Understanding Urban Carbon Emissions with Space-Based Carbon Dioxide Observations

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June 2, 2022
Webinar Agenda

Part 1: An Introduction to XCO₂ 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 XCO₂ data
- Q&A

Part 3: XCO₂ 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: XCO₂ 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 CO₂.

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.
Significance of Urban Emissions

http://www.c40.org/c40_research
Sources of Carbon Emissions in Cities

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

CO₂

Mixing Height

CO₂

CO₂ 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, EVIE CROPPHAN, DANIELE L. MANZOLI, MARTIN BUCHET, RYAN BISAL, BEN FAIOZ, DAVID R. BOSOVICE, DANE FRIER, DOUGLAS CATBARINE, COURTNEY STRING, KEVIN R. GUNNELL, RISA PANHAS, MUNIRAH BAKASHORE, ALEXANDER JACQUES, SEBASTIAN HOD, JOHN HOES, AND JIM GELDBERGER

Observations and modeling of atmospheric CO₂ in the Salt Lake City, Utah, area help to quantify and understand urban carbon emissions and their linkage to air quality.
Key Scientific Questions

• How can atmospheric CO₂ 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
Salt Lake Valley CO$_2$ Observational Network
(Among the longest-running urban CO$_2$ networks in the world)

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

https://air.utah.edu/
Salt Lake City – CO₂ Long-Term Trends at various sites
(3-letter site codes below)

- RPK
- MUR
- DBK
- UOU
- SUG
- HDP

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

Logan E. Mitchell², John C. Lin³, David R. Bowling³, Diane E. Patak⁴, Courtenay Strong⁵, Andrew J. Schauer⁶, Ryan Bares⁷, Susan E. Bush⁷, Britton B. Stephens⁸, Daniel Mendoza⁹, Derek Mallia⁹, Lacey Holland¹⁰, Kevin R. Gurney¹, and James R. Ehleringer¹

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Salt Lake City – CO$_2$ Long-Term Trends

Trends vary across the urban area!

(Mitchell et al., 2018)
Trends vary across the urban area!

Mitchell et al., 2018
Salt Lake City – CO₂ 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.

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

https://www.slc.gov/s
Seen as Nature Lovers’ Paradise, Utah Struggles With Air Quality

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

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

March 15 - April 11 Excess CO₂ at UUCON Sites

COVID Shutdown Signal

March 15-31 Air Quality at Utah DAQ Hawthorne Site

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

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

Logan E. Mitchell\textsuperscript{a},\textsuperscript{b}, Erik T. Croesman\textsuperscript{a}, Alexander A. Jacques\textsuperscript{a}, Benjamin Faloli\textsuperscript{a},
Luke Declair-Marzolf\textsuperscript{a}, John Horel\textsuperscript{a}, David R. Bowling\textsuperscript{a}, James R. Elderinger\textsuperscript{a}, John C. Lin\textsuperscript{a}

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\textsuperscript{b}Department of Biology, University of Utah, Salt Lake City, UT, United States
Spatial Distribution of CO₂ 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
Information in Atmospheric CO₂ Observations
Atmospheric Measurement Carries INFORMATION About EMISSIONS & PROCESSES in Upwind Source Region

(1) Boundary conditions (from transport and emissions outside of domain)

(2) Emissions

(3) Transport, mixing

(4) Observations at receptor
Information in Atmospheric CO₂ 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:
- CO₂, CH₄
- CO, PM₂.₅, NOx
- H₂O, D₂O, H₂^{18}O
- And many others…
Information in Atmospheric CO$_2$ Observations

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

(1) Boundary conditions (from transport and emissions outside of domain)

(2) Emissions

(3) Transport, mixing

(4) Observations at receptor

**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
Constraining Urban CO₂ 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
Problem: Lack of High-Precision CO$_2$ Measurements in Most Cities Around the World!
Satellites to the Rescue

Launched on July 1st, 2014
Global Coverage from Space-Based CO₂ Measurements

Orbiting Carbon Observatory - 2
Atmospheric Carbon Dioxide Concentration (09/06/14 - 07/30/2017)

How Do Emissions Vary Between:

Typical N. American city (less dense) versus Dense city
Q: Do denser cities emit less carbon to the atmosphere (per capita)?
Do Denser Cities Emit Less Carbon to the Atmosphere (Per Capita)?

Per Capita Annual Gasoline Use (Gallon, 1980)

Urban Density (Persons Per Acre) [Newman and Kenworthy, 1989]

[Atlanta, GA] [Baltimore, MD] [Detroit, MI] [Philadelphia, PA] [Boston, MA] [Houston, TX] [Salt Lake City, UT] [Chicago, IL] [Los Angeles, CA] [San Francisco, CA]

[Denver, CO] [New York City, NY] [Seattle, WA] [Washington, D.C.]

2010

Thousand persons - km$^{-2}$

Mg CO$_2$ - person$^{-1}$ [Gately et al., 2015]
A Lagrangian approach towards extracting signals of urban CO₂ emissions from satellite observations of atmospheric column CO₂ (XCO₂): X-Stochastic Time-Inverted Lagrangian Transport model (“X-STILT v1”)

Dien Wu¹, John C. Lin¹, Benjamin Fasoli¹, Tomohiro Oda², Xinxin Ye³, Thomas Lauvaux³, Emily G. Yang⁴, and Eric A. Kort⁴

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X-STILT to interpret OCO-2

Riyadh

Backward-Time
WRF-/GDAS-
Derived Wind
Vector

OCO-2
Nadir

Column
Receptors
(up to 6km)

OCO-2
Sounding
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

Large population density from GPWv4 > 500 [cap km⁻²] with 20 target urban areas

Daily mean clear-sky CSIF [mW m⁻² nm⁻¹ sr⁻¹] during NH non-growing season in 2016

NASA’s Applied Remote Sensing Training Program
Methodology – Estimate Urban Signals

Normalized kernel density of STILT particles

Enhanced Latitude Range

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

$ppm \cdot deg N$
Methodology – Calculate Carbon Fluxes from XCO₂

Column Trajectory

\[
x\text{-footprint/receptor/track} \quad \frac{\text{ppm}}{\mu\text{mol/m}^2/\text{s}}
\]
Methodology – Calculate Carbon Fluxes from XCO₂

\[ x_{\text{foot}}(x, y) = \frac{1}{\text{lat}_2} \int_{\text{lat}_1} \text{lat}_2 x_{\text{foot}}(x, y, \text{lat}) \text{ dlat} \]

x-footprint/receptor/track

\[ \frac{\text{ppm}}{\mu\text{mol/m}^2/\text{s}} \]

Lat-integrated x-footprint

\[ \frac{\text{ppm} \cdot \text{degN}}{\mu\text{mol/m}^2/\text{s}} \]
Methodology – Calculate Carbon Fluxes from XCO₂

Weight by Gridded Population Density (PPS) capita km²

Lat-integrated x-footprint ppm·degN μmol/m²/s

x-footprint/receptor/track ppm μmol/m²/s
Methodology – Calculate Carbon Fluxes from XCO₂

Column Trajectory

weight xfoot by gridded population density (PPS)
capita/km²

x-footprint/receptor/track
ppm
µmol/m²/s

Lat-integrated x-footprint
ppm-degN
µmol/m²/s

PPS weighted lat-integrated x-footprint (FP)
ppm-degN
µmol/capita/s
Methodology – Calculate Carbon Fluxes from XCO₂

Satellite-observed urban signals in the atmosphere

Population-weighted and lat-integrated x-footprint

Per Capita Emissions

\[ \frac{ppm \cdot degN}{\mu mol/capita/s} \]
Results: Urban Scaling Relations

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

Environmental Research Letters
Space-based quantification of per capita CO2 emissions from cities

Dien Wu, John C Lin, Tomohiro Oda, and Eric A Kort

Effective population density, PPS_{eff} [cap km^{-2}]
Per capita emissions, Epc [CO2 cap^{-1} yr^{-1}]

Cities with heavy power industries

https://doi.org/10.1088/1748-9326/ab0e0b
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 CO₂ to the atmosphere!
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 emission.

- Denser cities indeed appear to emit less CO₂ 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)

A Model for Urban Biogenic CO₂ Fluxes: Solar-Induced Fluorescence for Modeling Urban biogenic Fluxes (SMUrF v1)

Dien Wu1,*, John C. Lin1, Henrique F. Duarte1,2, Vineet Yadav2, Nicholas C. Parazoo2, Tomohiro Oda2,3,4,5, and Eric A. Kort6

https://doi.org/10.5194/gmd-2020-301
Preprint. Discussion started: 7 October 2020
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Exciting New Datastream: OCO-3 on the International Space Station (ISS)

Launched on May 4th, 2019 from Kennedy Space Center

Credit: NASA
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

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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

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Simulated versus Observed XCO$_2$ from OCO-3

X-STILT Simulated

OCO-3 Observed

X-STILT Simulations by Dustin Roten (Ph.D. Student)
Simulated versus Observed XCO₂ from OCO-3

X-STILT simulations by Dustin Roten (Ph.D. student)
Simulated versus Observed XCO$_2$ from OCO-3

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

Significant meteorology-induced variability!

Urban-focused satellite CO$_2$ observations from the Orbiting Carbon Observatory-3: A first look at the Los Angeles megacity

Matthias Kiel*, Annmarie Eldering*, Dustin D. Roten*, John C. Lin, Sha Feng, Ruixue Lei, Thomas Lauvaux, Tomohiro Oda, Coleen M. Roehl, Jean-François Blavier, Laura T. Iraei
References


Contacts

• Trainers:
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• Training Webpage:

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Thank You!