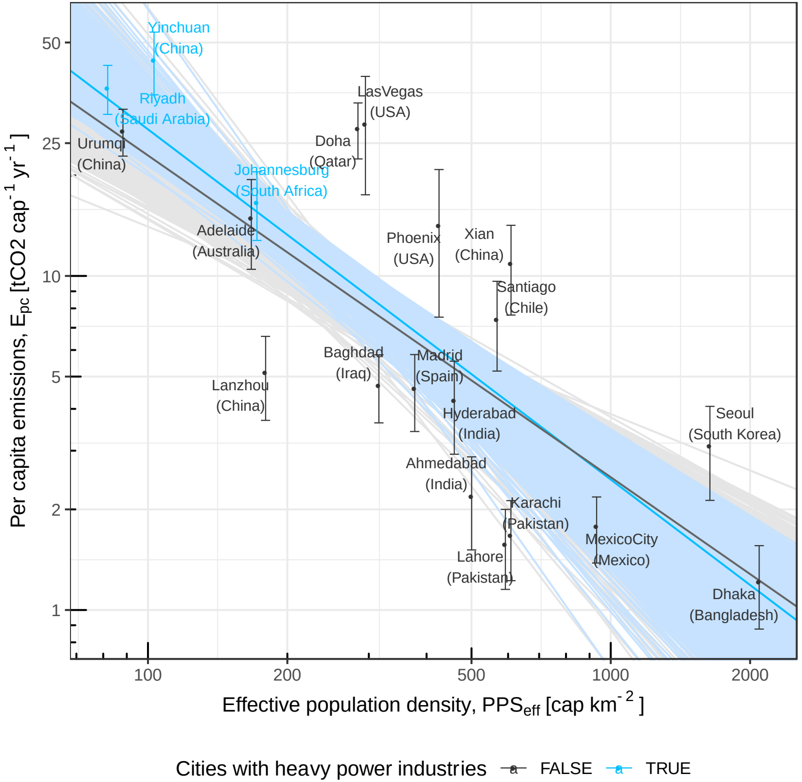
- ❑ **Sub-linear relation between urban emissions & population** derived for the first time from space-based measurements for 20 cities
- ❑ Cities with large shares for power industry → higher per capita emission
- ❑ **Denser cities indeed appear to emit less CO_2 to the atmosphere!**

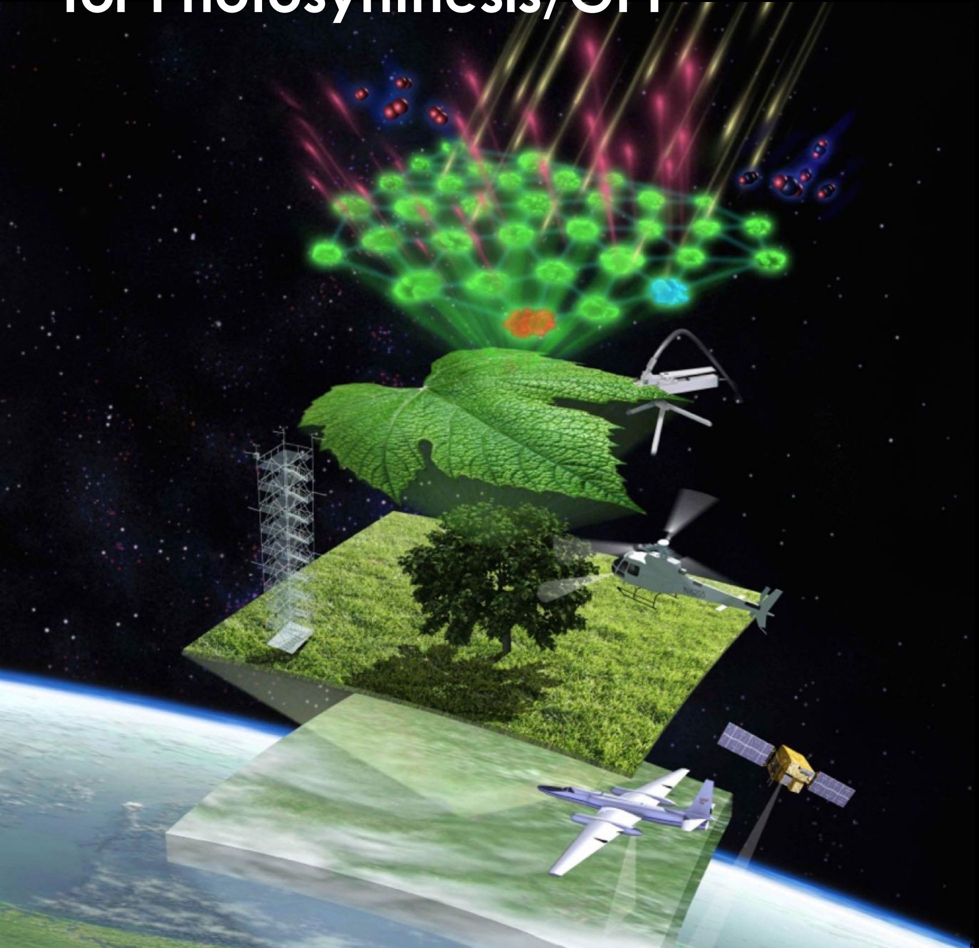


Limitations

- Limited sample size of cities
- No temporal variation
- Direct emissions ≠ carbon footprint

But will be addressed soon!

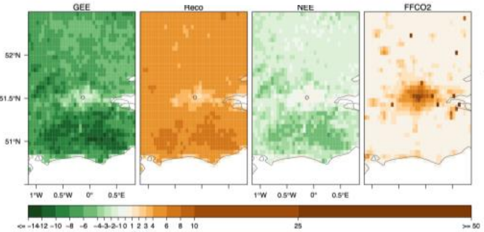
Satellite-Observed Solar-Induced Fluorescence (SIF) as a Proxy for Photosynthesis/GPP

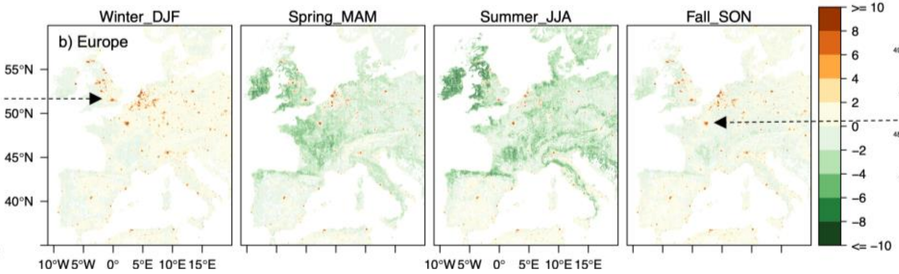


http://web.gps.caltech.edu/~cfranken/research.html

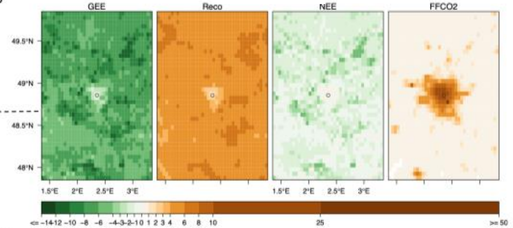
Urban Biological Carbon Fluxes from SIF (SMUrF)

London





Paris



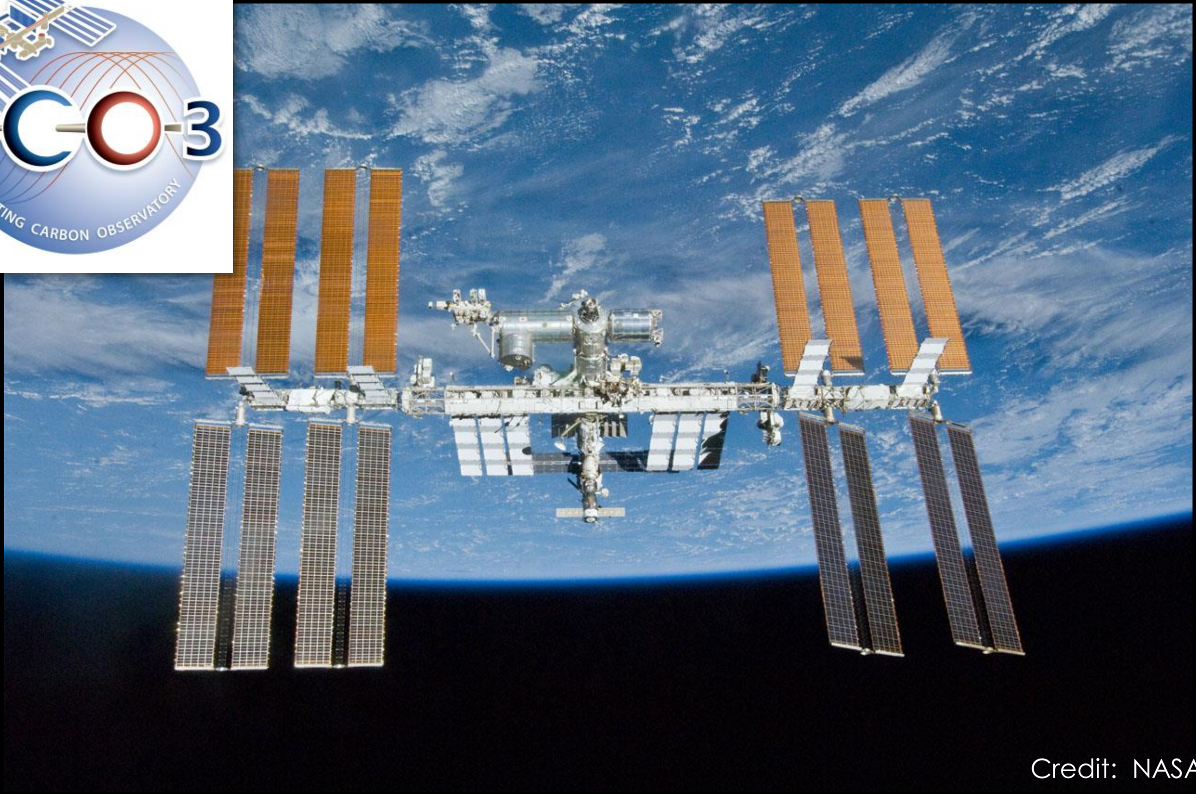
https://doi.org/10.5194/gmd-2020-301
Preprint. Discussion started: 7 October 2020

Geoscientific Model Development Discussions
Open Access

A Model for Urban Biogenic CO_2 Fluxes: Solar-Induced Fluorescence for Modeling Urban biogenic Fluxes (SMUrF v1)

Dien Wu[1,*], John C. Lin[1], Henrique F. Duarte[1,‡], Vineet Yadav[2], Nicholas C. Parazoo[2], Tomohiro Oda[3,4,5], and Eric A. Kort[6]

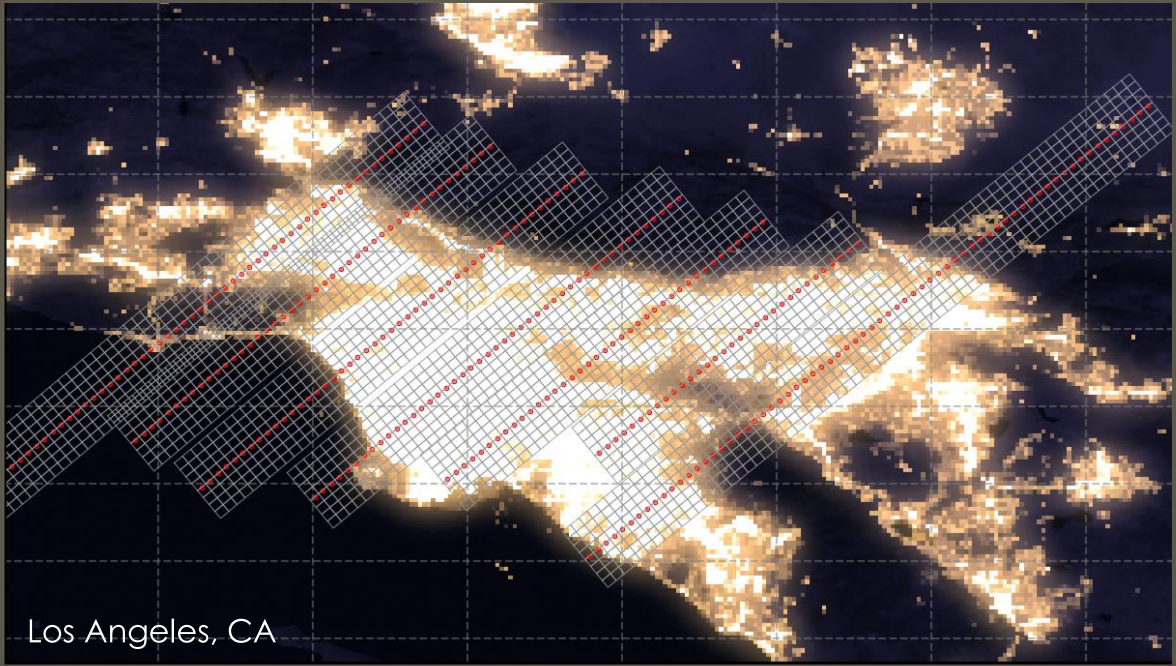
Exciting New Datastream: OCO-3 on the International Space Station (ISS)



Credit: NASA

Launched on May 4th, 2019 from Kennedy Space Center

OCO-3 Snapshot Area Map (SAM) Coverage – Los Angeles



OCO-3 Center Footprints

OCO-3 Cross-Track Pixels: ~14km width; 8 pixels. (image rotation pending)

Slide from Thomas Kurosu, NASA-JPL

OCO-3 Snapshot Area Map (SAM) Coverage – Los Angeles

OCO-3 allows us to both zoom IN and OUT of cities!

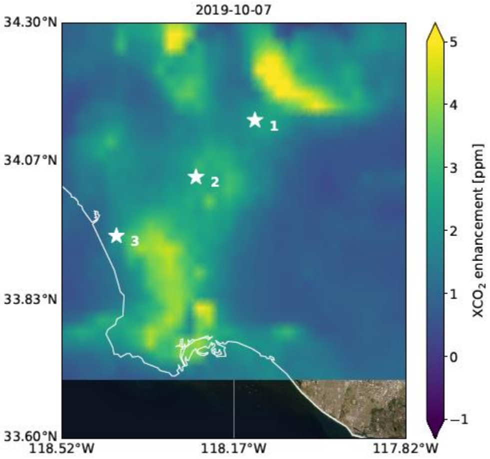
OCO-3 Center Footprints

OCO-3 Cross-Track Pixels: ~14km width; 8 pixels. (image rotation pending)

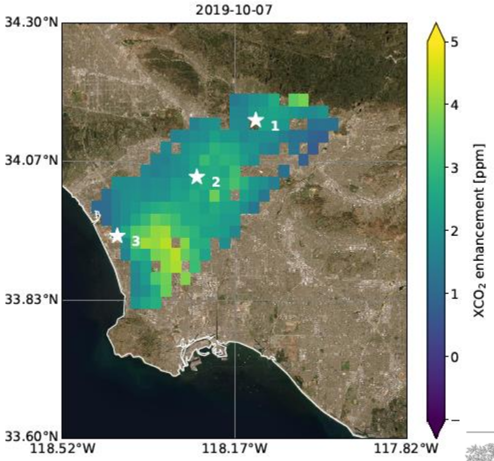
Slide from Thomas Kurosu, NASA-JPL

Simulated versus Observed XCO_2 from OCO-3

X-STILT Simulated



OCO-3 Observed



X-STILT Simulations by Dustin Roten (Ph.D. Student)

Remote Sensing of Environment 258 (2021) 112314

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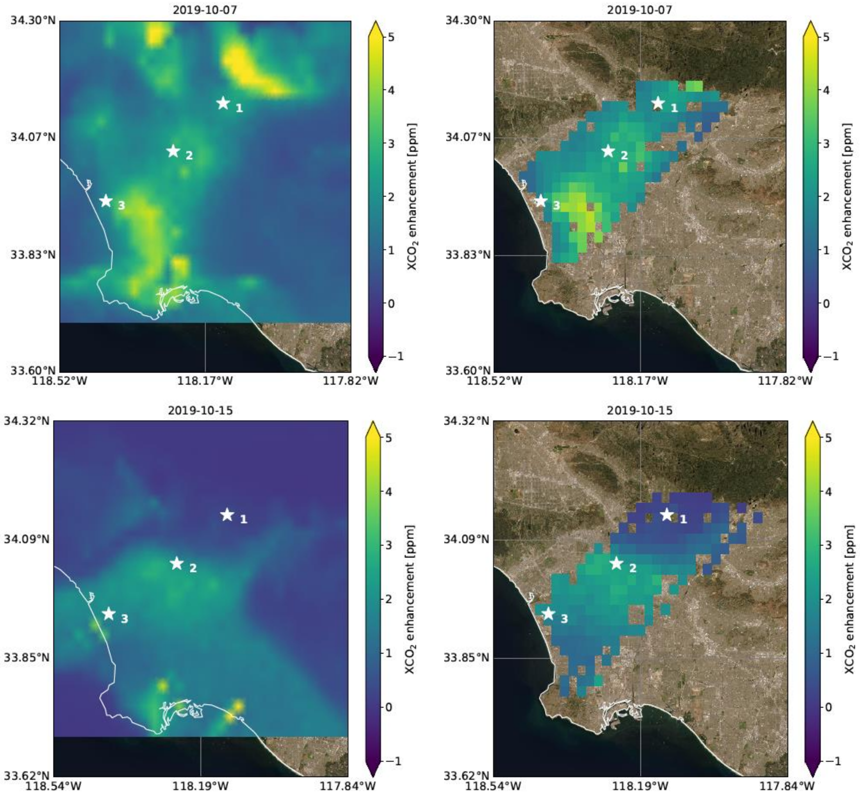
Matthäus Kiel [a,*], Annmarie Eldering [a], Dustin D. Roten [d], John C. Lin [d], Sha Feng [b,j], Ruixue Lei [b], Thomas Lauvaux [c], Tomohiro Oda [e,f,g], Coleen M. Roehl [h], Jean-Francois Blavier [a], Laura T. Iraci [i]

Simulated versus Observed XCO_2 from OCO-3

X-STILT Simulated **OCO-3 Observed**



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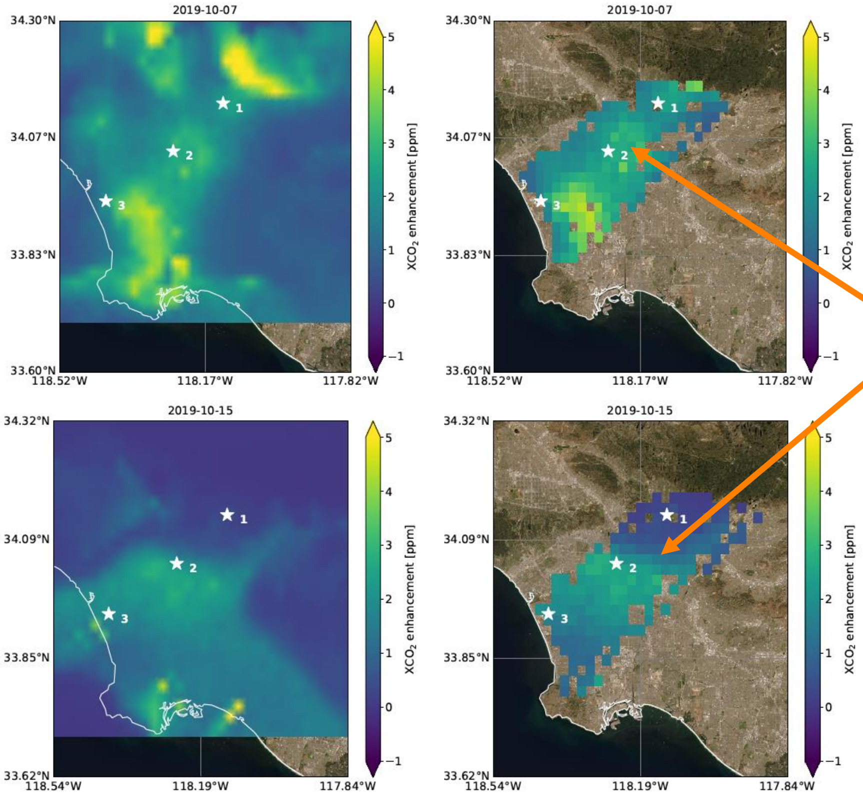
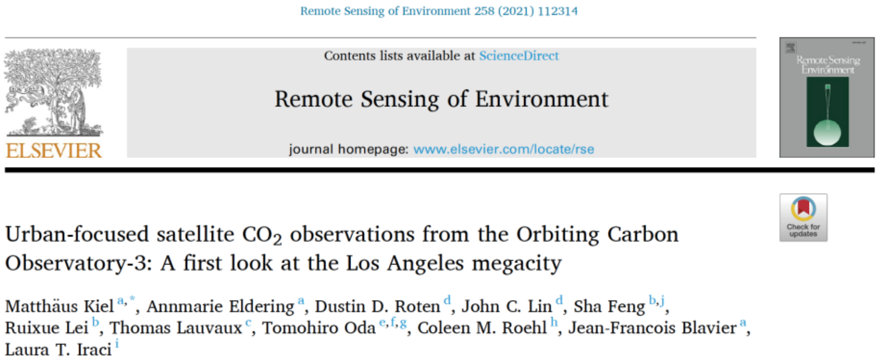
X-STILT Simulated **OCO-3 Observed**



X-STILT simulations by Dustin Roten (Ph.D. student)

Significant meteorology-induced variability!



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Land-Atmosphere Interactions Research (LAIR) Group

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