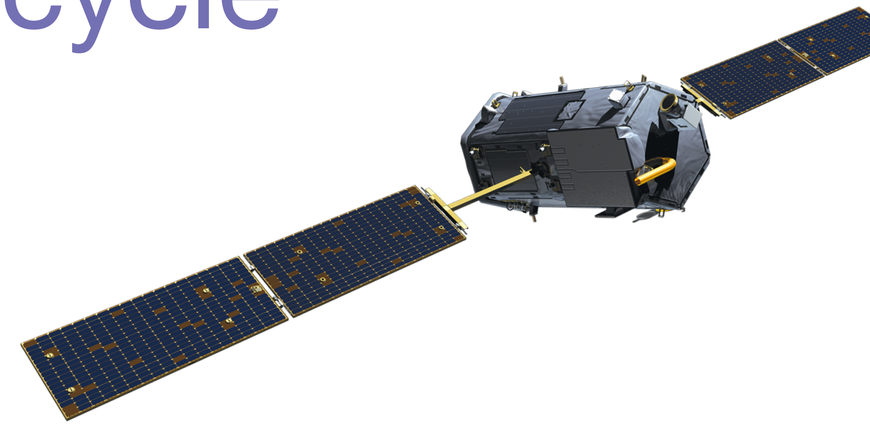
Using atmospheric measurements to inform climate action: from leaky tanks to the global carbon cycle



William Daniels

Department of Environmental Health and Engineering

Johns Hopkins University

JOHNS HOPKINS UNIVERSITY

My research involves greenhouse gas fluxes

Flux = rate at which something passes through a surface

My research involves greenhouse gas fluxes

Flux = rate at which something passes through a surface

Something: Pico’s kibble
Surface: Pico’s mouth

Flux = 10 kibbles / second

My research involves greenhouse gas fluxes

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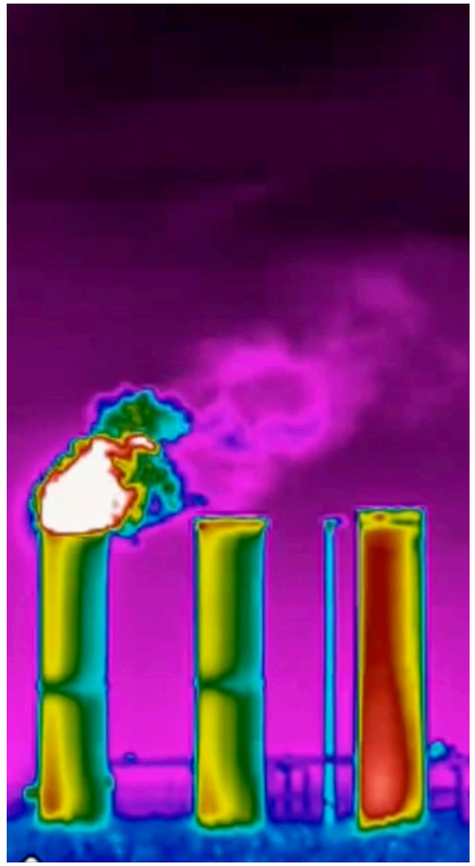


Something: Methane
Surface: Oil and gas combustor

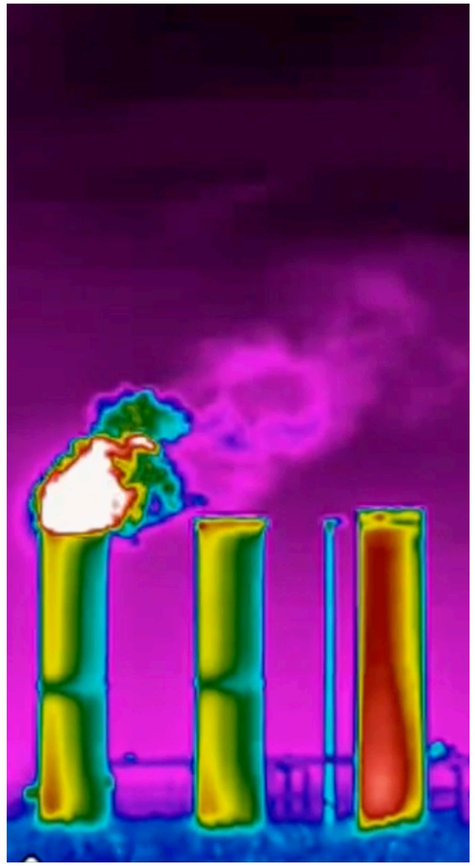
Flux = 80 kg/hr from combustor

My research involves greenhouse gas fluxes

Flux = rate at which something passes through a surface

Something: Pico's kibble
Surface: Pico's mouth

Flux = 10 kibbles / second



Something: Methane
Surface: Oil and gas combustor

Flux = 80 kg/hr from combustor

Something: Carbon dioxide
Surface: 1x1 degree grid cell

Flux = -0.5 umol/m2/s from [57, -105]

Unfortunately… measuring fluxes directly is hard

Especially at the scale necessary to cover all emission sources

One option: **flux chambers.**
Must completely enclose the emission source.

Williams et al. (2023)

Unfortunately… measuring fluxes directly is hard

Especially at the scale necessary to cover all emission sources

One option: **flux chambers.**
Must completely enclose the emission source.

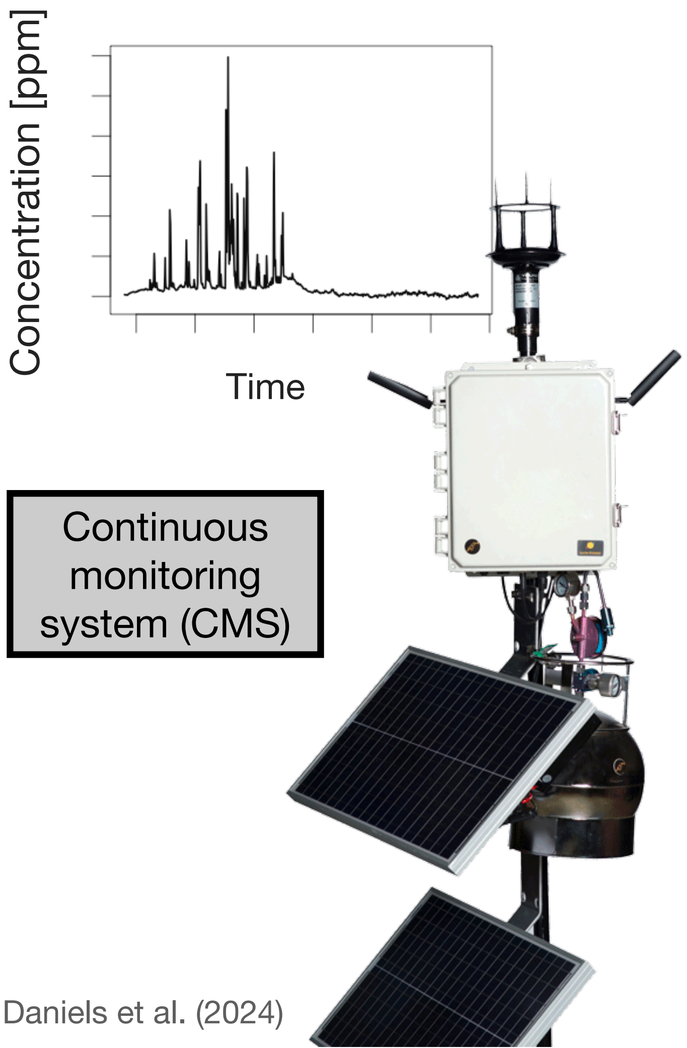
Williams et al. (2023)

Another option: **eddy covariance towers.**
Estimates surface flux, but only within a radius of meters or kilometers.

AmeriFlux (2014).

What we can measure at scale: atmospheric concentrations

Concentration = amount of something in the ambient air at a specific location

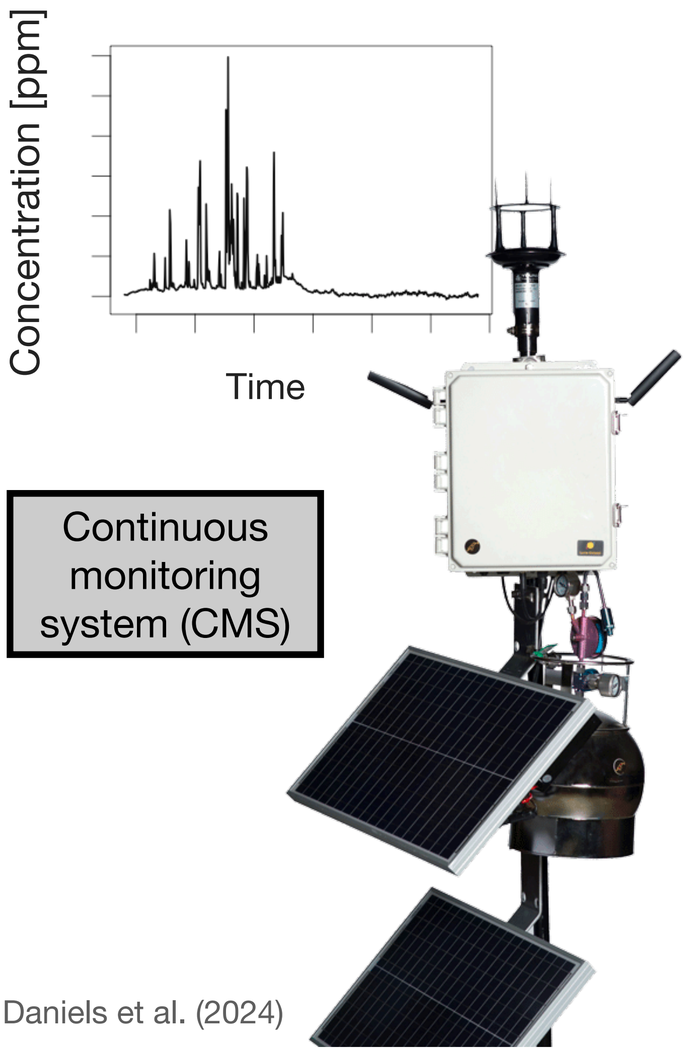


Continuous monitoring system (CMS)

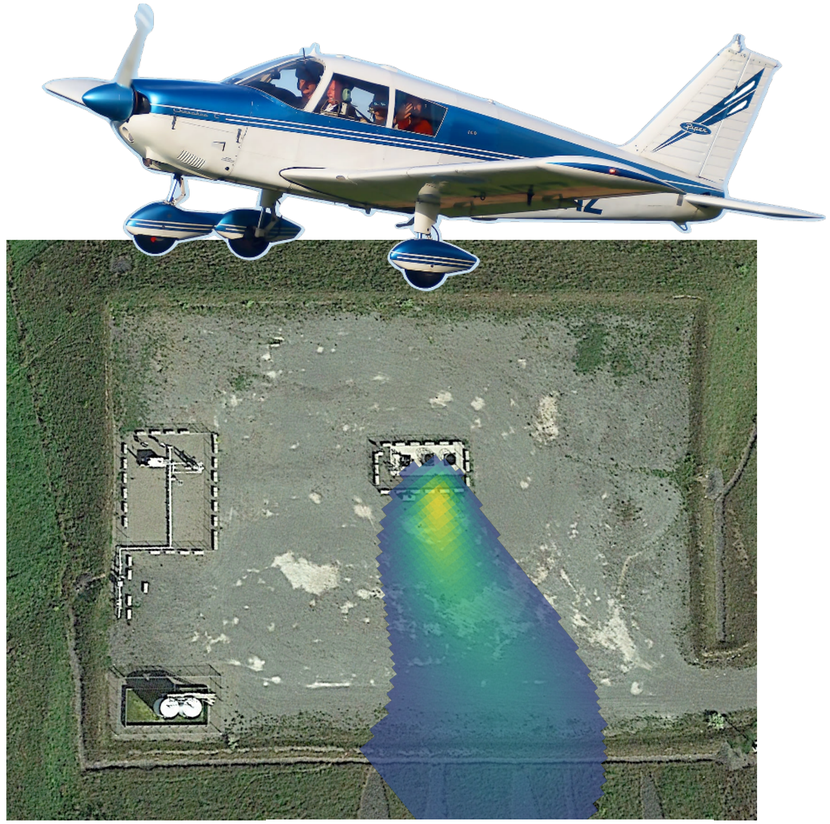
Daniels et al. (2024)

What we can measure at scale: atmospheric concentrations

Concentration = amount of something in the ambient air at a specific location



Continuous monitoring system (CMS)

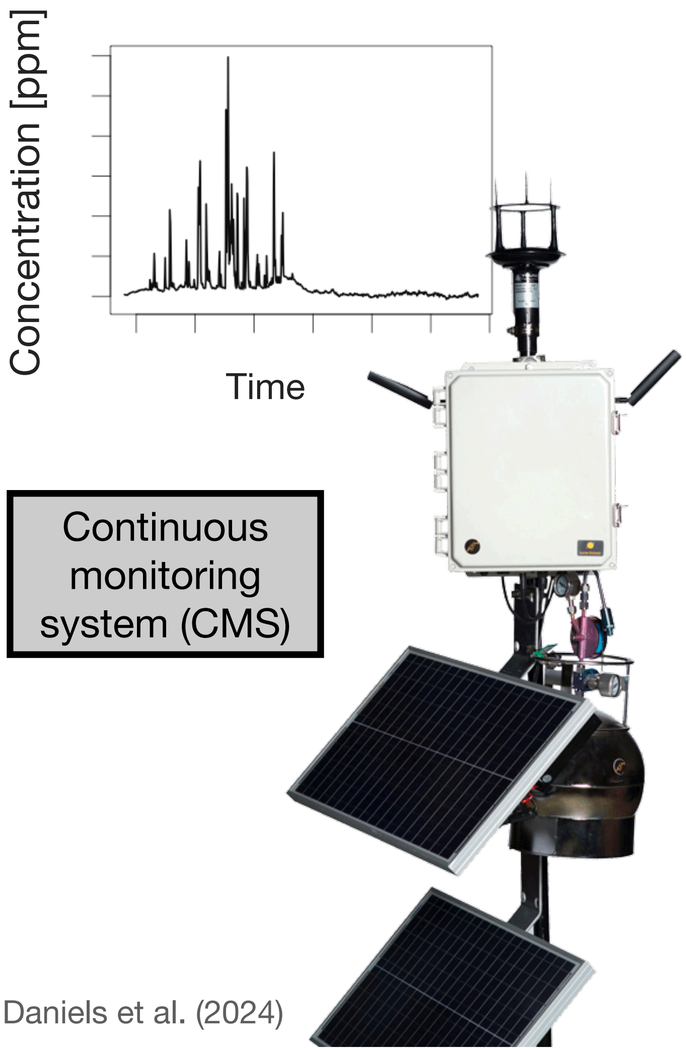


Aerial measurement technology

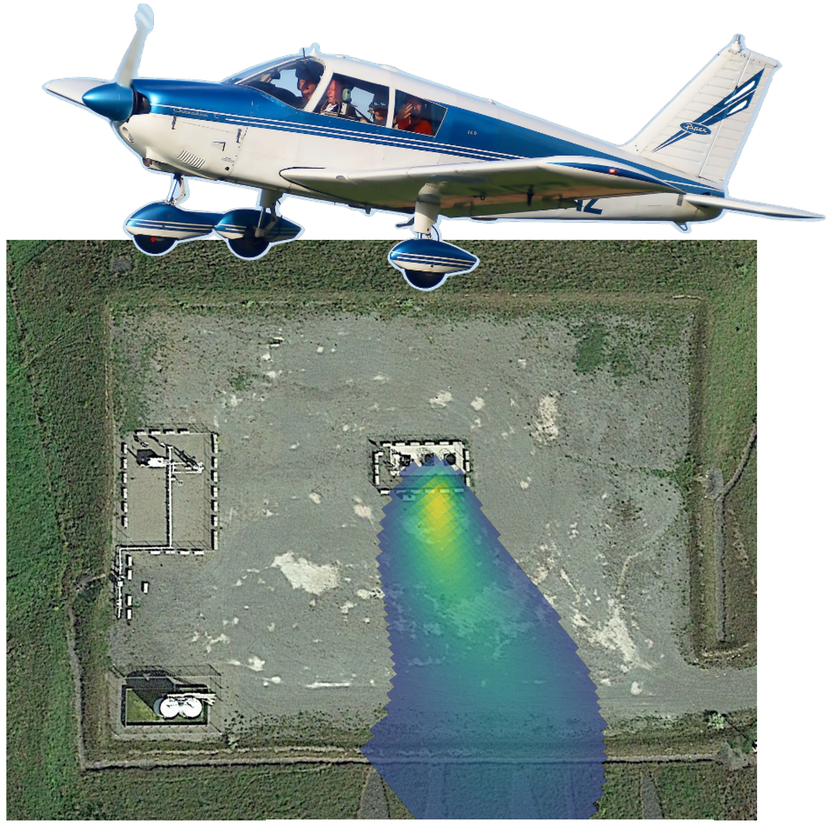
Daniels et al. (2024)

What we can measure at scale: atmospheric concentrations

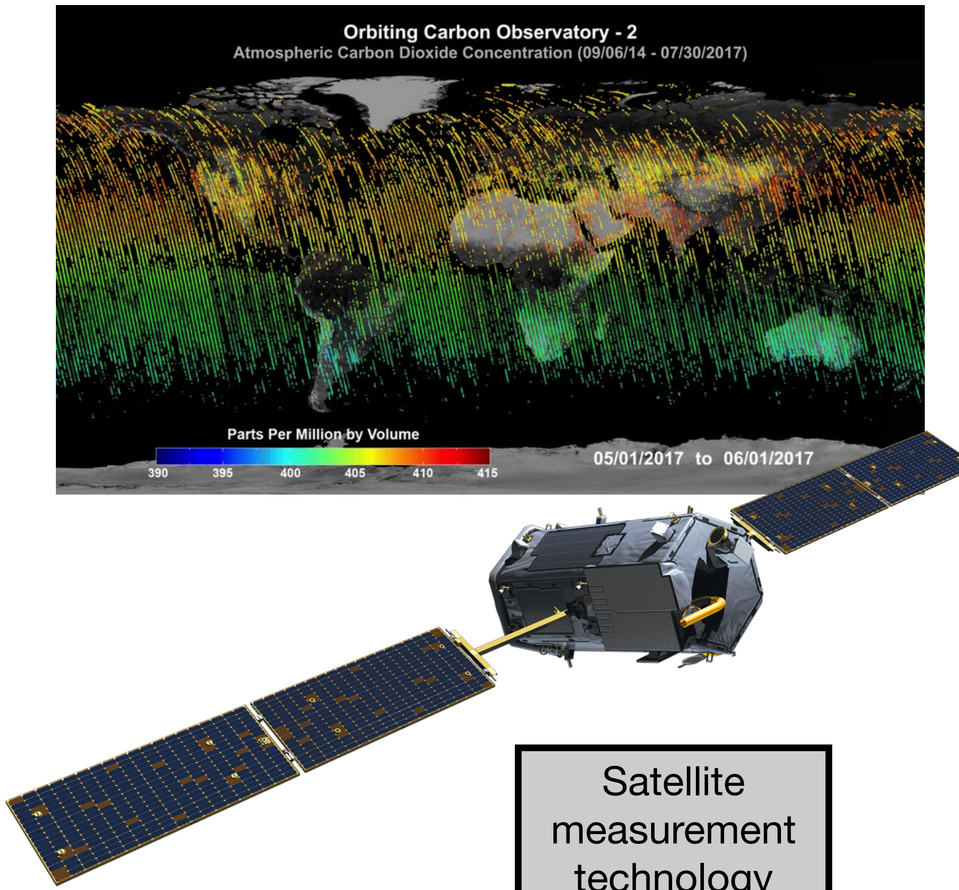
Concentration = amount of something in the ambient air at a specific location



Continuous monitoring system (CMS)



Aerial measurement technology



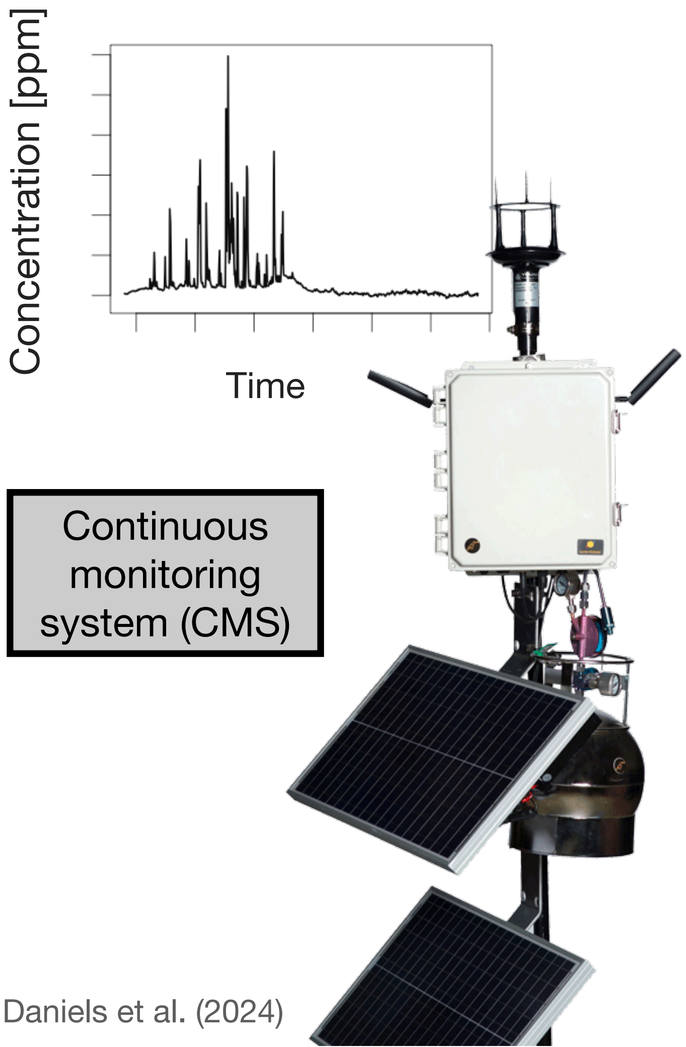
Satellite measurement technology

Daniels et al. (2024)

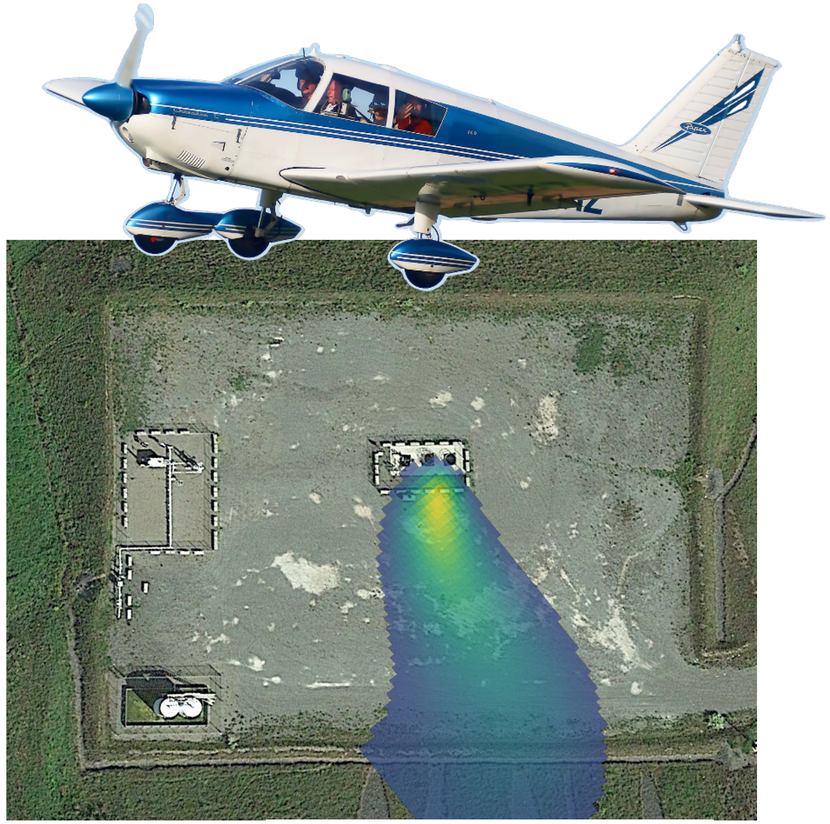
NASA/JPL

What we can measure at scale: atmospheric concentrations

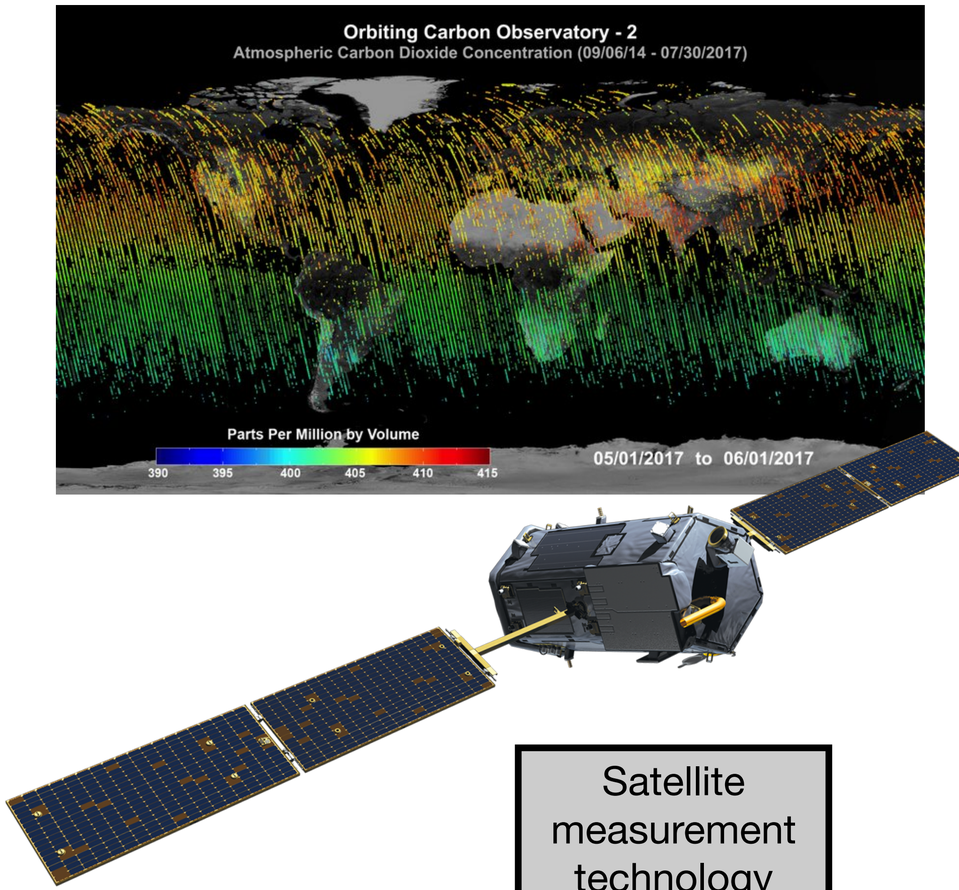
However, concentrations ≠ fluxes!



Continuous monitoring system (CMS)



Aerial measurement technology



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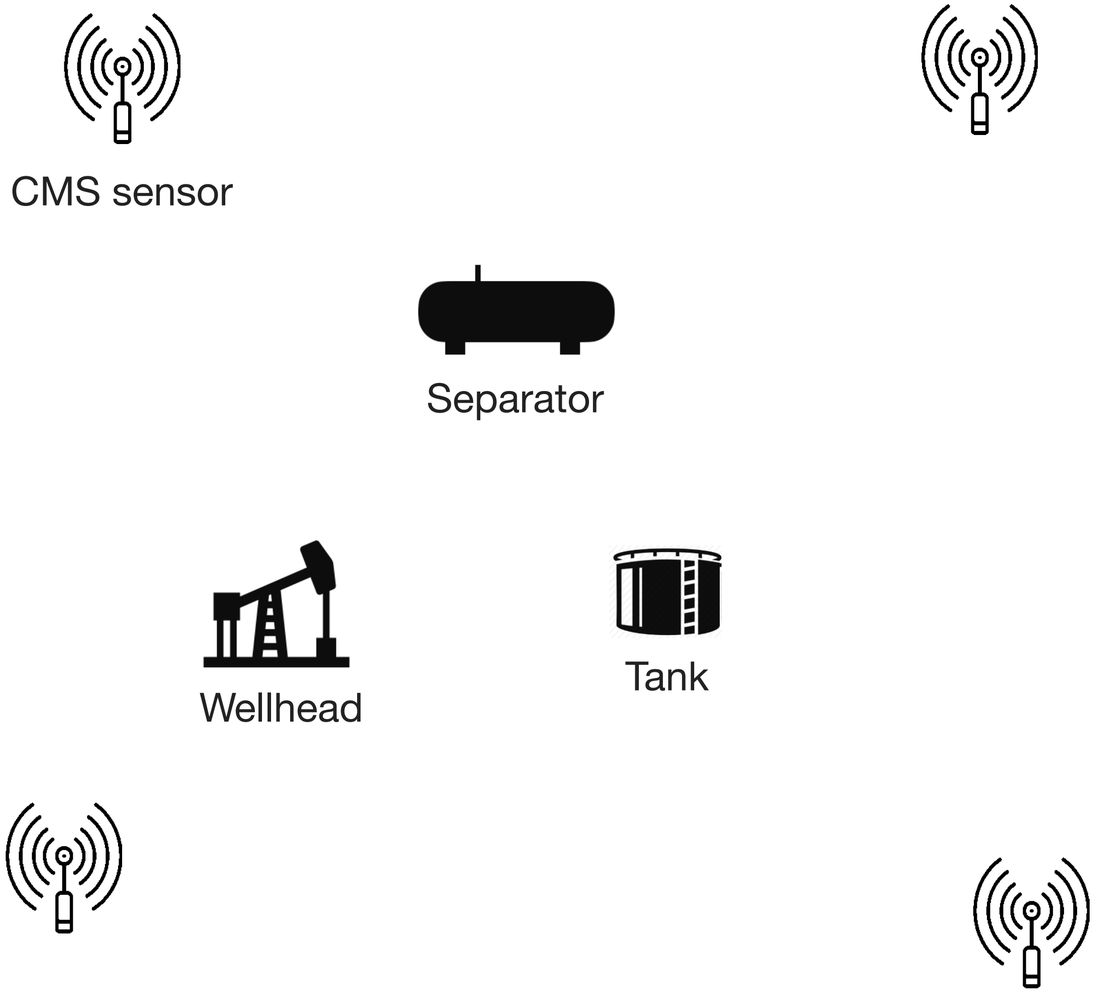
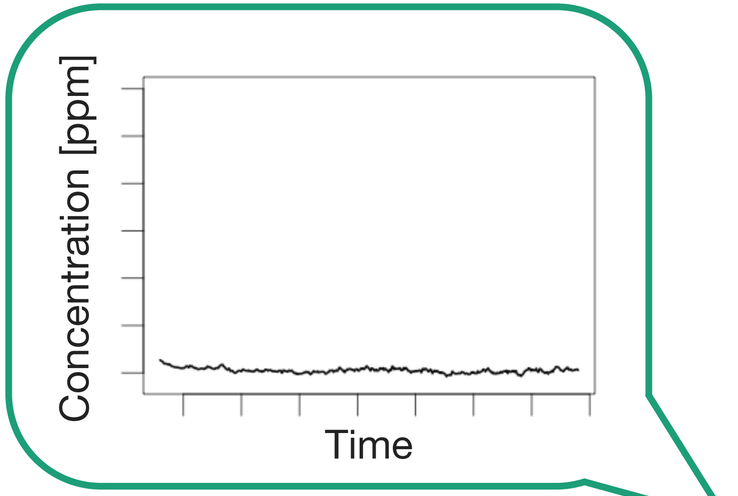


Atmospheric inversions: translate concentrations into fluxes

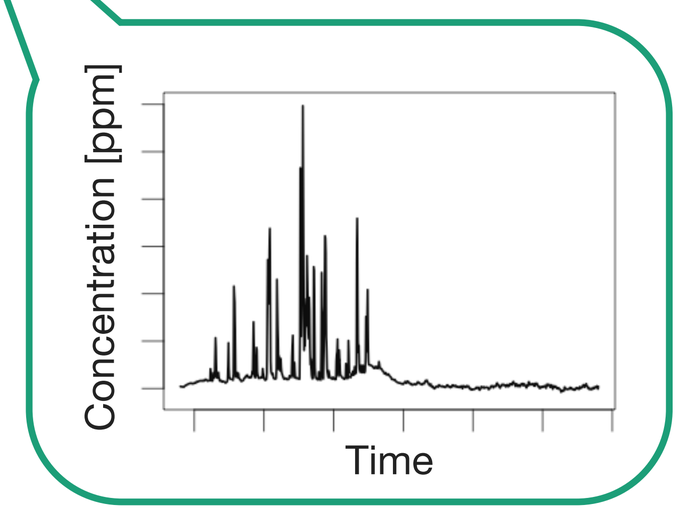
Wind direction

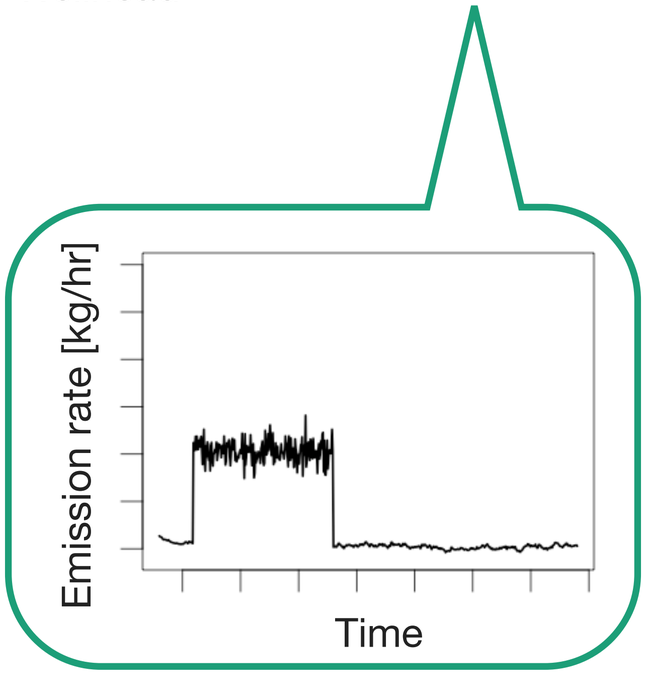
CMS sensor



Separator

Wellhead





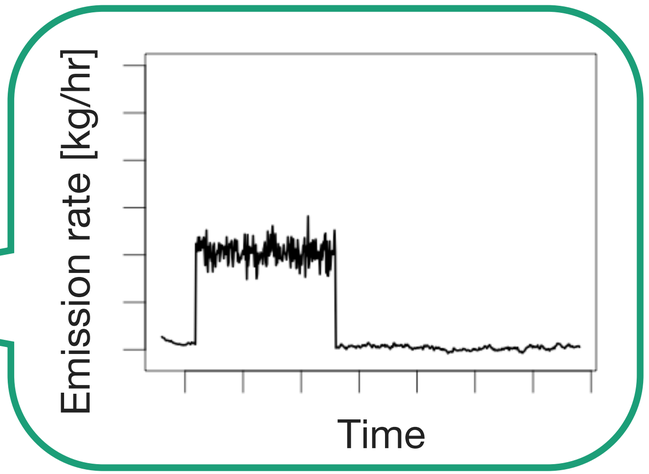
Wind direction

CMS sensor

Separator

Wellhead

Tank



“Forward problem”

(Know)

Fluxes

(Know, kind of)

Atmospheric transport

(Don’t know)

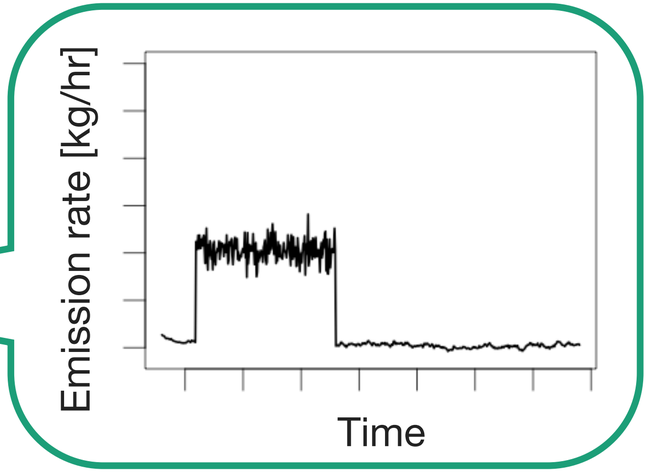
Concentrations

Wind direction

Separator

Wellhead

Tank



“Forward problem”

(Know)

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Concentrations

Wind direction

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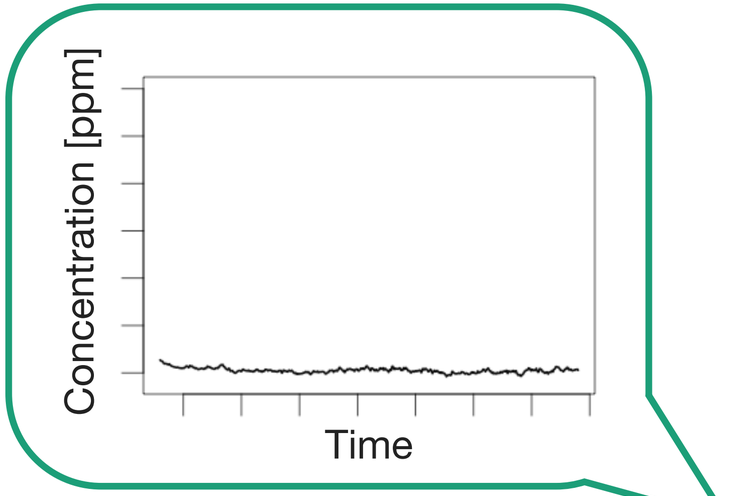
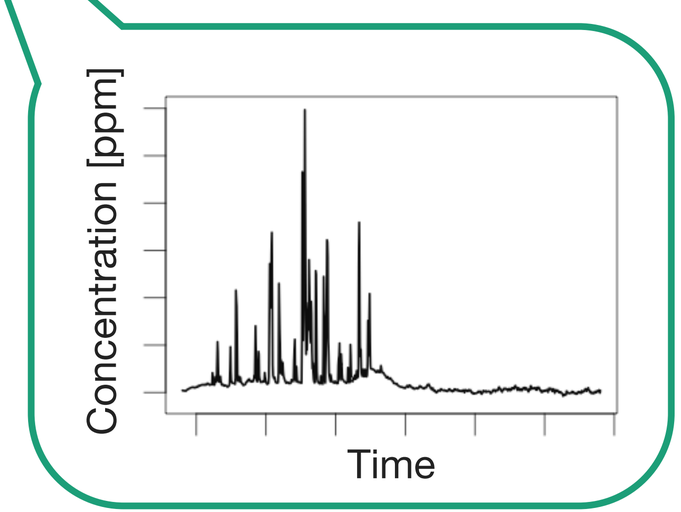


Separator

Wellhead

Tank



“Inverse problem”

(Don’t know)

Fluxes

(Know, kind of)

Atmospheric transport

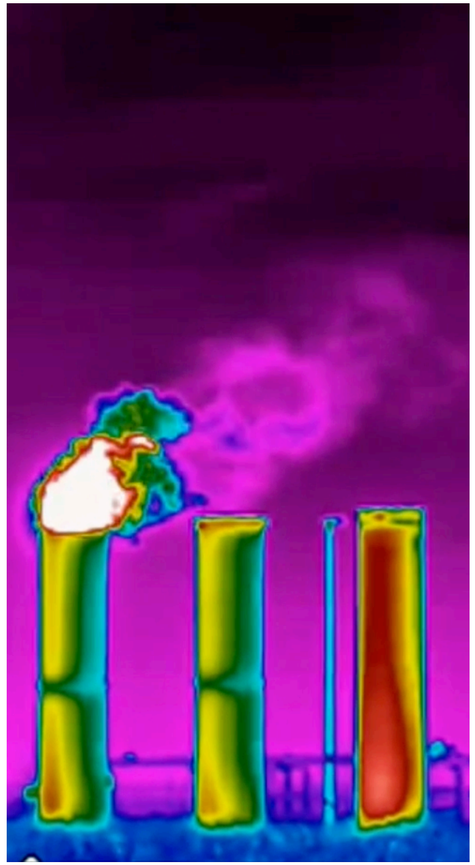
(Know)

Concentrations

Why do fluxes matter?

Many operational decisions and science questions are based on fluxes

Vet: “5 kibbles per second max!”



Helps prioritize mitigation efforts. Necessary for regulatory penalties.

Necessary to understand the drivers of rising CO2 concentrations.

My research: estimate emission fluxes to inform climate action

Mitigating methane emissions

Find and quantify equipment leaks

↓

Boots-on-the-ground emission mitigation

Carbon cycle science

Climate action across scales

My research: estimate emission fluxes to inform climate action

Mitigating methane emissions

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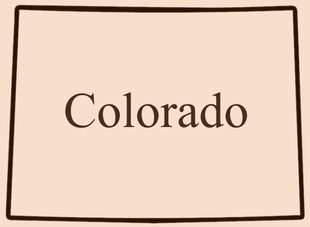
Boots-on-the-ground emission mitigation



Set state-wide emissions regulations

↓

Economic incentives for emission reduction

Carbon cycle science

Climate action across scales

My research: estimate emission fluxes to inform climate action

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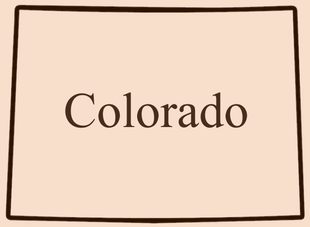
Boots-on-the-ground emission mitigation



Set state-wide emissions regulations

↓

Economic incentives for emission reduction

Carbon cycle science

Improve process-based understanding of the carbon cycle

↓

Better process-based understanding = better future projections = more accurate emission reduction goals

Climate action across scales

Project 1 Find and quantify equipment leaks

Find and quantify equipment leaks

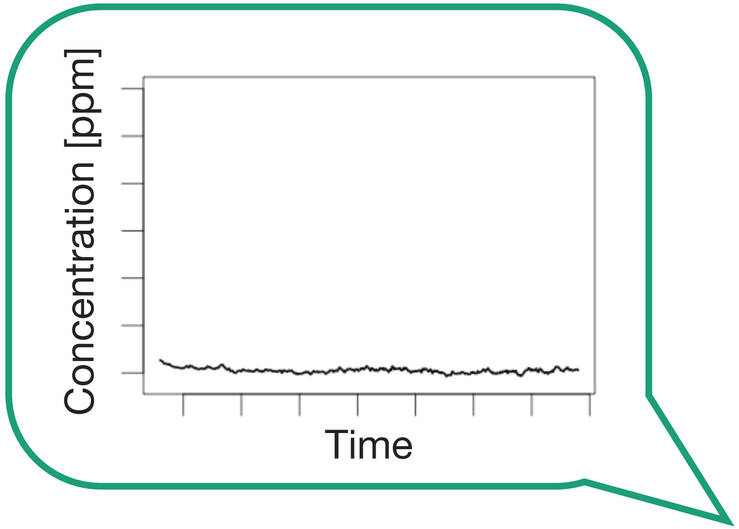
↓

Boots-on-the-ground emission mitigation

COLORADO SCHOOL OF MINES

Wind direction

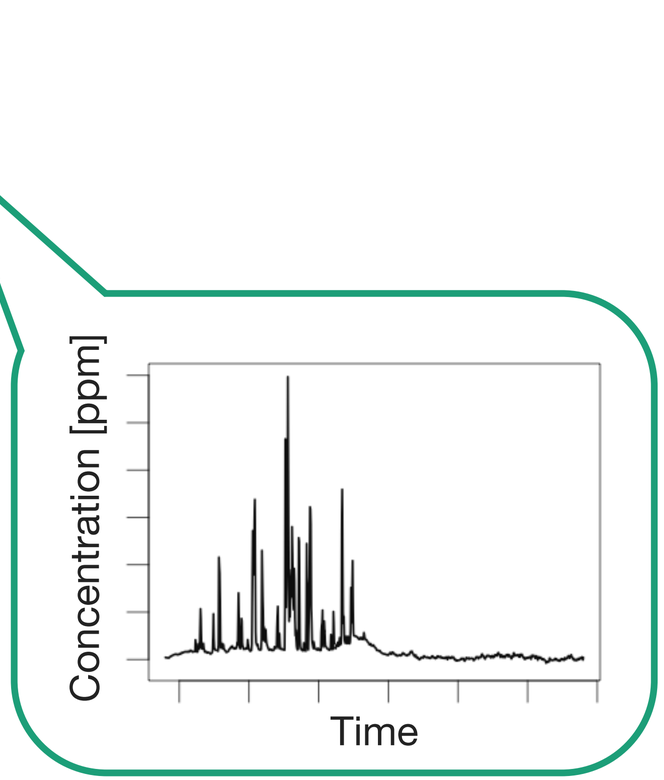
CMS sensor



Separator ?

Wellhead ?

Tank ?



(Know)

Concentrations

(Know, kind of)

Atmospheric transport

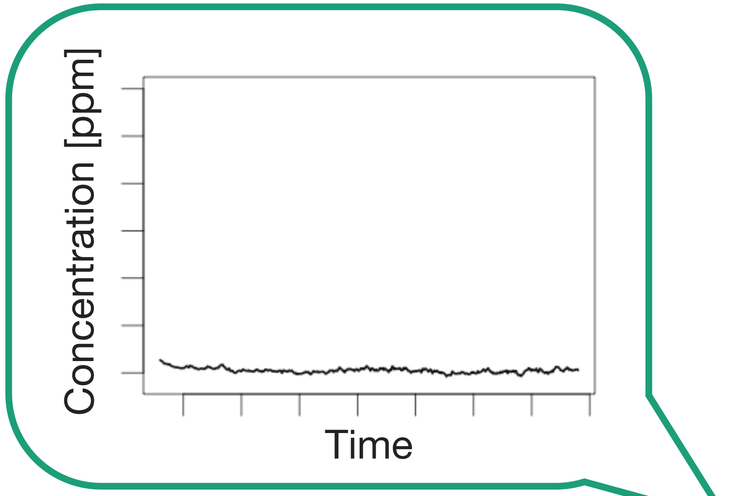
(Don't know)

Fluxes

"Inverse problem"

Wind direction

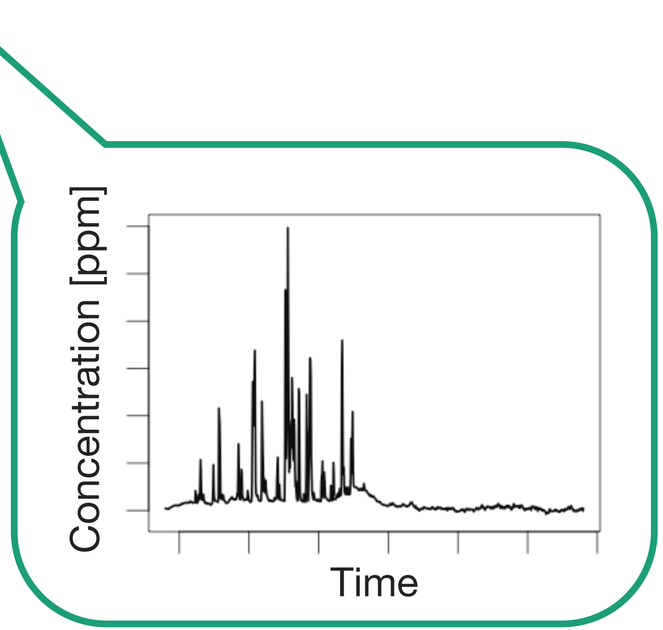
CMS sensor



Separator

Wellhead

Tank



How do we do this?

“Inverse problem”

(Don’t know)

Fluxes

(Know, kind of)

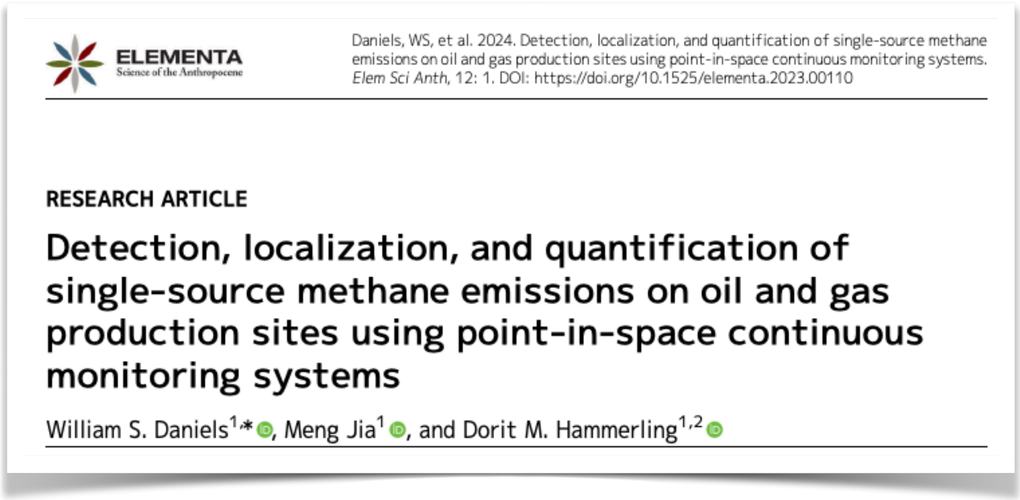
Atmospheric transport

(Know)

Concentrations

Open source framework for solving inverse problem

STEP 1: Background removal and event detection → STEP 2: Simulation → STEP 3: Localization → STEP 4: Quantification



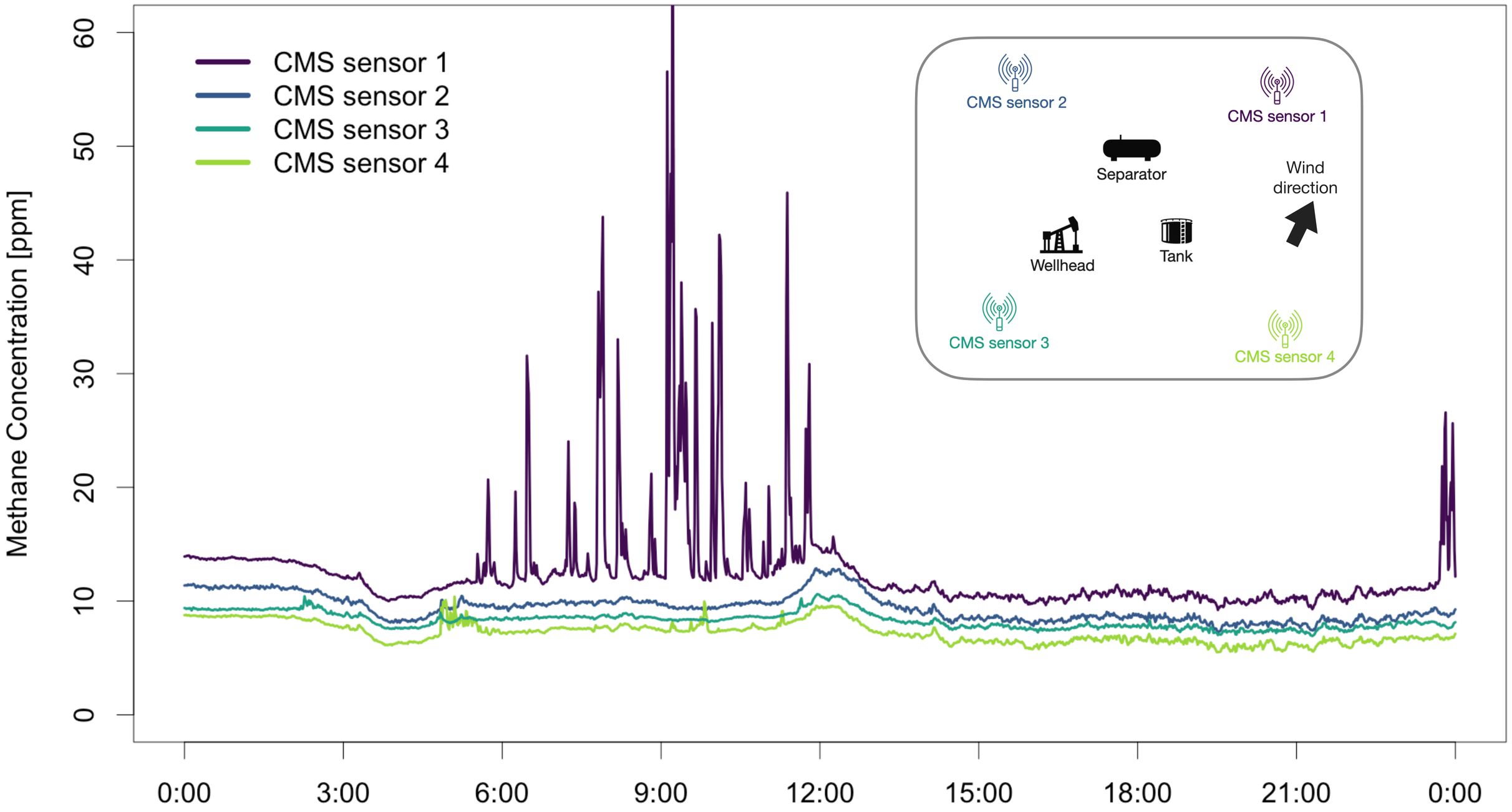
ELEMENTA Science of the Anthropocene

Daniels, WS, et al. 2024. Detection, localization, and quantification of single-source methane emissions on oil and gas production sites using point-in-space continuous monitoring systems. *Elem Sci Anth*, 12: 1. DOI: https://doi.org/10.1525/elementa.2023.00110

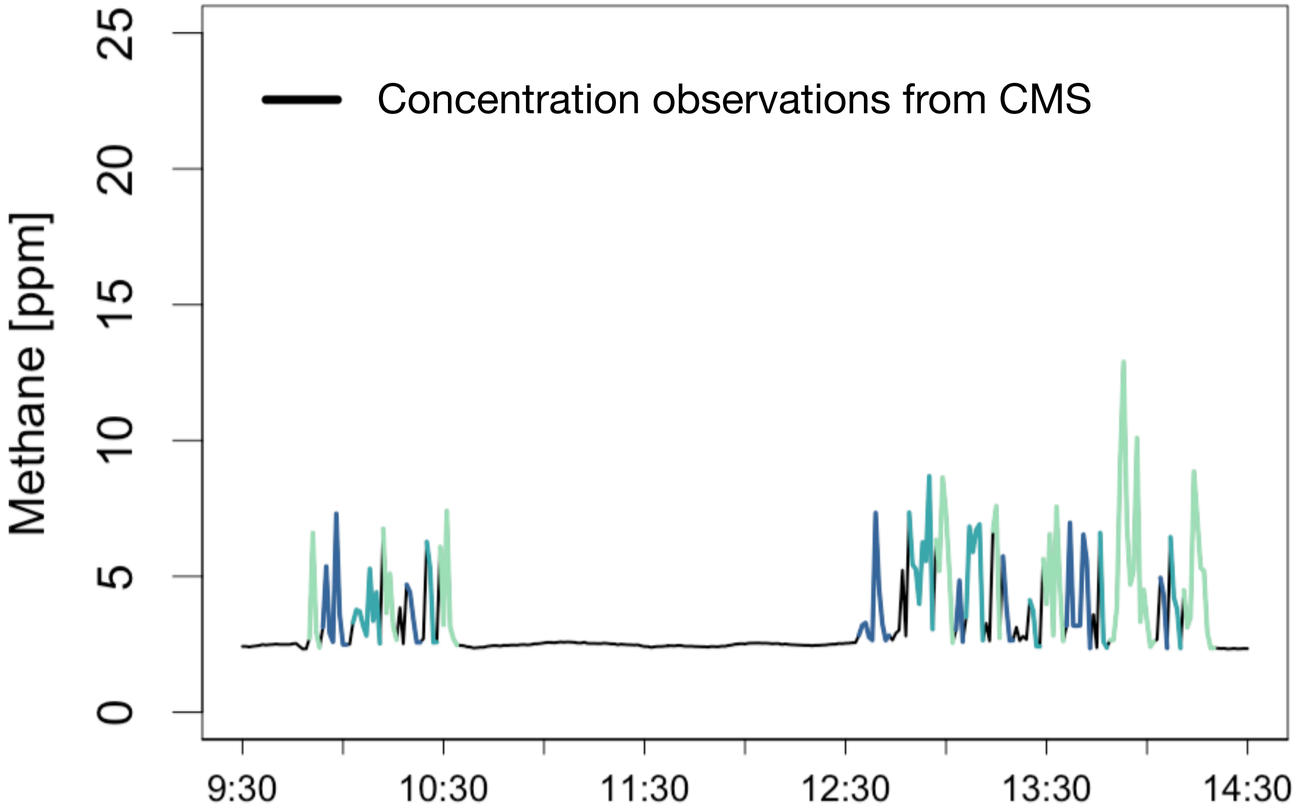
RESEARCH ARTICLE

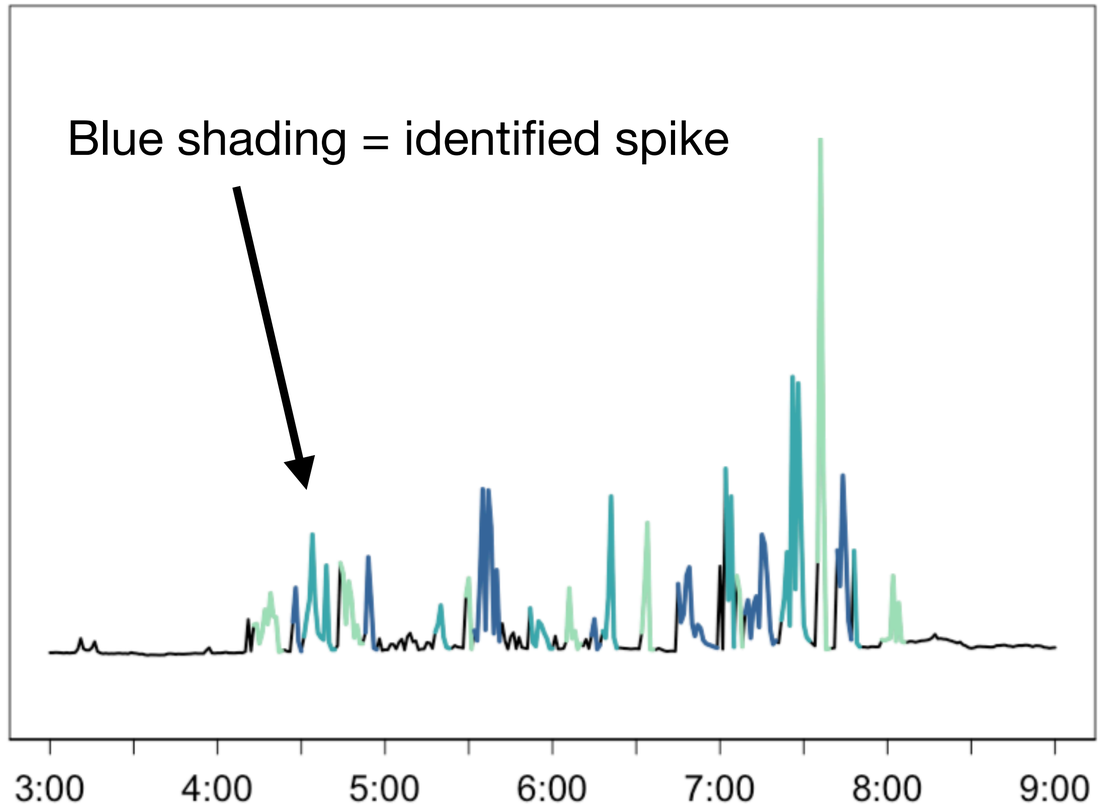
Detection, localization, and quantification of single-source methane emissions on oil and gas production sites using point-in-space continuous monitoring systems

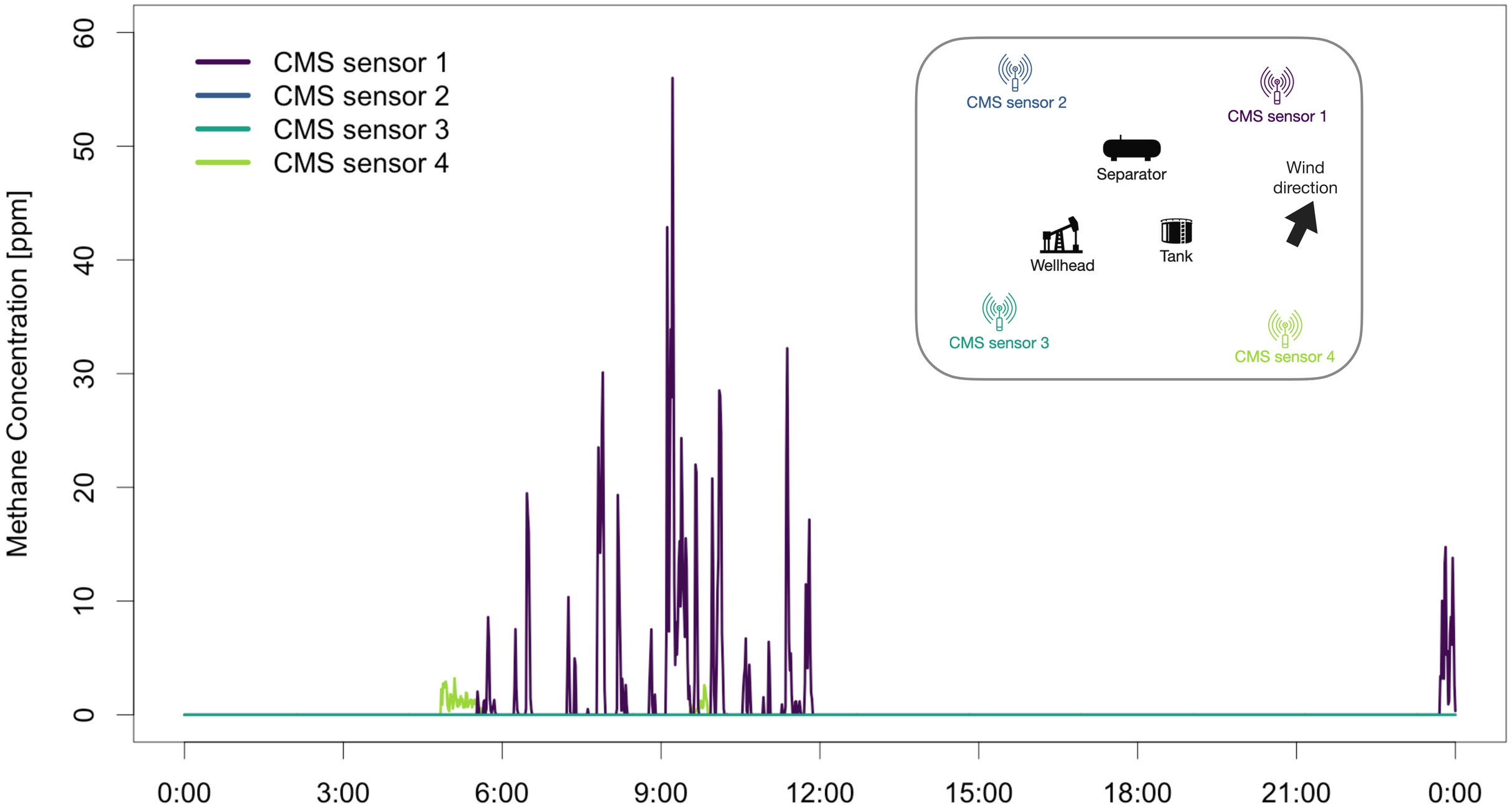
William S. Daniels[1,*], Meng Jia[1], and Dorit M. Hammerling[1,2]

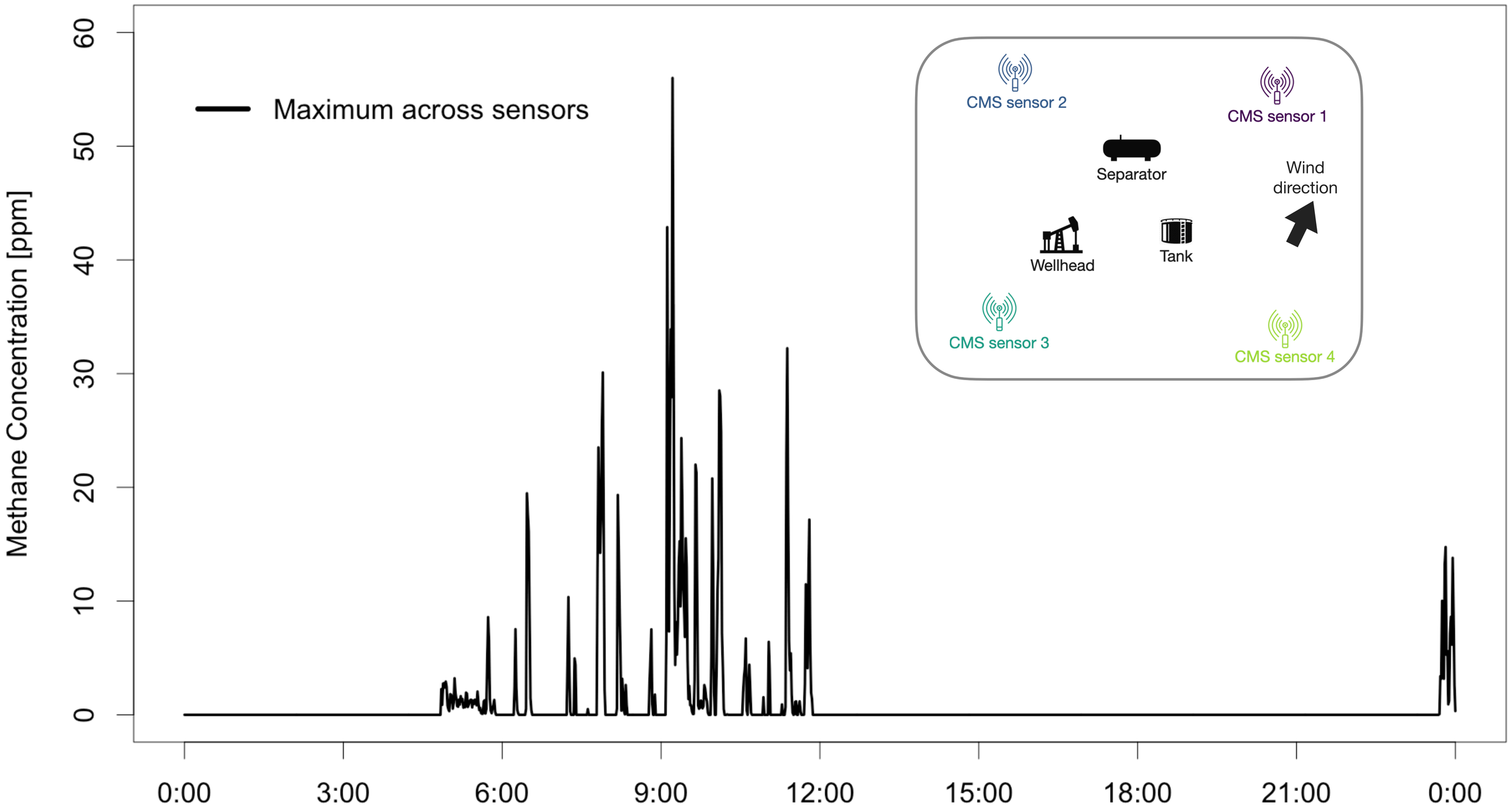

CMS sensor 1
CMS sensor 2
CMS sensor 3
CMS sensor 4
Methane Concentration [ppm]
0
10
20
30
40
50
60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
CMS sensor 3
CMS sensor 4

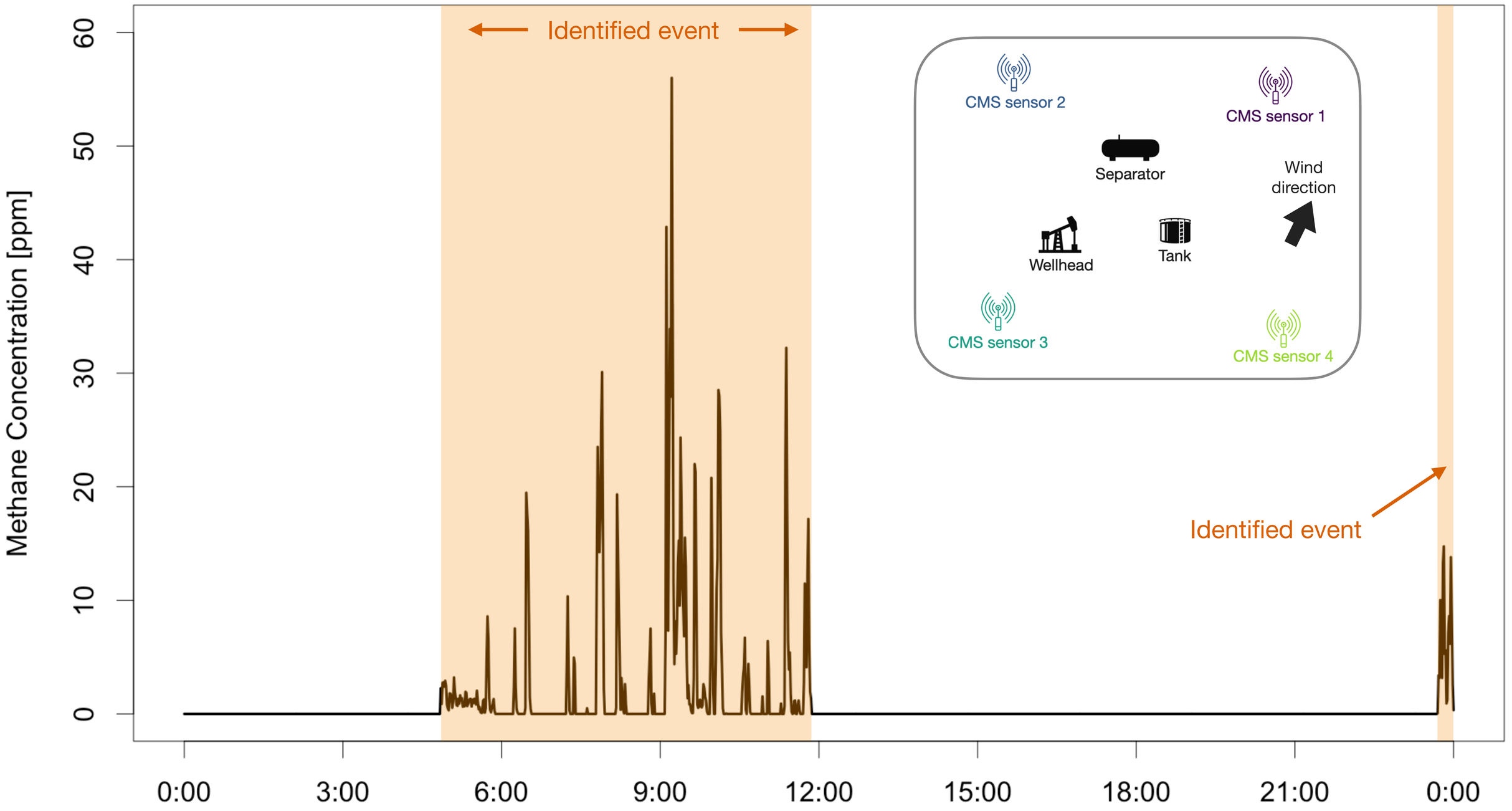
Spike detection algorithm examples



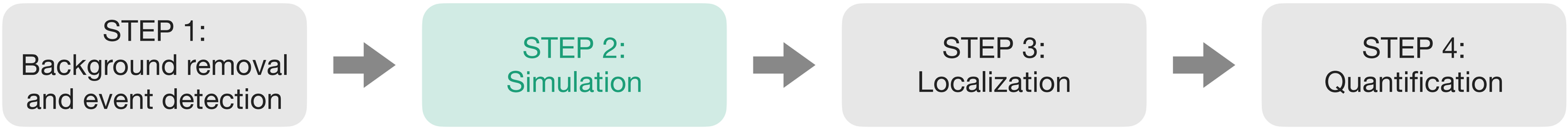



CMS sensor 1
CMS sensor 2
CMS sensor 3
CMS sensor 4
Methane Concentration [ppm]
0
10
20
30
40
50
60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
CMS sensor 3
CMS sensor 4


Maximum across sensors
Methane Concentration [ppm]
0
10
20
30
40
50
60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
CMS sensor 3
CMS sensor 4

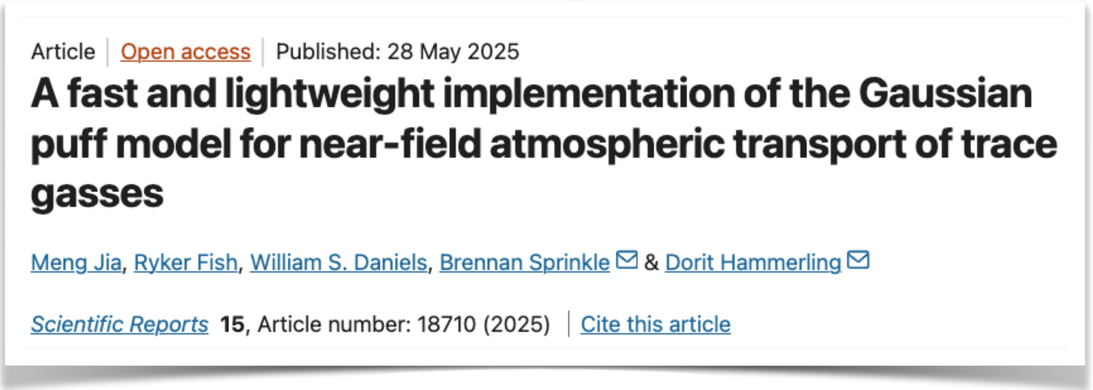

Identified event
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
CMS sensor 3
CMS sensor 4
Identified event
Methane Concentration [ppm]
0
10
20
30
40
50
60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

Open source framework for solving inverse problem



Gaussian puff atmospheric dispersion model

Total volume of methane contained in puff p



$$c_p(x, y, z, t, Q) = \frac{Q}{(2\pi)^{3/2}\sigma_y^2\sigma_z} \exp\left(-\frac{(x-ut)^2 + y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right]$$

Concentration contribution of puff p

Decay in puff concentration in horizontal plane (x, y)

Decay in puff concentration in vertical dimension (z)

Gaussian puff atmospheric dispersion model

Total volume of methane contained in puff p

Total concentration at (x, y, z, t)

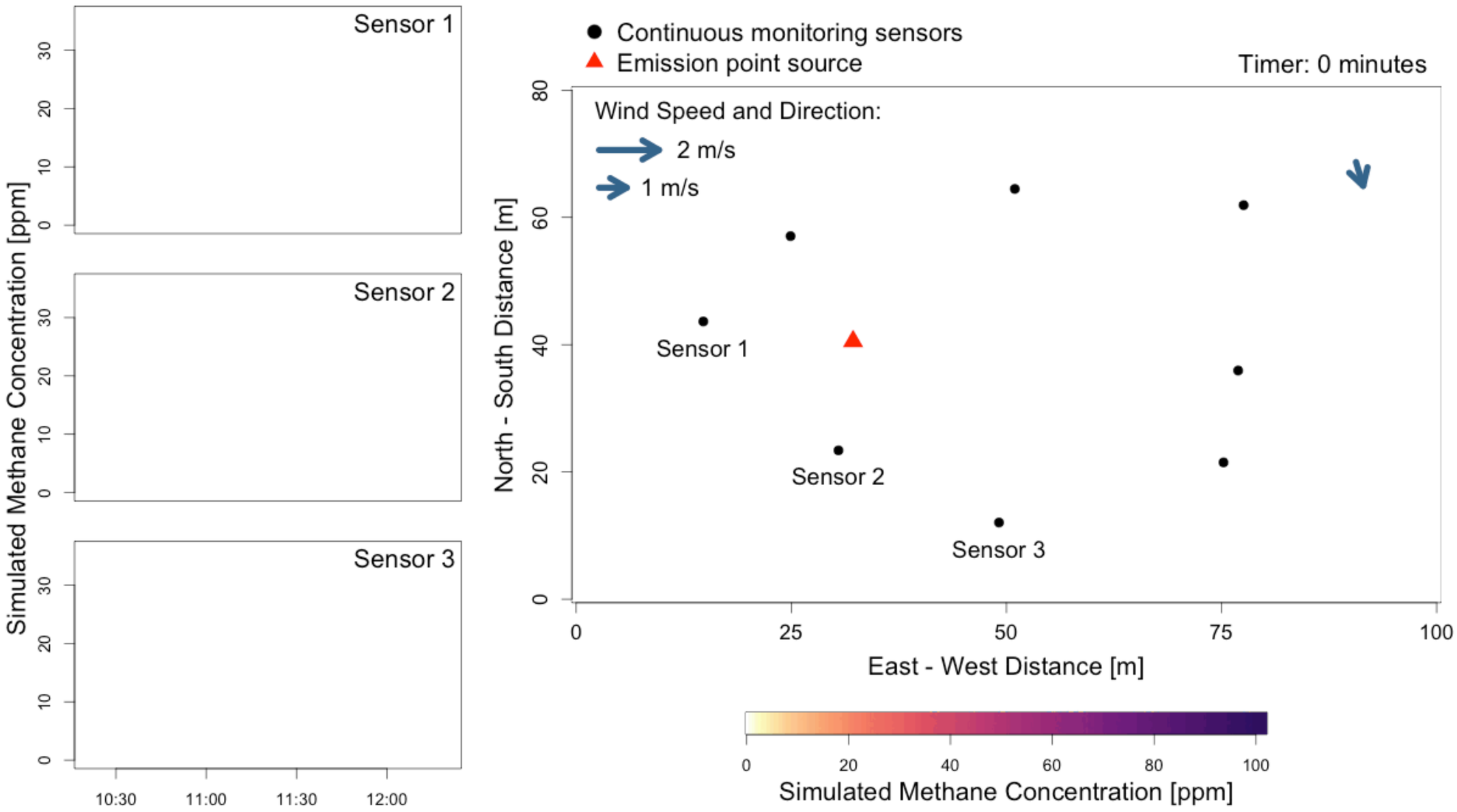
$$c(x, y, z, t, Q) = \sum_{p=1}^{P} c_p(x, y, z, t, Q)$$

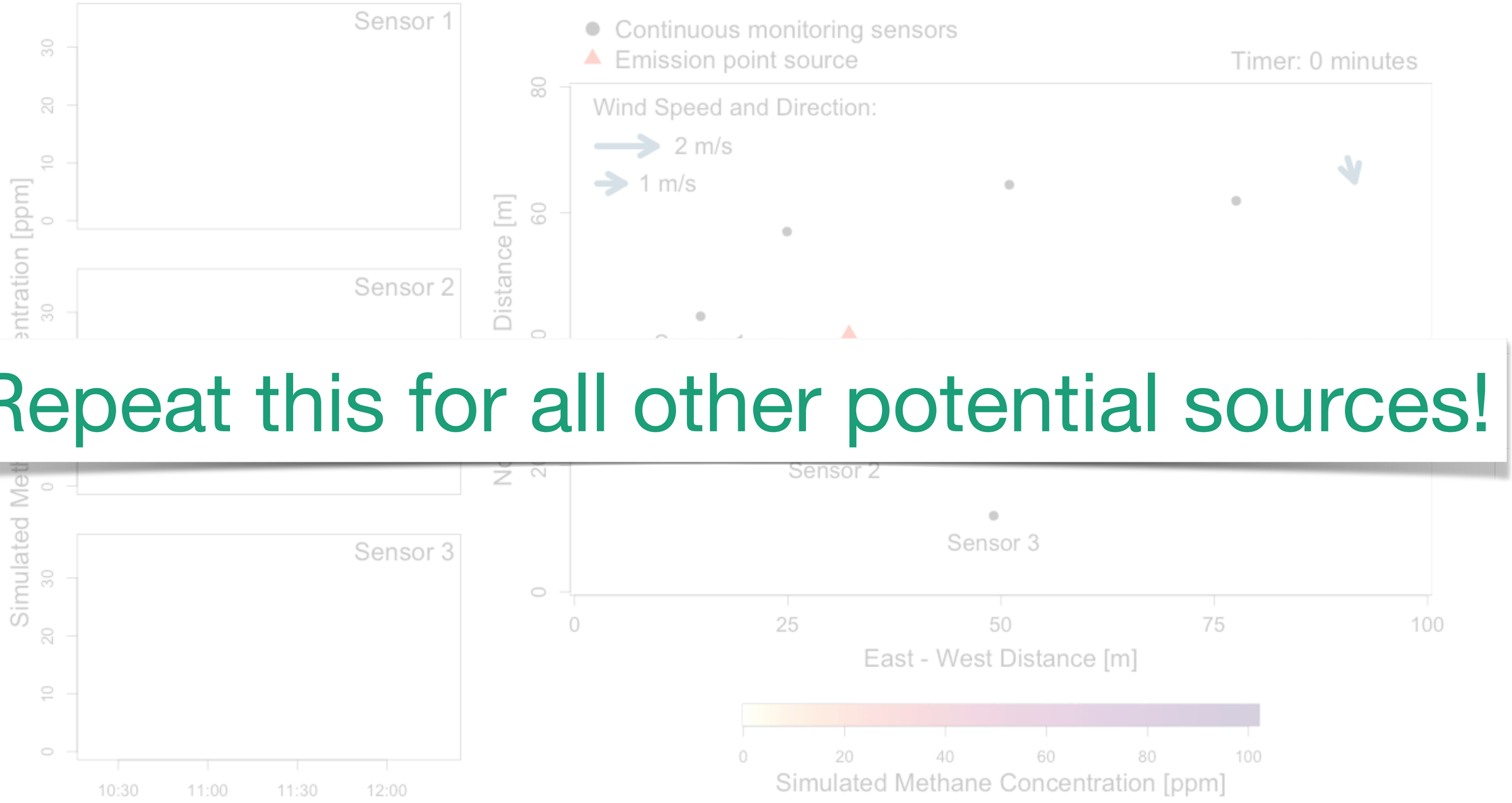
$$c_p(x, y, z, t, Q) = \frac{Q}{(2\pi)^{3/2}\sigma_y^2\sigma_z} \exp\left(-\frac{(x-ut)^2 + y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right]$$

Concentration contribution of puff p

Decay in puff concentration in horizontal plane (x, y)

Decay in puff concentration in vertical dimension (z)


Sensor 1
Sensor 2
Sensor 3
Simulated Methane Concentration [ppm]
0
10
20
30
10:30
11:00
11:30
12:00
Continuous monitoring sensors
Emission point source
Timer: 0 minutes
Wind Speed and Direction:
2 m/s
1 m/s
North - South Distance [m]
0
20
40
60
80
0
25
50
75
100
East - West Distance [m]
Sensor 1
Sensor 2
Sensor 3
0
20
40
60
80
100
Simulated Methane Concentration [ppm]



Repeat this for all other potential sources!

Open source framework for solving inverse problem

STEP 1:
Background removal
and event detection

→

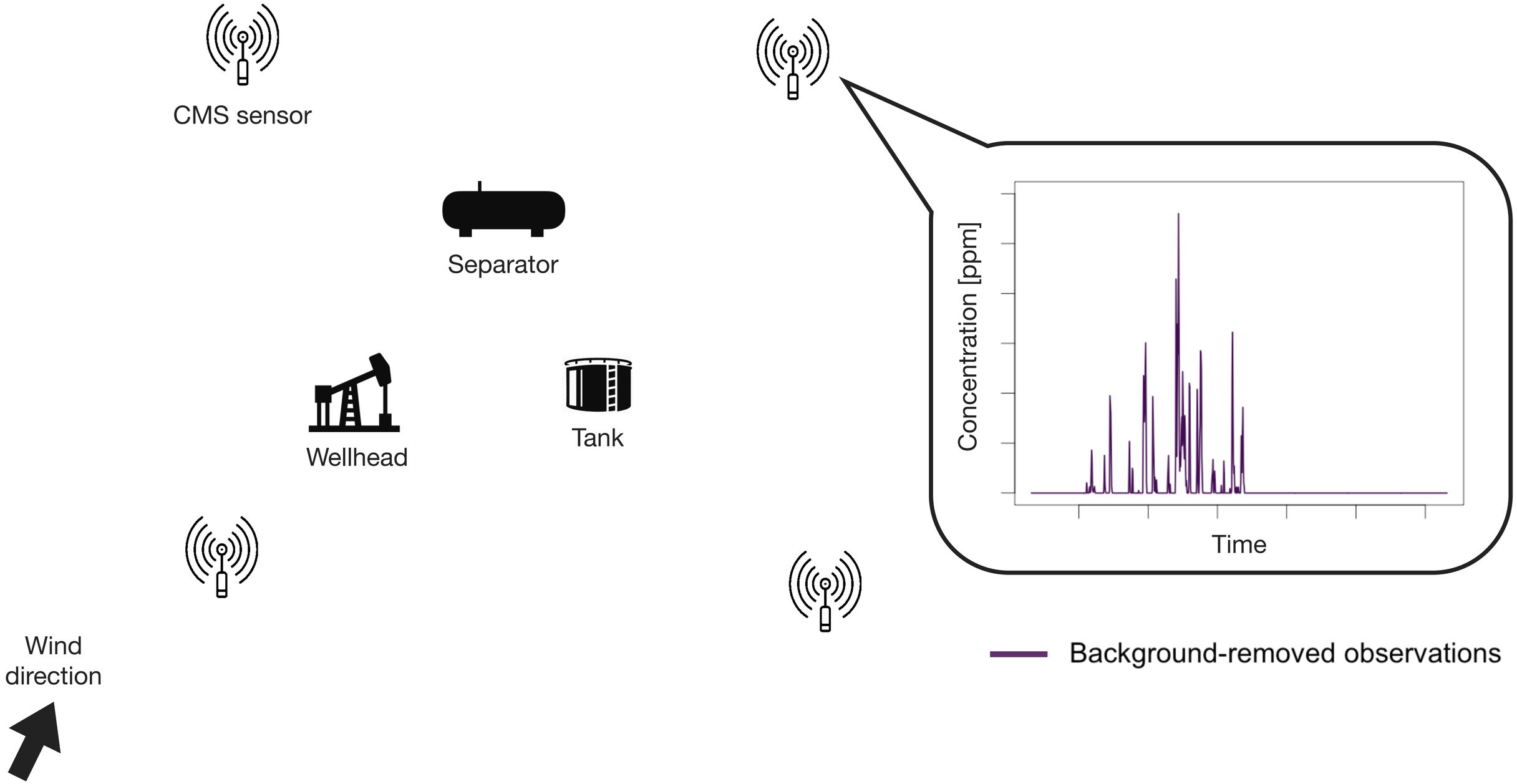
STEP 2:
Simulation

→

STEP 3:
Localization

→

STEP 4:
Quantification


CMS sensor
Separator
Wellhead
Tank
Wind direction
Concentration [ppm]
Time
Background-removed observations

CMS sensor

Simulation emission source

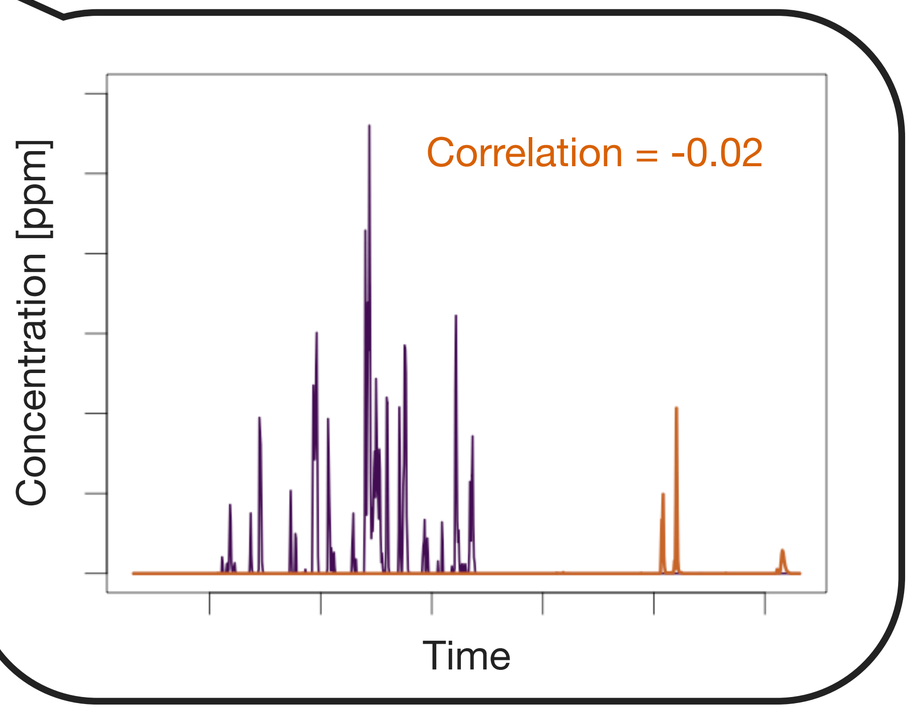
Separator

Wellhead

Tank

Wind direction

Pick source estimate using correlation coefficient



Background-removed observations

Simulated concentrations

CMS sensor

Separator

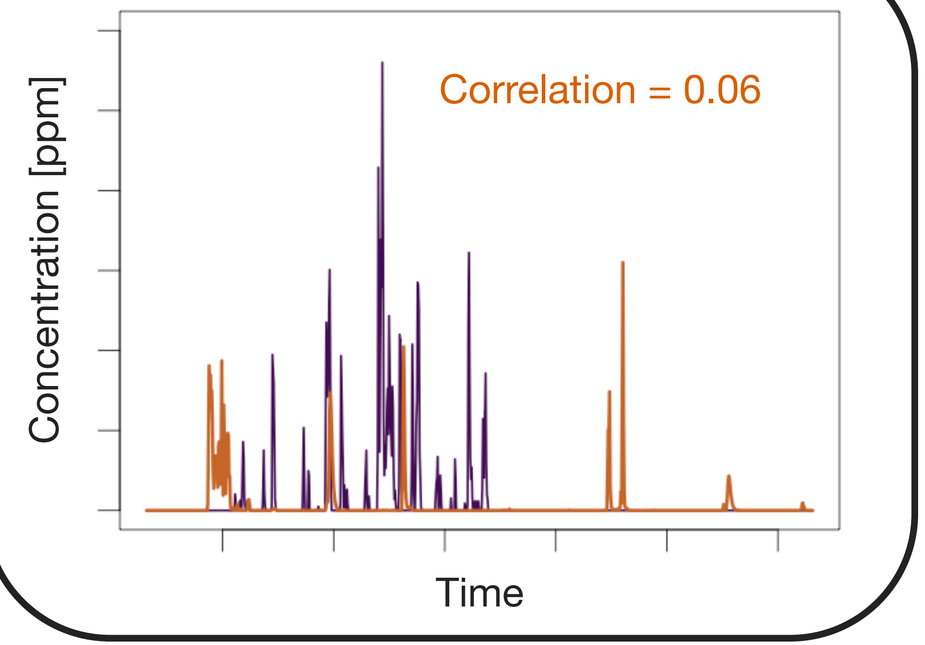
Wellhead

Simulation emission source

Tank

Wind direction

Pick source estimate using correlation coefficient



Background-removed observations

Simulated concentrations

CMS sensor

Separator

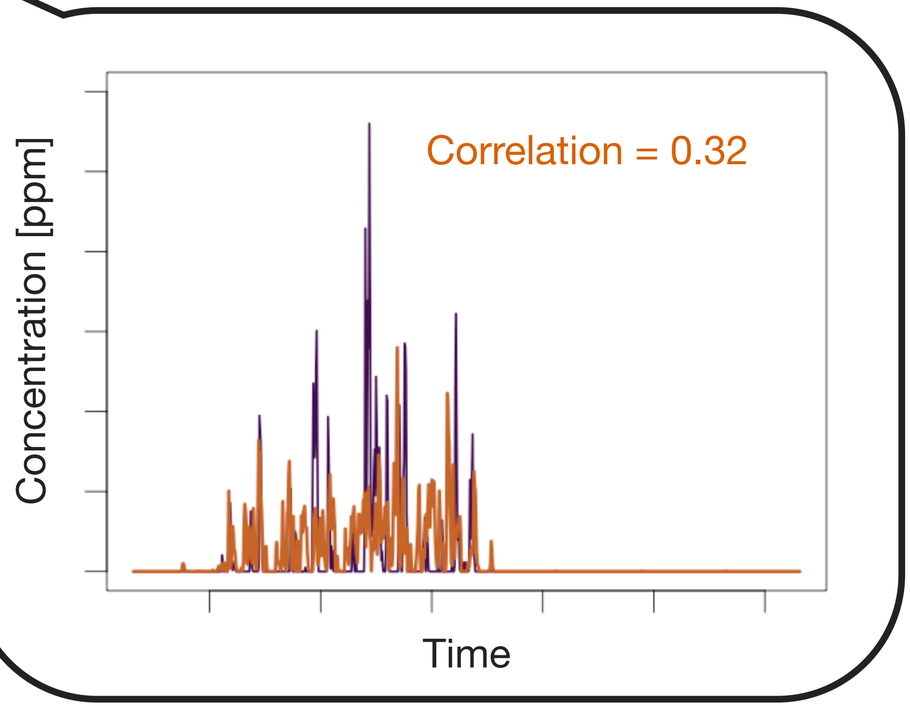
Wellhead

Tank

Simulation emission source

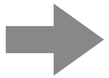
Wind direction

Pick source estimate using correlation coefficient

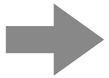


Open source framework for solving inverse problem

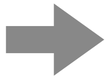
STEP 1:
Background removal
and event detection



STEP 2:
Simulation



STEP 3:
Localization



STEP 4:
Quantification

Simulation is a linear function of emission rate

Volume of methane contained in puff p

$$c_p(x, y, z, t, Q) = Q \frac{1}{(2\pi)^{3/2}\sigma_y^2\sigma_z} \exp\left(-\frac{(x-ut)^2 + y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right]$$

Concentration contribution of puff p

$$c(x, y, z, t, Q) = \sum_{p=1}^{P} c_p(x, y, z, t, Q)$$

Total concentration at (x, y, z, t)

Simulation is a linear function of emission rate

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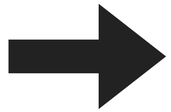
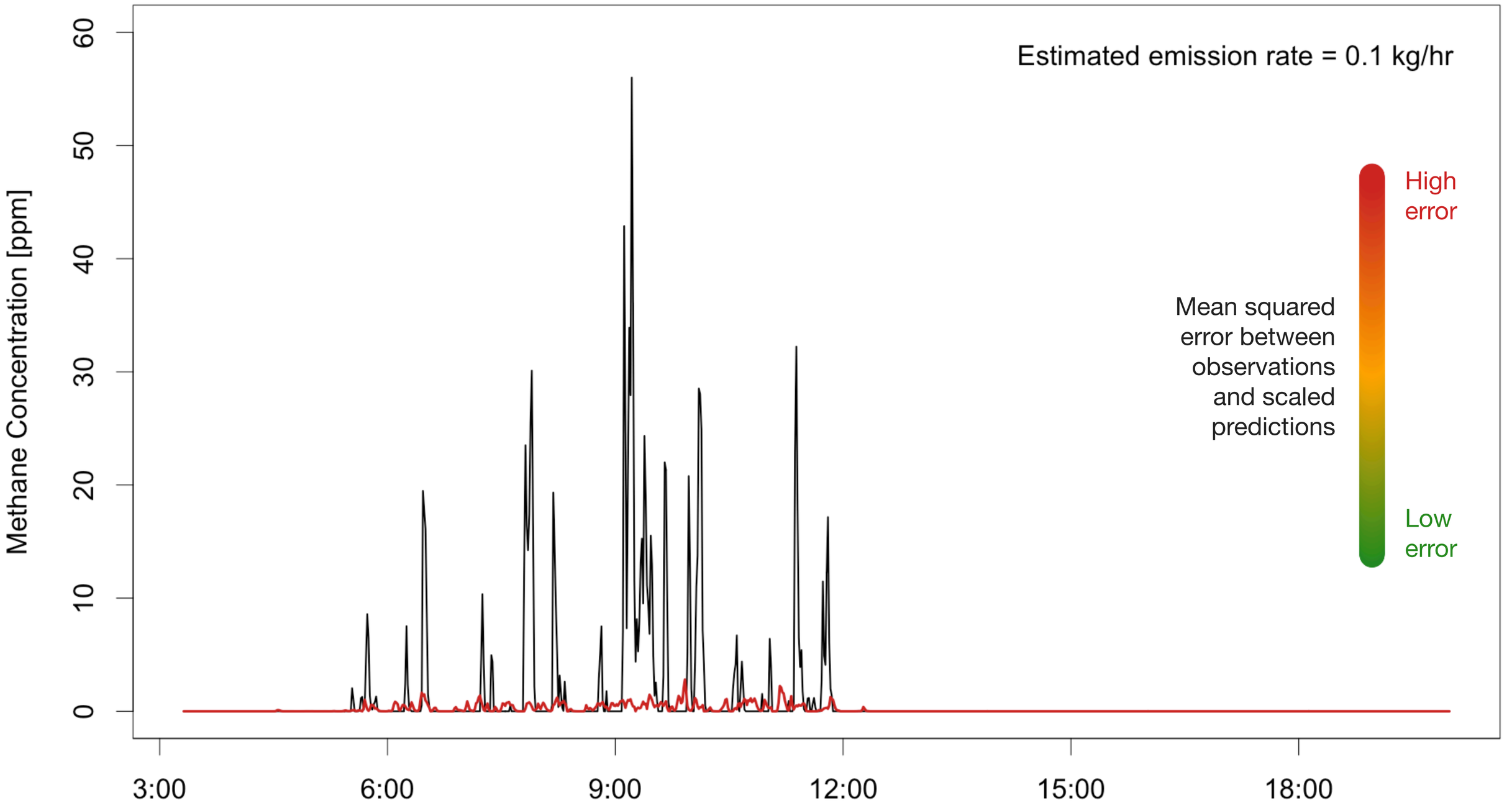


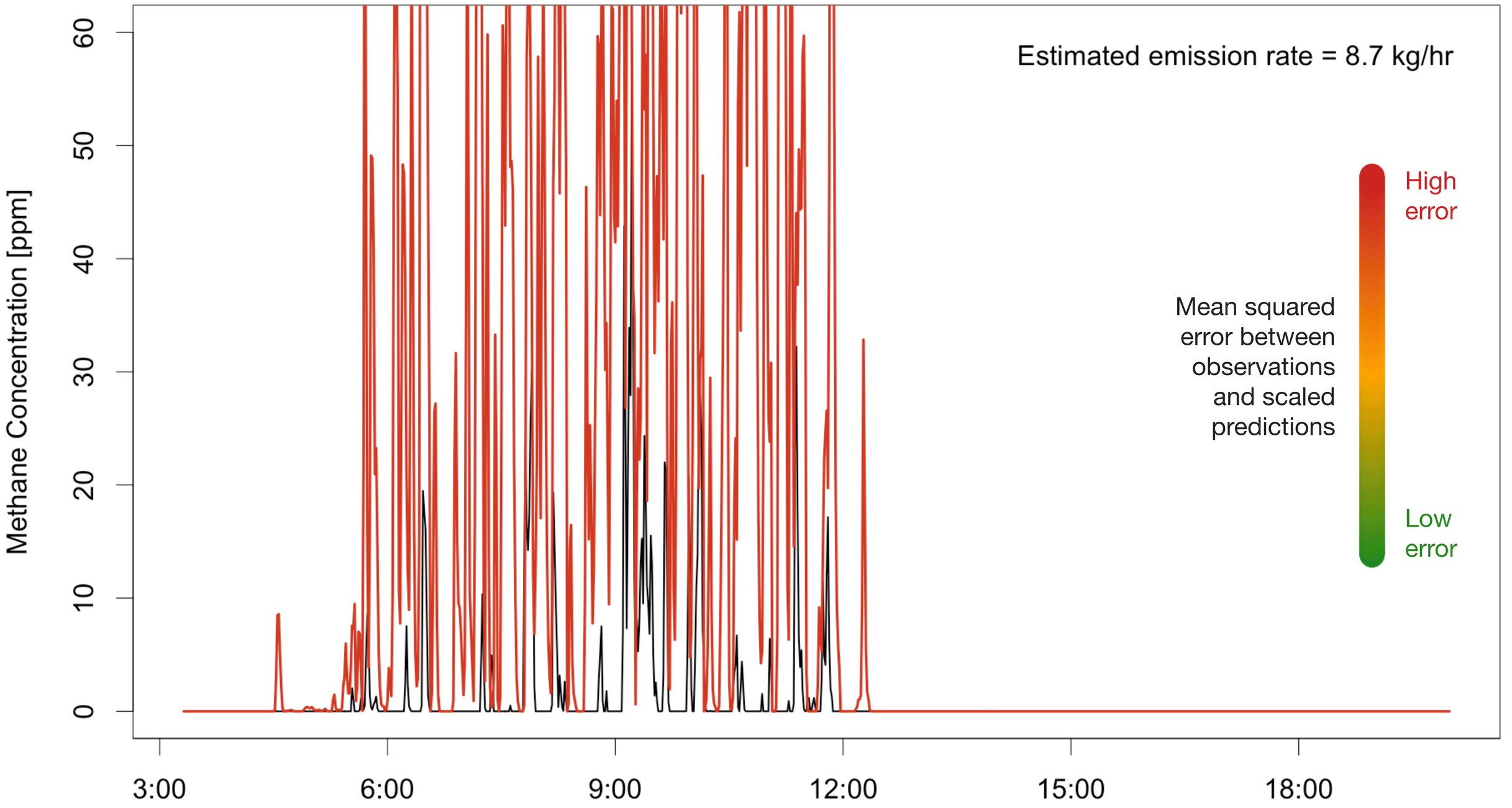
Concentration data

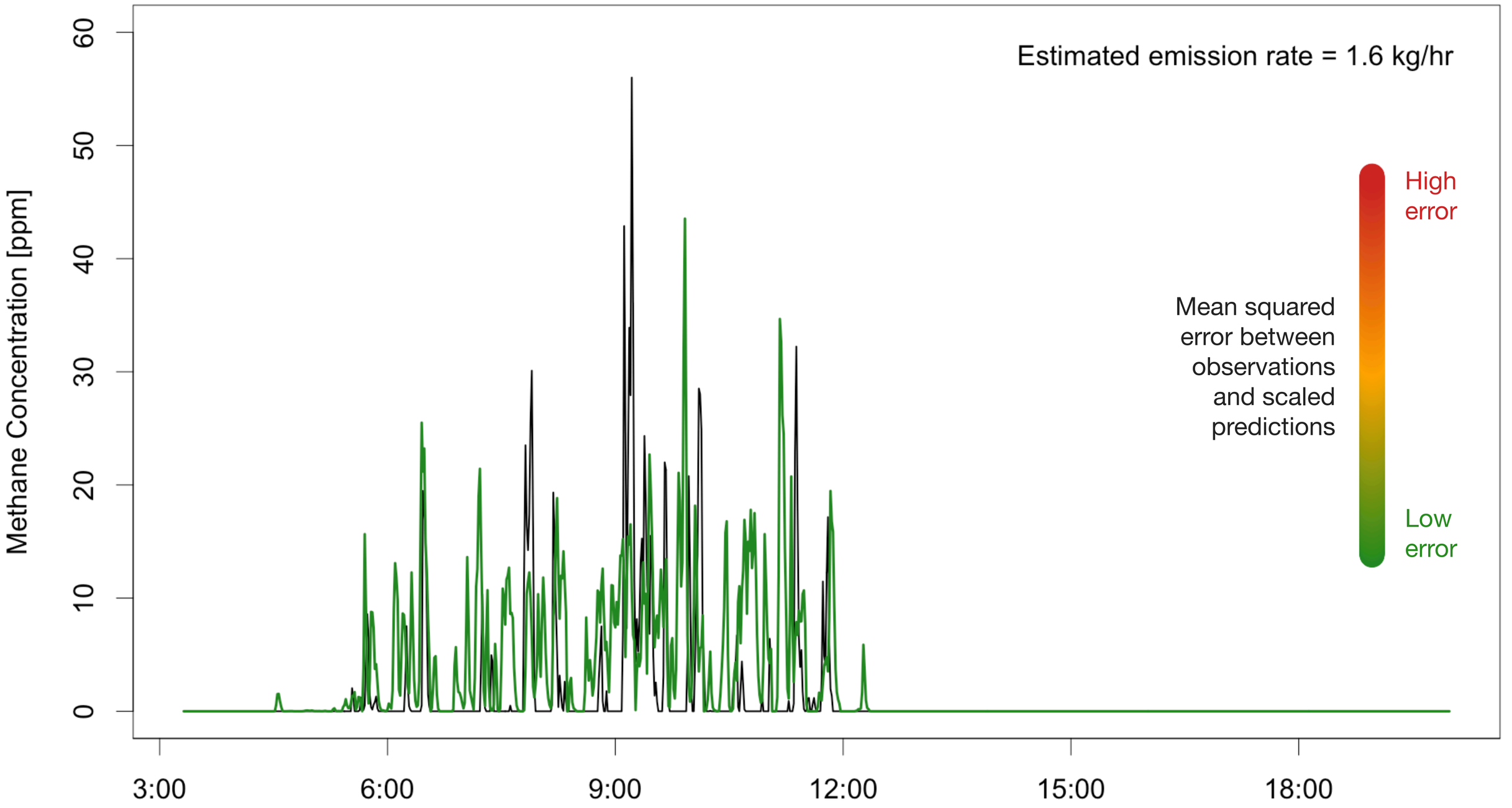
$$\hat{Q} = \underset{Q}{\operatorname{argmin}} \left\{ \frac{1}{n} \sum_{t=1}^{n} \left(d(x, y, z, t) - c(x, y, z, t, Q) \right)^2 \right\}$$

Emission rate estimate

Simulated concentrations

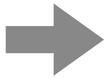

Estimated emission rate = 0.1 kg/hr
Methane Concentration [ppm]
0
10
20
30
40
50
60
3:00
6:00
9:00
12:00
15:00
18:00
Mean squared error between observations and scaled predictions
High error
Low error


Estimated emission rate = 8.7 kg/hr
Methane Concentration [ppm]
0
10
20
30
40
50
60
3:00
6:00
9:00
12:00
15:00
18:00
Mean squared error between observations and scaled predictions
High error
Low error


Estimated emission rate = 1.6 kg/hr
Methane Concentration [ppm]
0
10
20
30
40
50
60
3:00
6:00
9:00
12:00
15:00
18:00
Mean squared error between observations and scaled predictions
High error
Low error

Open source framework for solving inverse problem

STEP 1:
Background removal
and event detection



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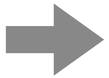

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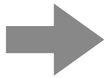
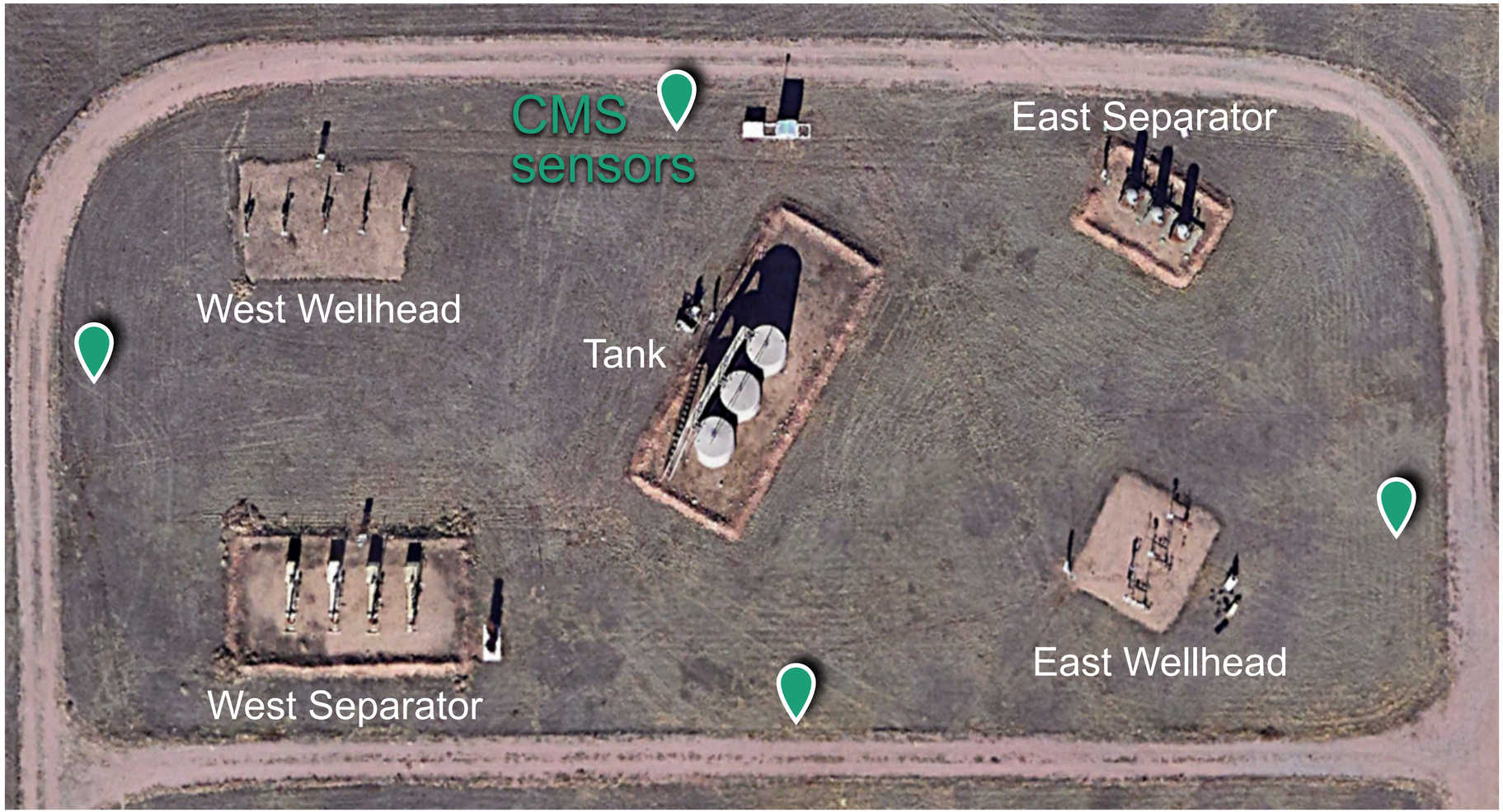


STEP 4:
Quantification

One problem… incomplete sensor coverage



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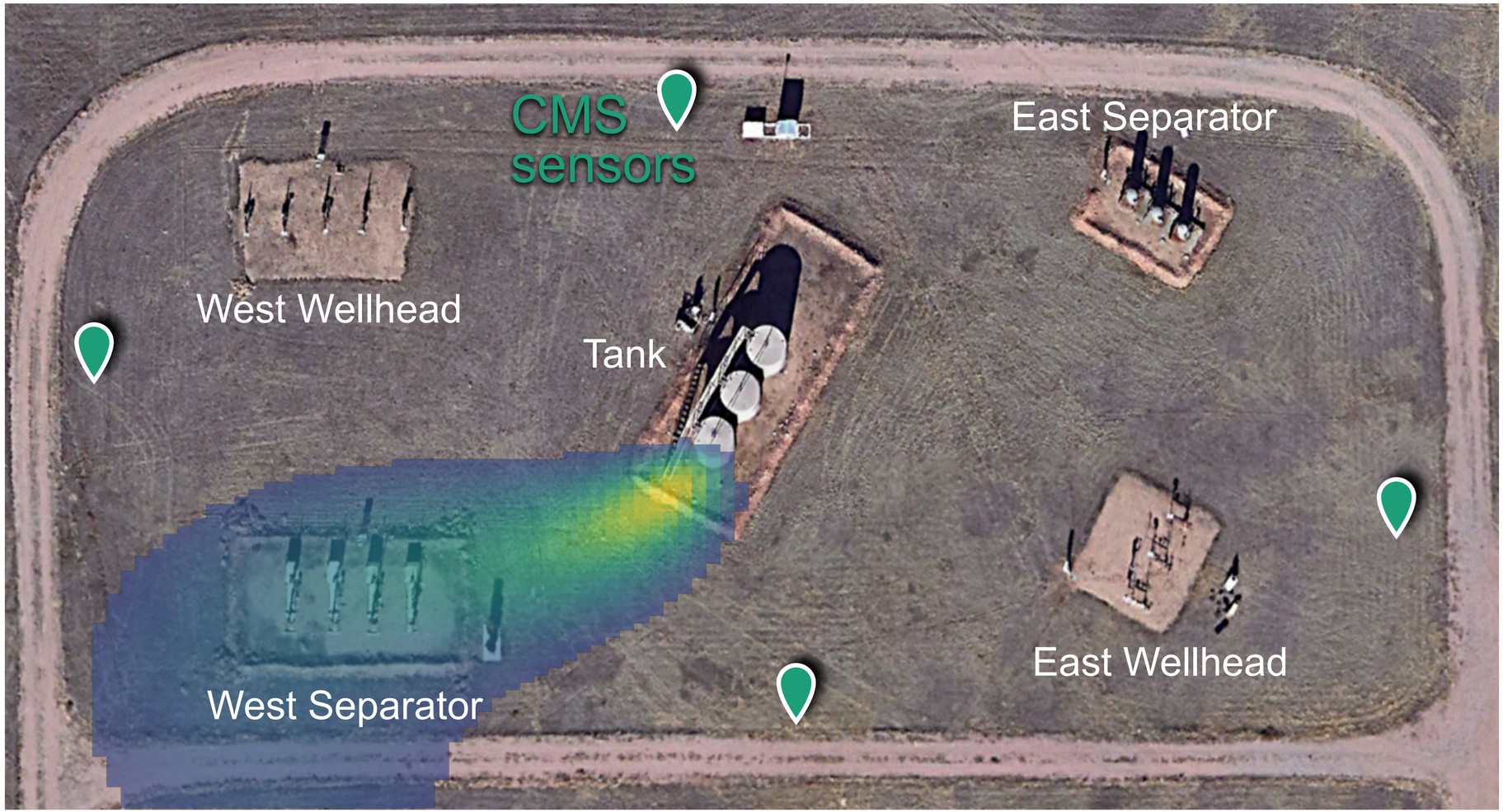

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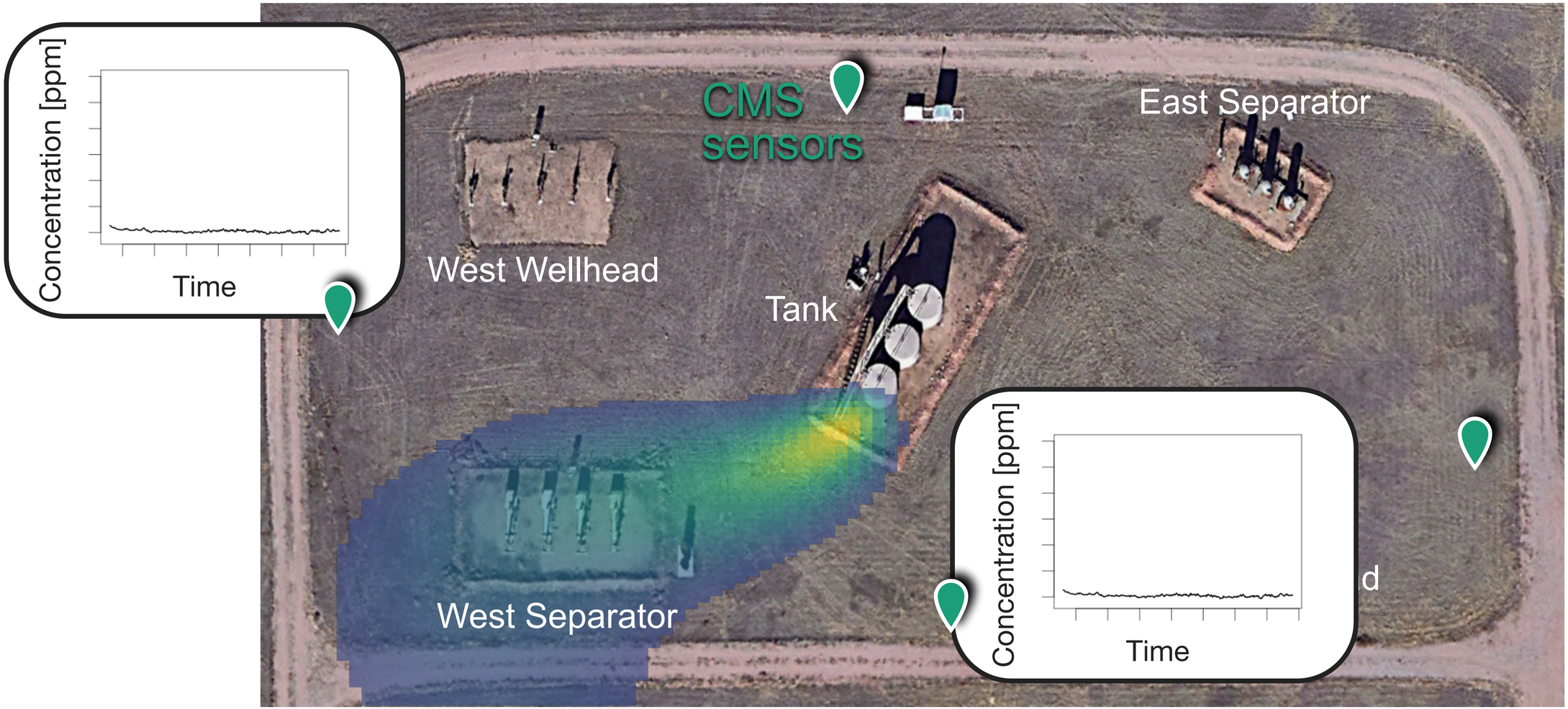
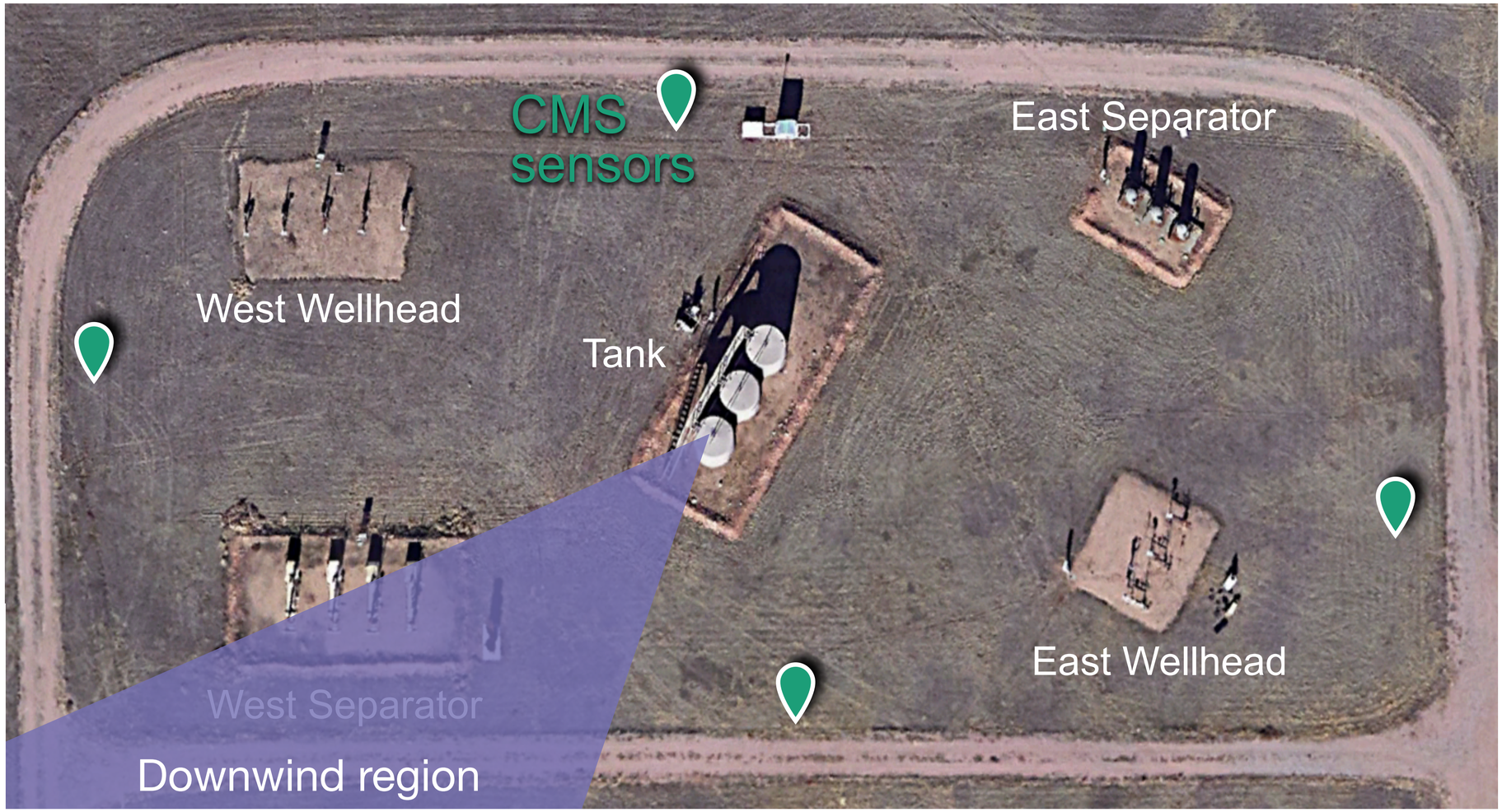


CMS do not provide emission information when the wind blows between sensors

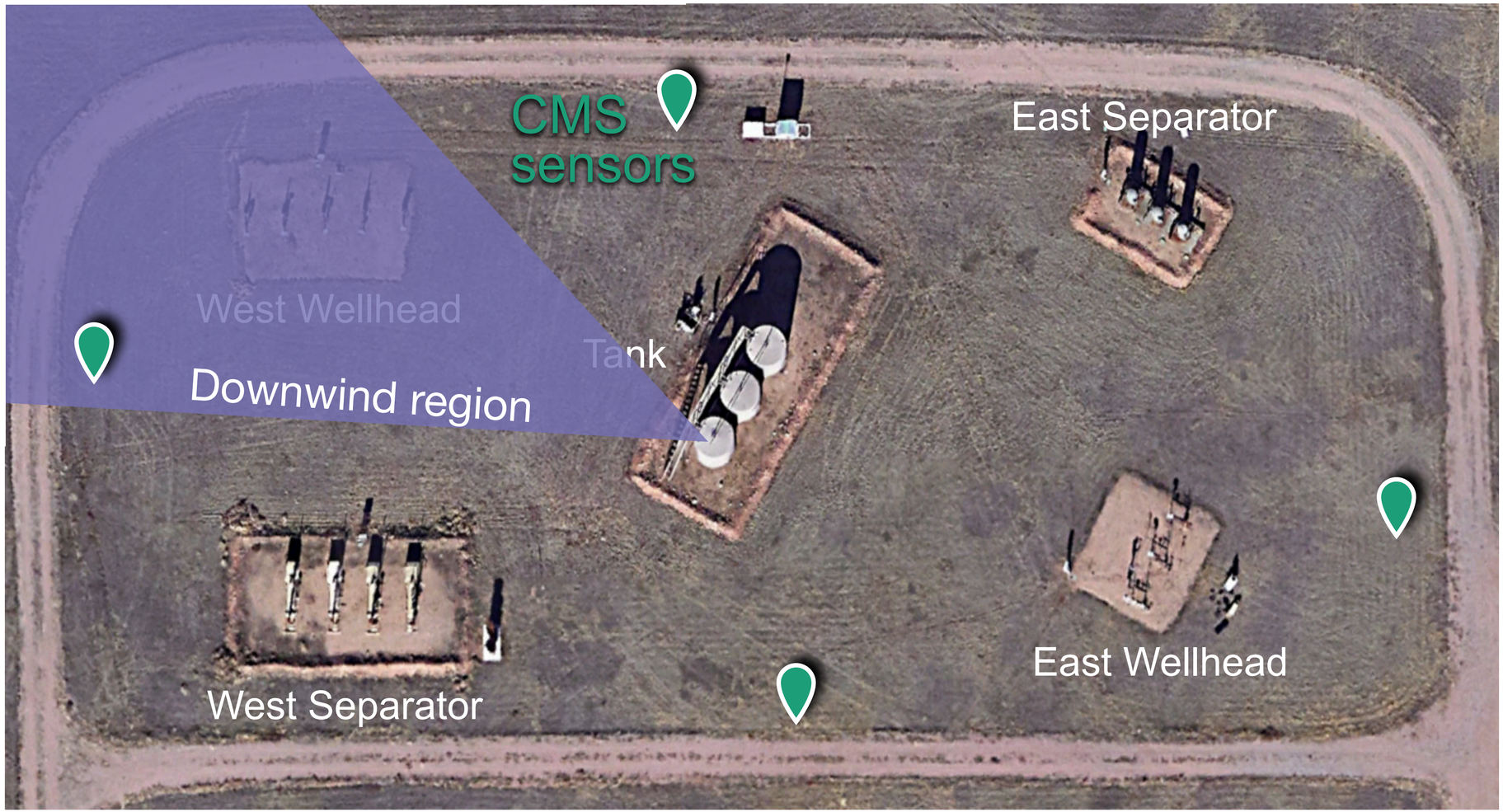
However, we can estimate when this happens!



Downwind region **does not** overlap with CMS sensors = period of “**no information**”

However, we can estimate when this happens!

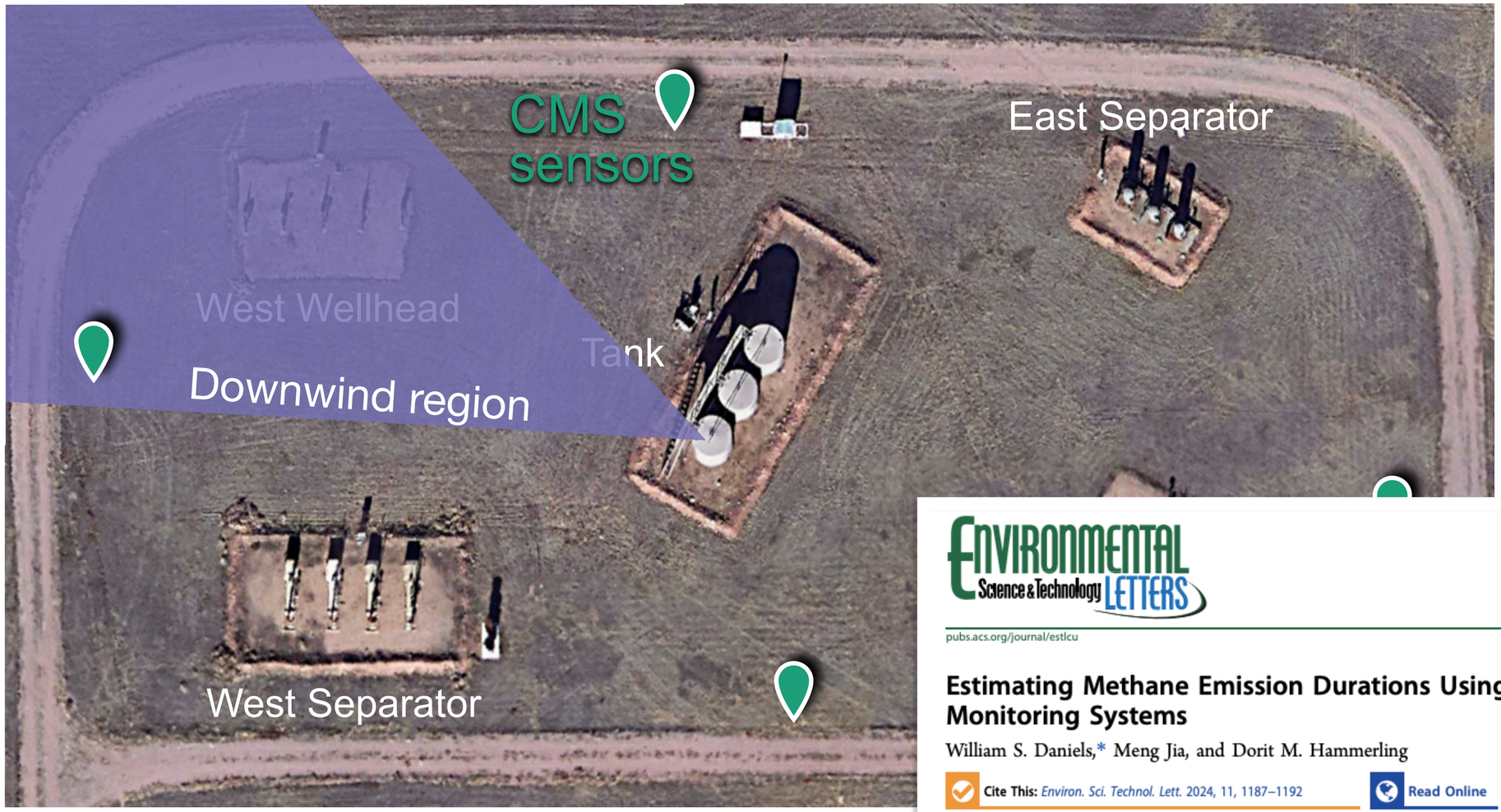
Wind direction



Downwind region **does** overlap with CMS sensors = period of “**information**”

However, we can estimate when this happens!

Wind direction



ENVIRONMENTAL Science & Technology LETTERS

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pubs.acs.org/journal/estlcu

Letter

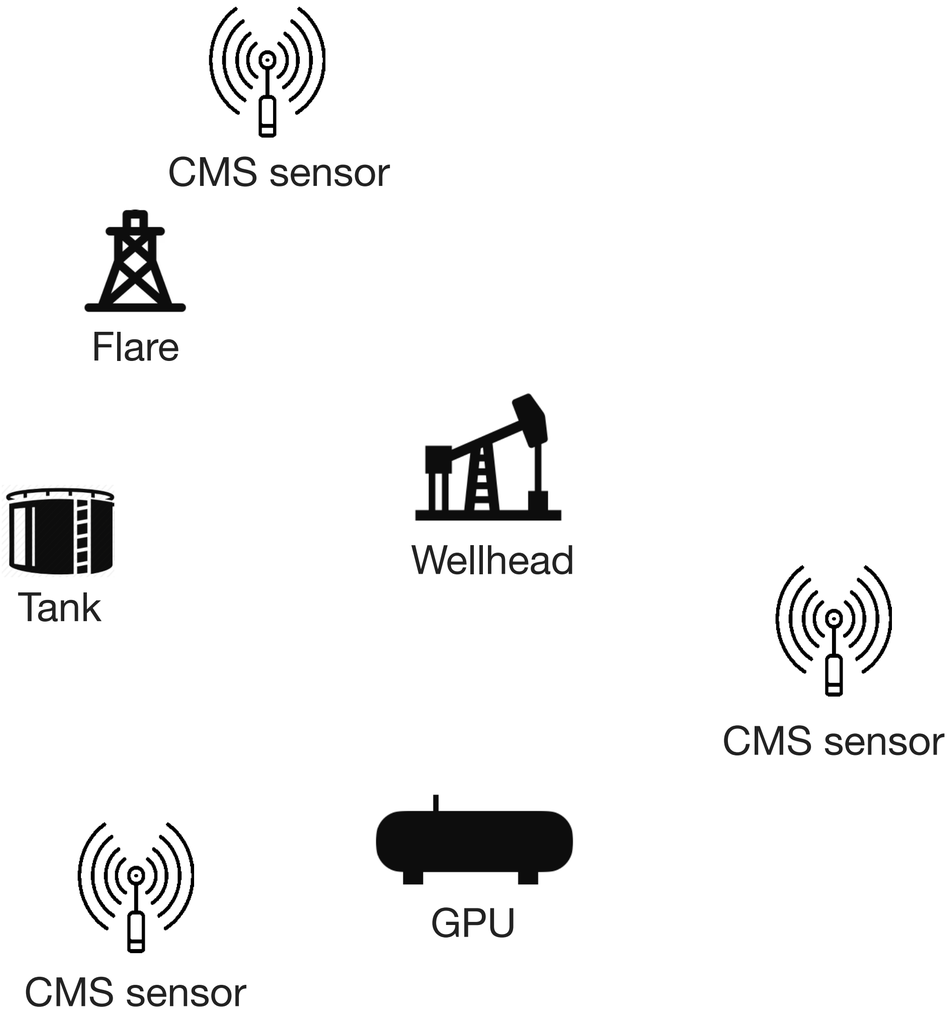
Estimating Methane Emission Durations Using Continuous Monitoring Systems

William S. Daniels,* Meng Jia, and Dorit M. Hammerling

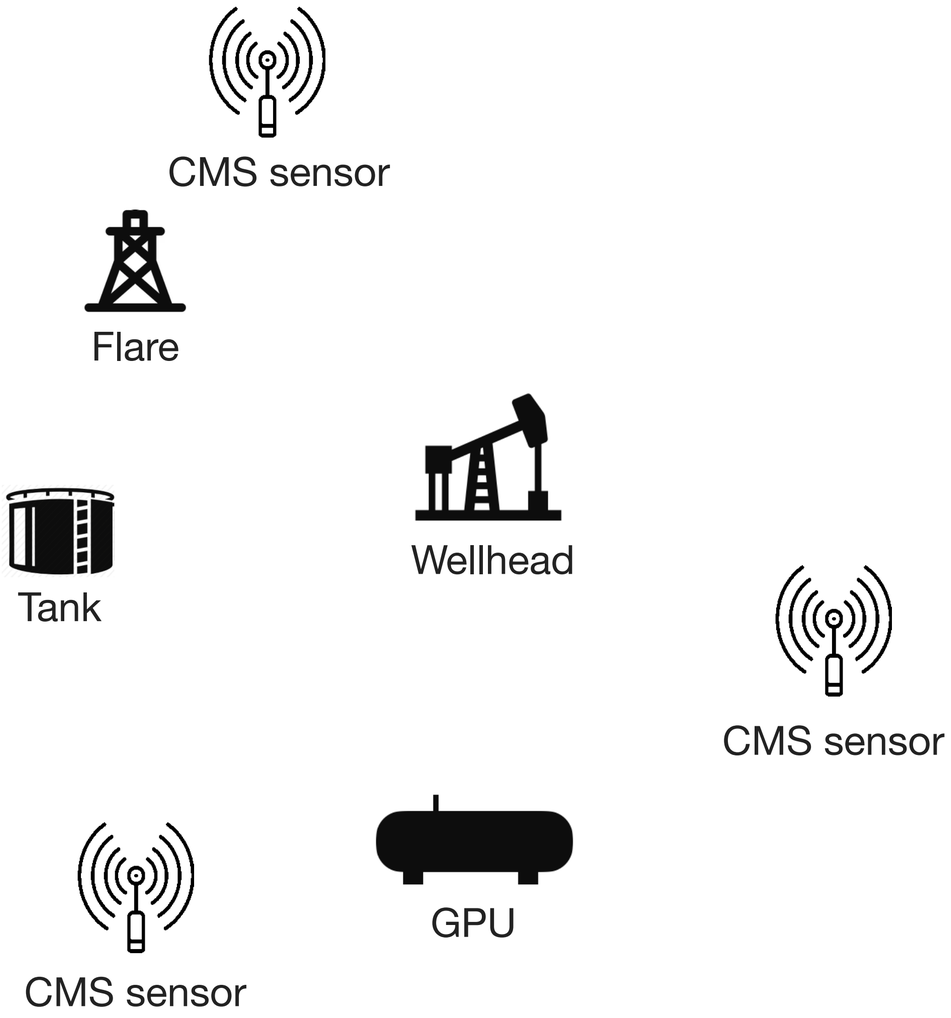
Cite This: *Environ. Sci. Technol. Lett.* 2024, 11, 1187−1192

Read Online

Downwind region **does** overlap with CMS sensors = period of "**information**"



Real data example



Why are we doing this again?

1. Methane is a potent greenhouse gas.
2. Methane emissions from oil and gas sites are often co-emitted with hazardous air pollutants that have adverse human health effects.
3. Methane is the “product” that oil and gas companies sell. Less leaks = more product.

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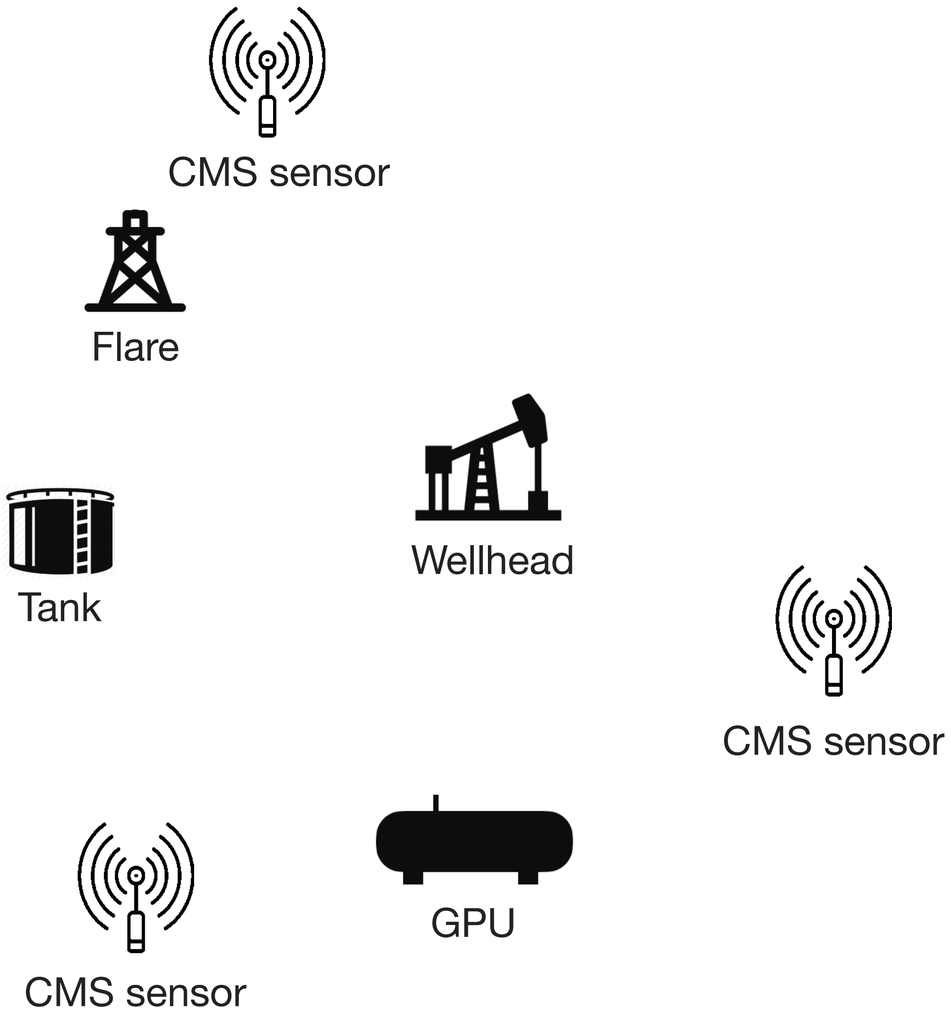

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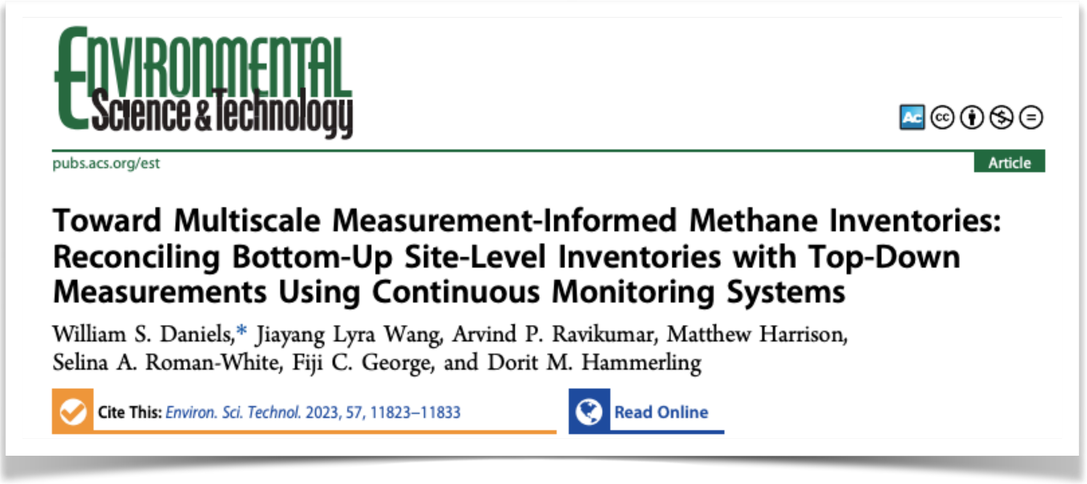

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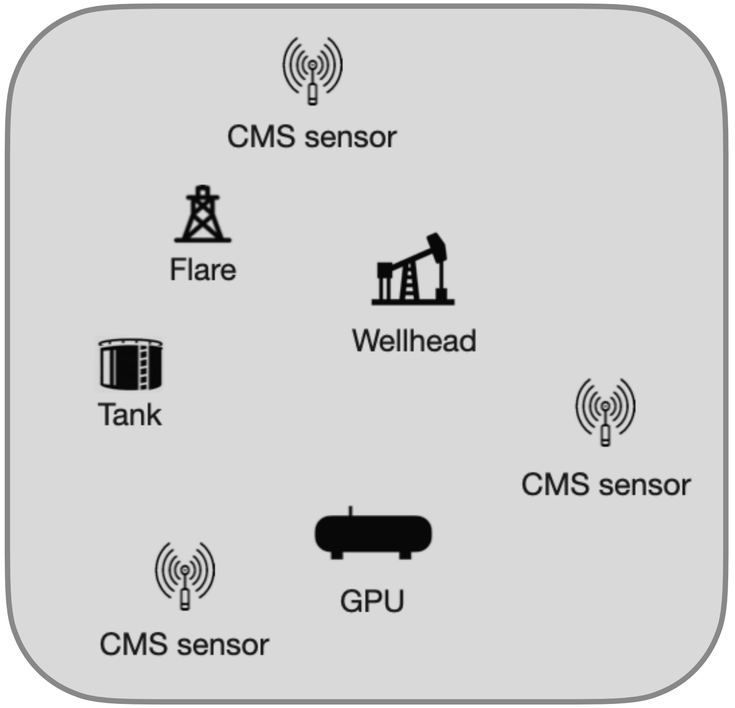
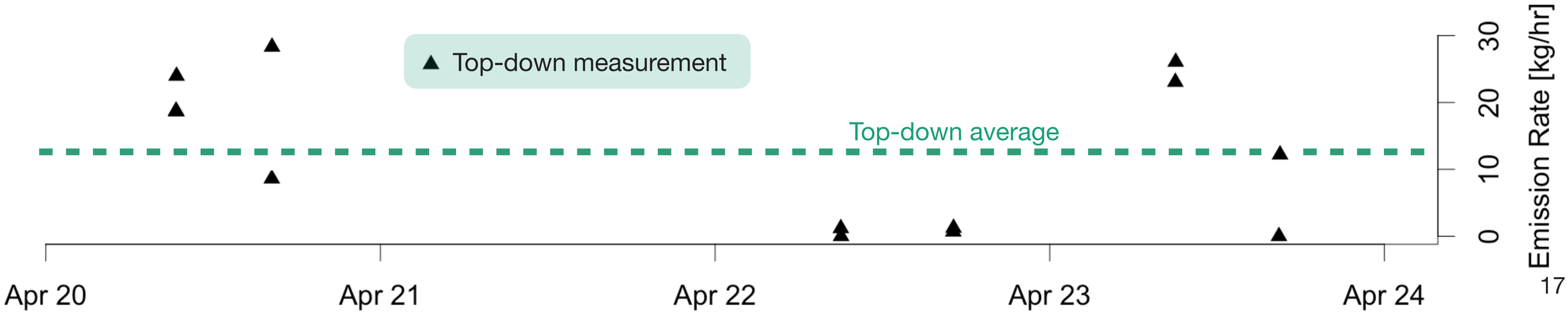
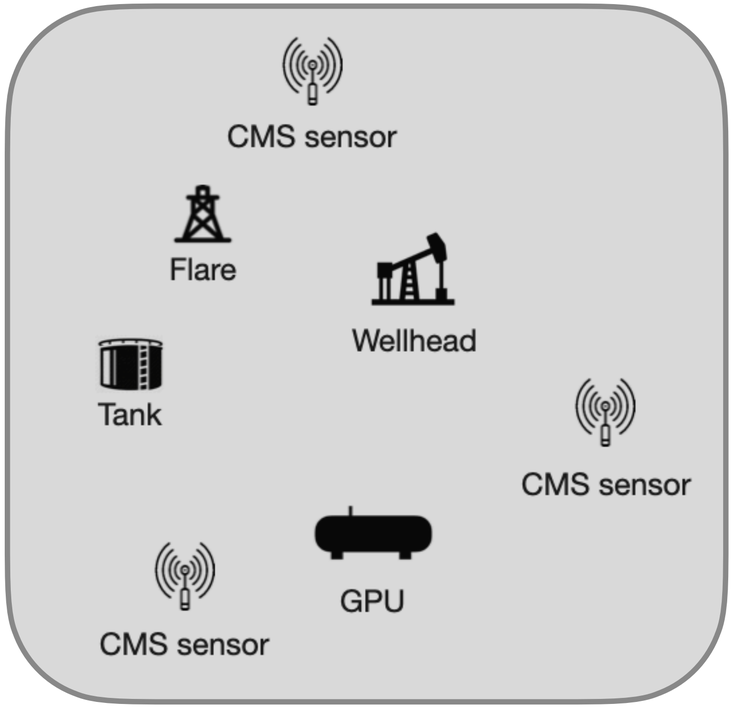


13 top-down measurements over 4 days

average = 12.5 kg/hr



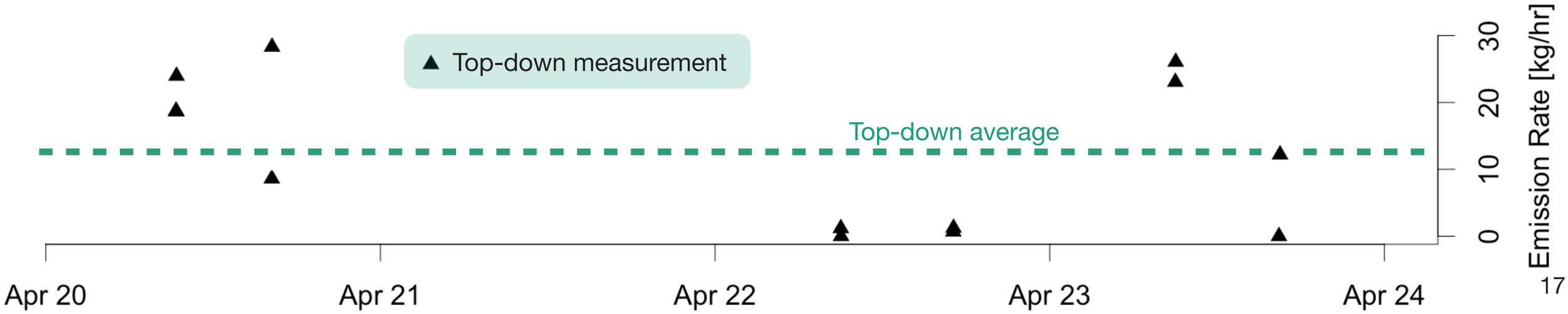


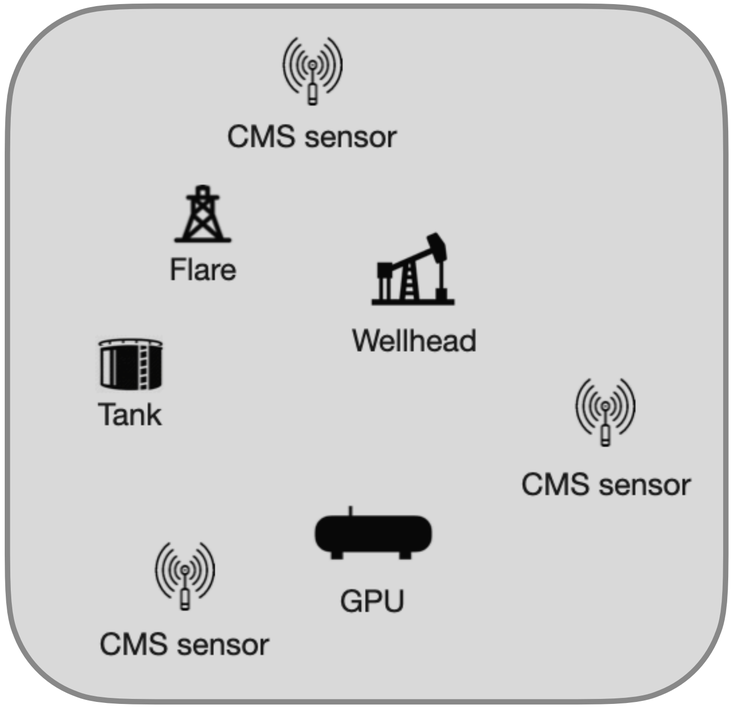
13 top-down measurements over 4 days → average = 12.5 kg/hr

Bottom-up inventory during top-down measurements → 0.8 kg/hr

Bottom-up inventory estimate =

1 wellhead	x	wellhead emission factor	+
1 GPU	x	GPU emission factor	+
1 tank	x	tank emission factor	+ …





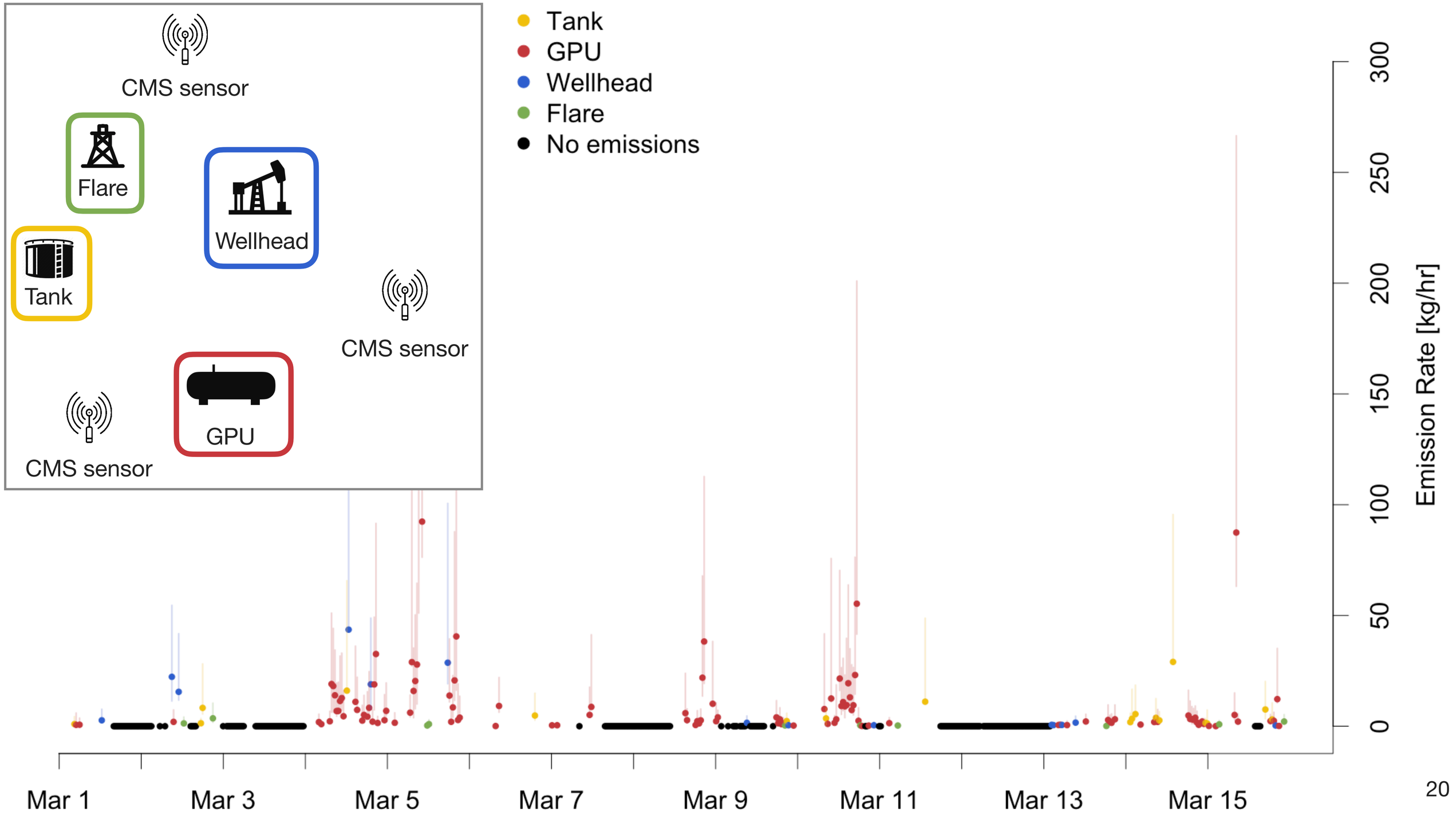
13 top-down measurements over 4 days → average = 12.5 kg/hr

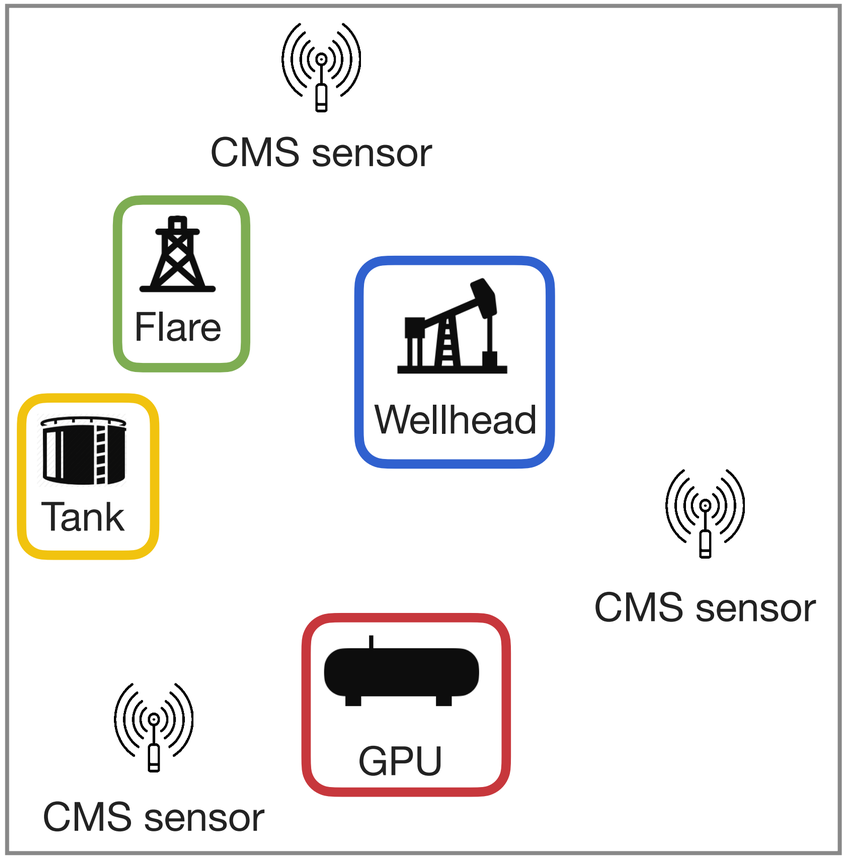
Bottom-up inventory during top-down measurements → 0.8 kg/hr

Is the bottom-up inventory wrong?

Or did the top-down measurements capture larger than average emissions?

Need real-time emissions information from the CMS to answer this question!


CMS sensor
Flare
Wellhead
Tank
CMS sensor
GPU
CMS sensor
Tank
GPU
Wellhead
Flare
No emissions
Emission Rate [kg/hr]
0
50
100
150
200
250
300
Mar 1
Mar 3
Mar 5
Mar 7
Mar 9
Mar 11
Mar 13
Mar 15



Top-down average

Company emissions inventory (shown as bars)

Site total

Oct

Nov

Dec

Jan

Feb

Mar

Apr

0

2

4

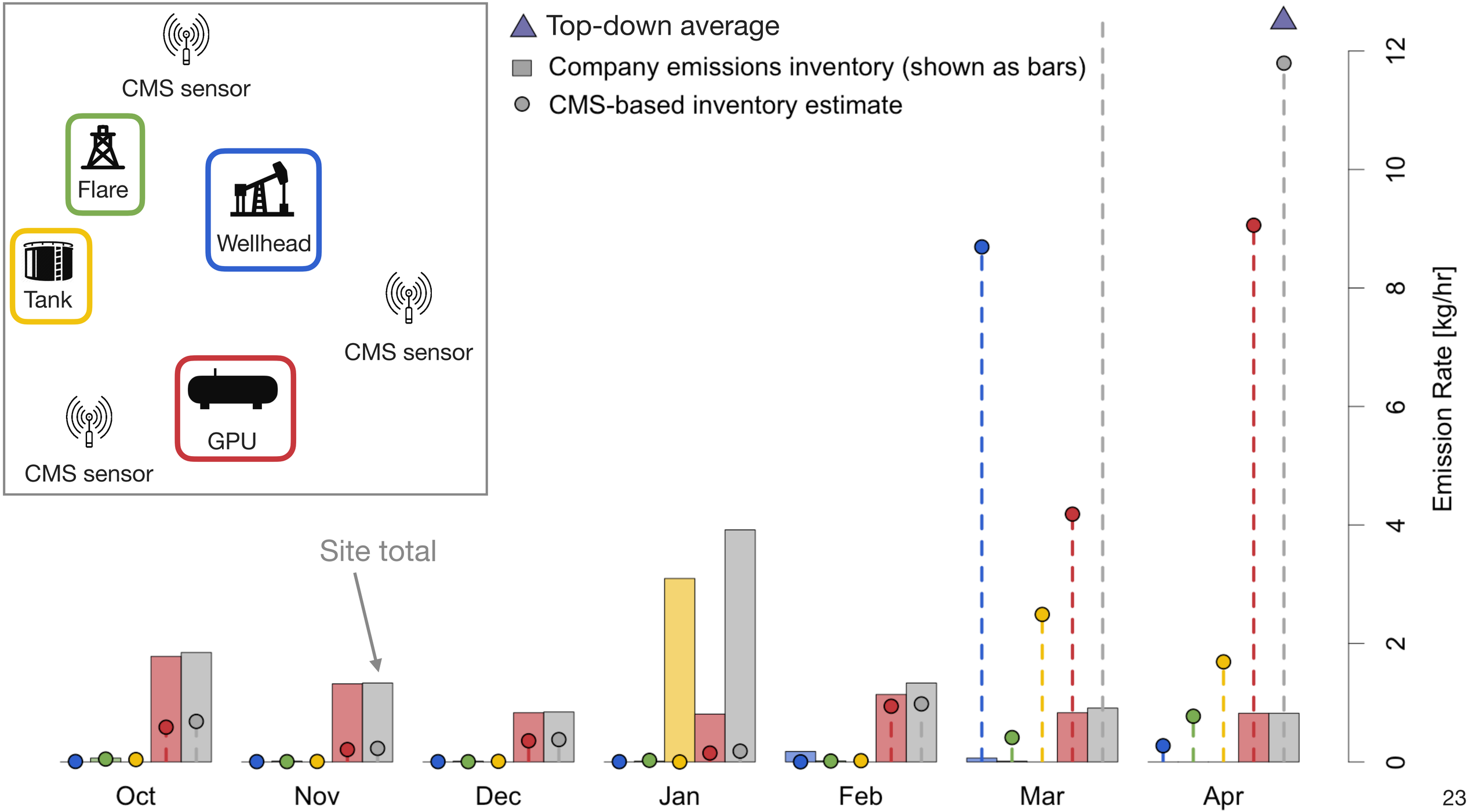
6

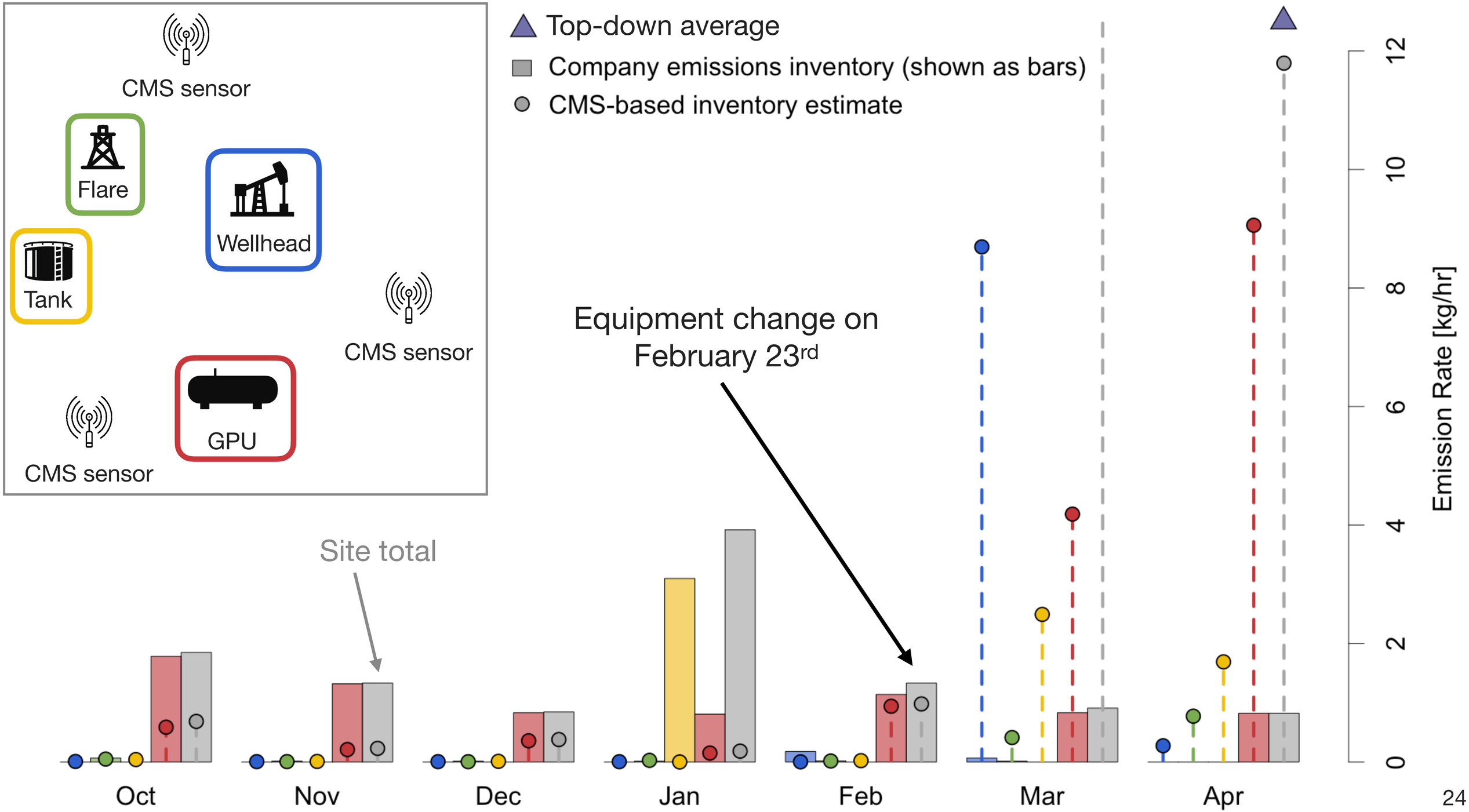
8

10

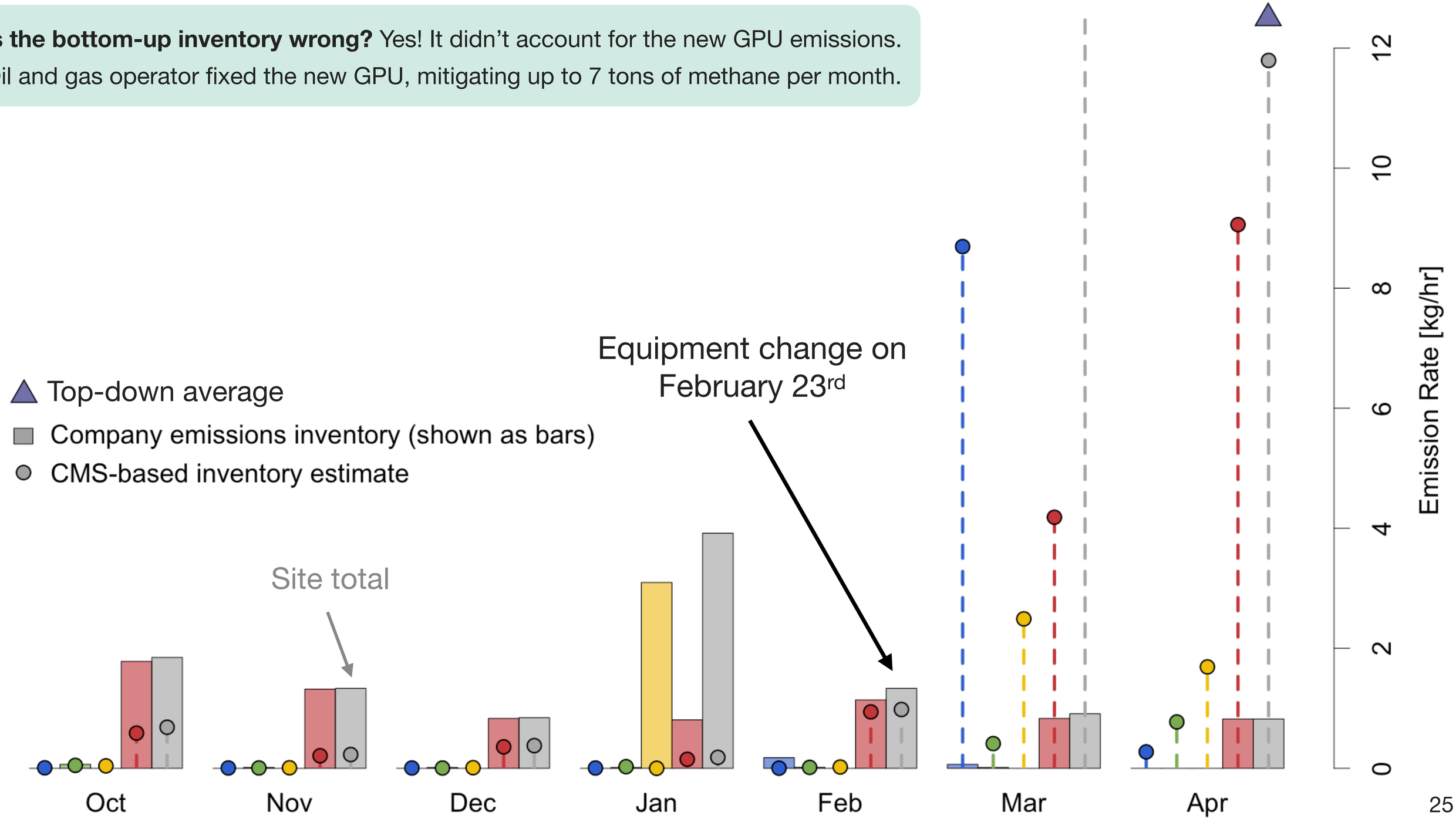
12

Emission Rate [kg/hr]


CMS sensor
Flare
Wellhead
Tank
CMS sensor
GPU
CMS sensor
Top-down average
Company emissions inventory (shown as bars)
CMS-based inventory estimate
Site total
Oct
Nov
Dec
Jan
Feb
Mar
Apr
0
2
4
6
8
10
12
Emission Rate [kg/hr]

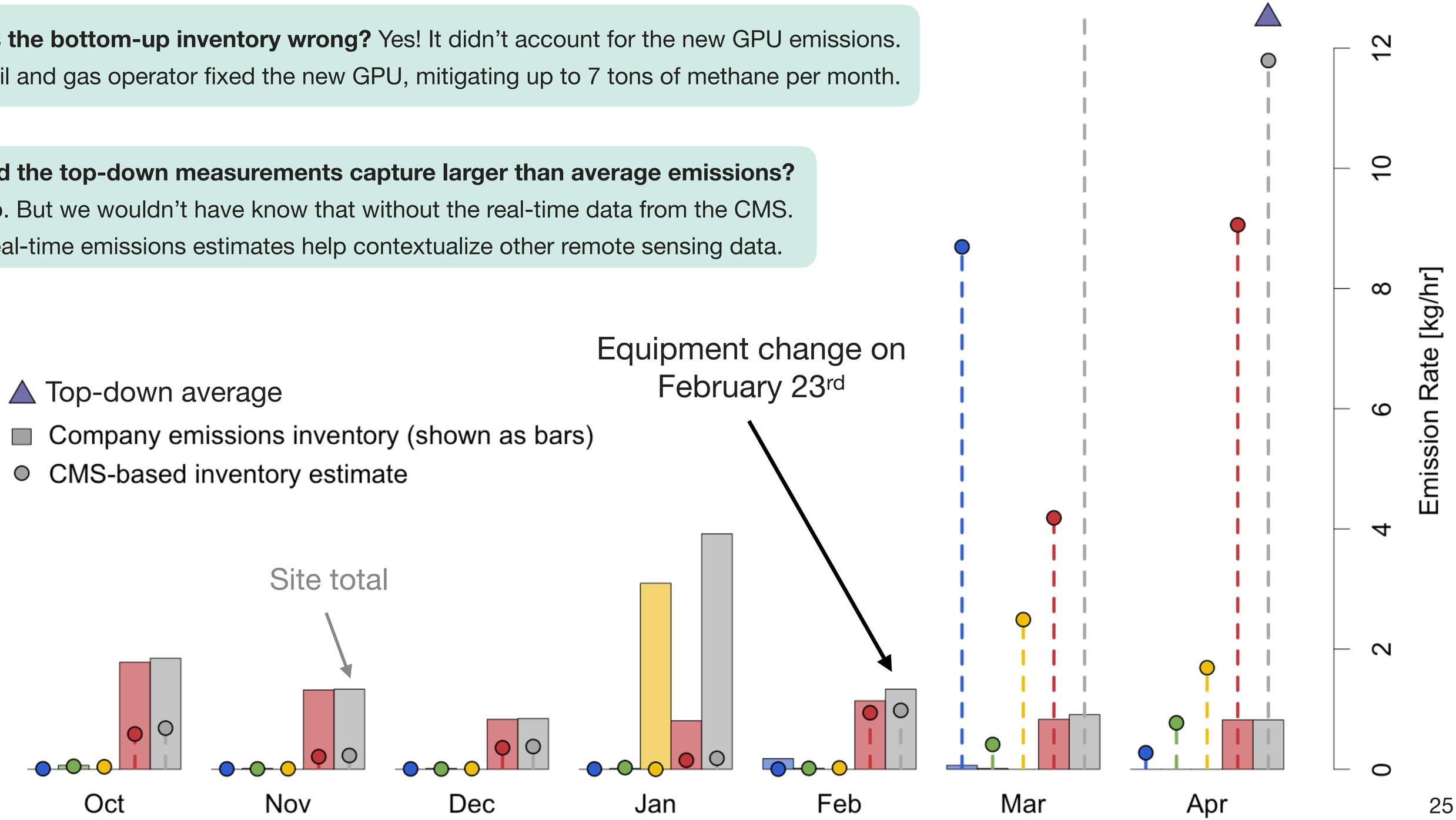

CMS sensor
Flare
Wellhead
Tank
CMS sensor
GPU
CMS sensor
Top-down average
Company emissions inventory (shown as bars)
CMS-based inventory estimate
Equipment change on February 23rd
Site total
Oct
Nov
Dec
Jan
Feb
Mar
Apr
0
2
4
6
8
10
12
Emission Rate [kg/hr]

Is the bottom-up inventory wrong? Yes! It didn't account for the new GPU emissions. Oil and gas operator fixed the new GPU, mitigating up to 7 tons of methane per month.



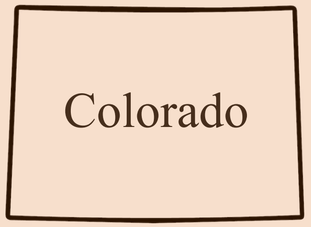
Is the bottom-up inventory wrong? Yes! It didn't account for the new GPU emissions. Oil and gas operator fixed the new GPU, mitigating up to 7 tons of methane per month.

Did the top-down measurements capture larger than average emissions? No. But we wouldn't have know that without the real-time data from the CMS. Real-time emissions estimates help contextualize other remote sensing data.



Project 2

Set state-wide emissions regulations



Set state-wide emissions regulations

↓

Economic incentives for emission reduction

COLORADO SCHOOL OF MINES

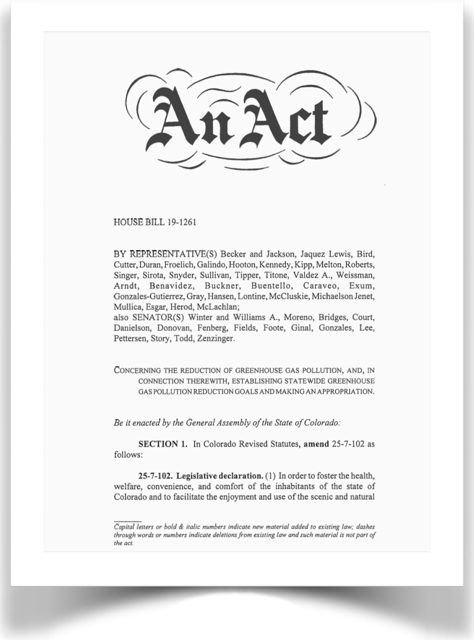
COLORADO STATE UNIVERSITY

COLORADO
Department of Public Health & Environment

A bit of Colorado's regulatory history..

2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026

Colorado passes HB19-1261 setting emission reduction targets



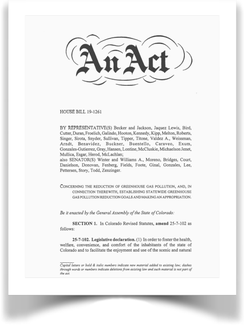
Requires greenhouse gas emissions to be reduced to 26% of 2005 levels by 2025, 50% by 2030, and 90% by 2050.

A bit of Colorado’s regulatory history..

2019 2020 2021 2022 2023 2024 2025 2026

Colorado passes HB19-1261 setting emission reduction targets

Colorado adopts new “intensity” requirements for upstream oil and gas facilities



An Act

HOUSE BILL 19-1261

BY REPRESENTATIVE(S) Becker and Jackson, Jaquez Lewis, Bird, Buentello, Caraveo, Esgar, Exum, Garnett, Gonzales-Gutierrez, Herod, Singer, Sirota, Snyder, Sullivan, Tipper, Titone, Valdez A., Weissman, Arndt, Benavidez, Buckner, Buentello, Caraveo, Exum, Gonzales-Gutierrez, Gray, Hansen, Lontine, McCluskie, Michaelson Jenet, Mullica, Esgar, Herod, McLachlan, Roberts, Singer, Sirota, Snyder, Sullivan, Tipper, Titone, Valdez A., Weissman, Bridges, Court, Danielson, Donovan, Froelich, Fields, Foote, Ginal, Gonzales, Lee, Peltonen, Story, Todd, Zenzinger

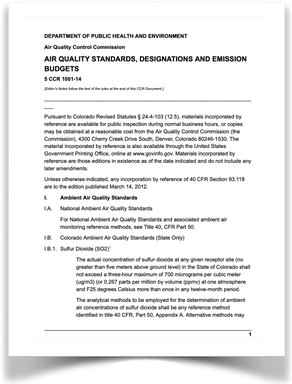
CONCERNING THE REDUCTION OF GREENHOUSE GAS POLLUTION, AND, IN CONNECTION THEREWITH, ESTABLISHING STATEWIDE GREENHOUSE GAS POLLUTION REDUCTION GOALS AND MAKING AN APPROPRIATION.

Be it enacted by the General Assembly of the State of Colorado:

SECTION 1. In Colorado Revised Statutes, **amend** 25-7-102 as follows:

25-7-102. Legislative declaration. (1) In order to foster the health, welfare, and economic vitality of the inhabitants of the state of Colorado and to facilitate the enjoyment and use of the scenic and natural

Capital letters or bold & italic numbers indicate new material added to existing law; dashes through words or numbers indicate deletions from existing law and such material is not part of the act.



DEPARTMENT OF PUBLIC HEALTH AND ENVIRONMENT

Air Quality Control Commission

AIR QUALITY STANDARDS, DESIGNATIONS AND EMISSION BUDGETS

5 CCR 1001-14

[Editor’s Notes follow the text of the rules at the end of this CCR Document.]

Pursuant to Colorado Revised Statutes § 24-4-103 (12.5), materials incorporated by reference are available for public inspection during normal business hours, or copies may be obtained at a reasonable cost from the Air Quality Control Commission (the Commission), 4300 Cherry Creek Drive South, Denver, Colorado 80246-1530. The material incorporated by reference is also available through the United States Government Printing Office, online at www.govinfo.gov. Materials incorporated by reference are those editions in existence as of the date indicated and do not include any later amendments.

Unless otherwise indicated, any incorporation by reference of 40 CFR Section 93.118 are to the edition published March 14, 2012.

I. **Ambient Air Quality Standards**

I.A. National Ambient Air Quality Standards

For National Ambient Air Quality Standards and associated ambient air monitoring reference methods, see Title 40, CFR Part 50.

I.B. Colorado Ambient Air Quality Standards (State Only)

I.B.1. Sulfur Dioxide (SO_2)[1]

The actual concentration of sulfur dioxide at any given receptor site (no greater than five meters above ground level) in the State of Colorado shall not exceed a three-hour maximum of 700 micrograms per cubic meter (ug/m3) (or 0.267 parts per million by volume (ppmv) at one atmosphere and F25 degrees Celsius more than once in any twelve-month period.

The analytical methods to be employed for the determination of ambient air concentrations of sulfur dioxide shall be any reference method identified in title 40 CFR, Part 50, Appendix A. Alternative methods may

1

$$\textbf{Intensity} = \frac{\textbf{Total methane emissions}}{\textbf{Total methane produced}}$$

Note: this is a “bottom-up” calculation

A bit of Colorado’s regulatory history..

2019 — Colorado passes HB19-1261 setting emission reduction targets

An Act

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BY REPRESENTATIVE(S) Becker and Jackson, Jaquez Lewis, Bird, Buentello, Caraveo, Esgar, Exum, Gonzales-Gutierrez, Gray, Hansen, Singer, Sirota, Snyder, Sullivan, Tipper, Titone, Valdez A., Weissman, Arndt, Benavidez, Buckner, Buentello, Caraveo, Exum, Gonzales-Gutierrez, Gray, Hansen, Lontine, McCluskie, Michaelson Jenet, Mullica, Esgar, Herod, McLachlan, Roberts, Sirota, Snyder, Sullivan, Tipper, Titone, Valdez A., Weissman, Bridges, Court, Danielson, Donovan, Froelich, Fields, Foote, Ginal, Gonzales, Lee, Peltonen, Story, Todd, Zenzinger.

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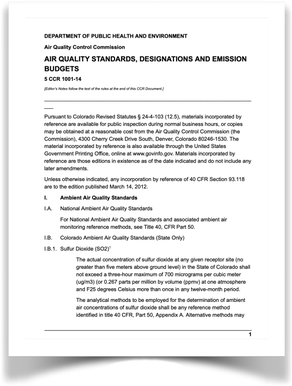
2020

2021 — Colorado adopts new “intensity” requirements for upstream oil and gas facilities



DEPARTMENT OF PUBLIC HEALTH AND ENVIRONMENT

Air Quality Control Commission

AIR QUALITY STANDARDS, DESIGNATIONS AND EMISSION BUDGETS

5 CCR 1001-14

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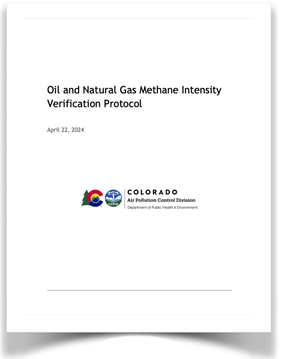

Oil and Natural Gas Methane Intensity Verification Protocol

April 22, 2024

COLORADO
Air Pollution Control Division
Department of Public Health & Environment

2025

2026

Starting in 2025, oil and gas companies must either:

1) use atmospheric measurements to estimate their emissions, or

2) multiply their bottom-up estimate by a state-wide “default factor”

A bit of Colorado’s regulatory history..

2019 — Colorado passes HB19-1261 setting emission reduction targets

An Act

HOUSE BILL 19-1261

BY REPRESENTATIVE(S) Becker and Jackson, Jaquez Lewis, Bird, Buentello, Caraveo, Esgar, Exum, Gonzales-Gutierrez, Gray, Hansen, Singer, Sirota, Snyder, Sullivan, Tipper, Titone, Valdez A., Weissman, Arndt, Benavidez, Buckner, Buentello, Caraveo, Exum, Gonzales-Gutierrez, Gray, Hansen, Lontine, McCluskie, Michaelson Jenet, Mullica, Esgar, Herod, McLachlan, Roberts, Snyder, Tipper, Titone, and Williams A., Moreno, Bridges, Court, Danielson, Donovan, Fenberg, Fields, Froe, Ginal, Gonzales, Lee, Pettersen, Story, Todd, Zenzinger.

CONCERNING THE REDUCTION OF GREENHOUSE GAS POLLUTION, AND, IN CONNECTION THEREWITH, ESTABLISHING STATEWIDE GREENHOUSE GAS POLLUTION REDUCTION GOALS AND MAKING AN APPROPRIATION.

Be it enacted by the General Assembly of the State of Colorado:

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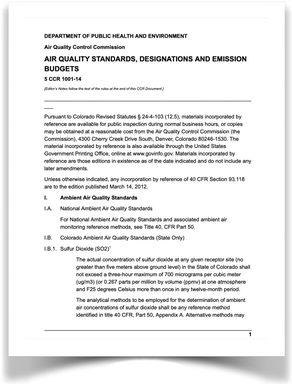

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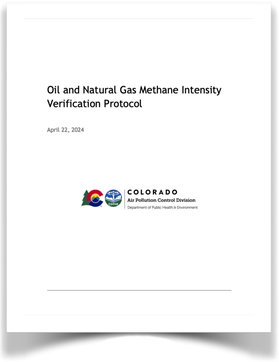

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2025 — Default factor = **1.164**

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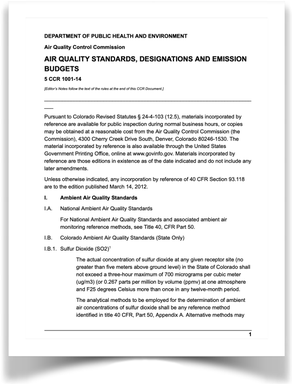

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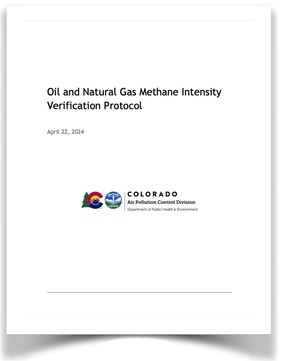

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April 22, 2024

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Department of Public Health & Environment

2025 — Default factor = **1.164**

2026 — Default factor = **???**

This project sets the 2026 factor

Emission factor arithmetic

As a reminder:

$$\text{Intensity} = \frac{\text{Total methane emissions}}{\text{Total methane produced}}$$

Using state-wide data from 2024:

$$\text{Bottom-up intensity} \times \text{Total methane production} = \text{Bottom-up methane emissions estimate}$$

$$\text{“Default factor”} = \frac{\text{Measurement-based emissions estimate}}{\text{Bottom-up emissions estimate}}$$

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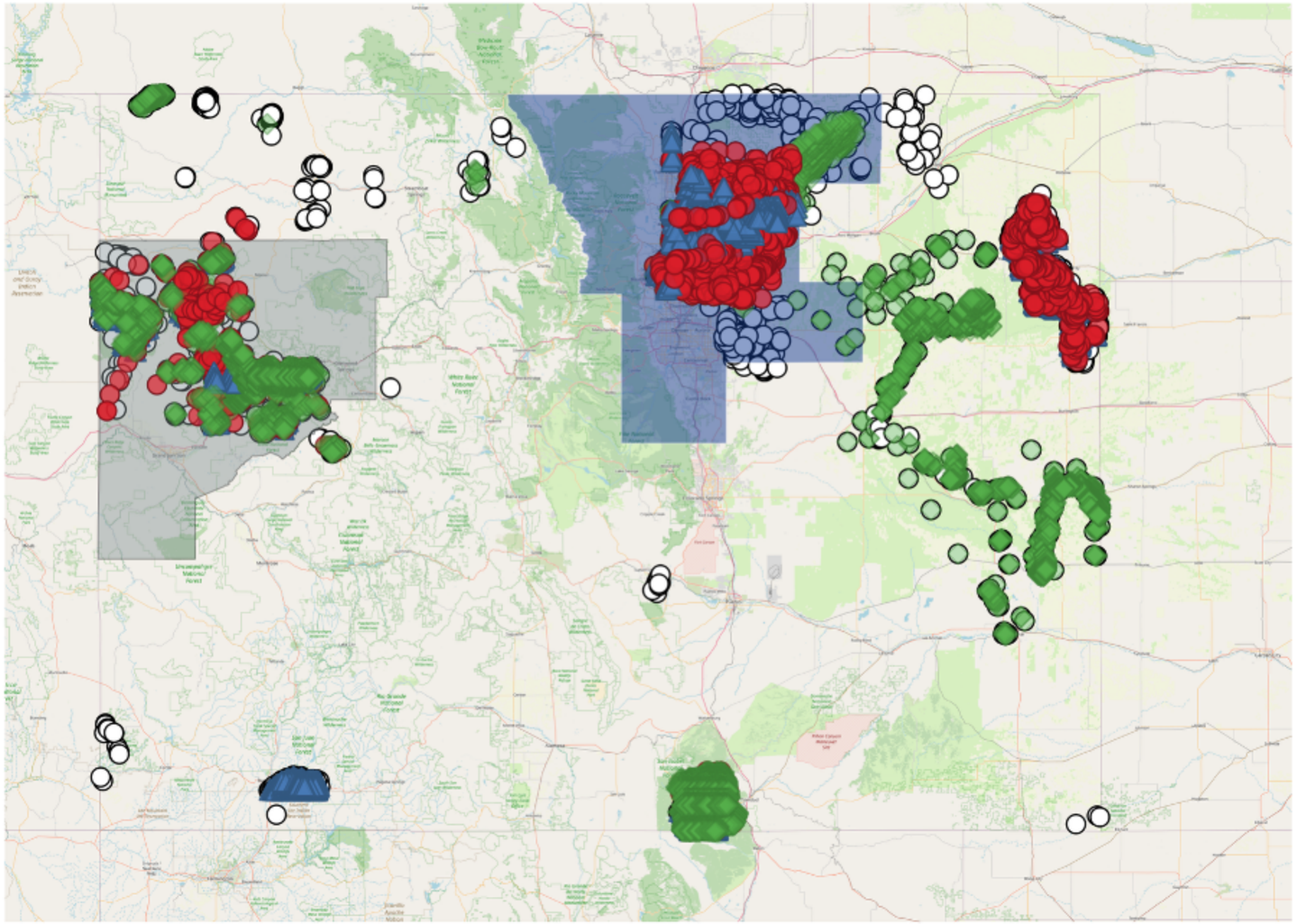
Just need to estimate this

How do you estimate a state's methane flux?

Measure as many sites as possible!

10,771 sites
(94% of total)



Challenge: each aerial technology has a different minimum detection threshold

~5 kg/hr
Conrad et al. (2023)

~10 kg/hr
El Abbadi et al. (2024)

~40 kg/hr
Conrad et al. (2023) and
El Abbadi et al. (2024)

Challenge: each aerial technology has a different minimum detection threshold

BRIDGER PHOTONICS

~5 kg/hr
Conrad et al. (2023)

GHGSAT

~10 kg/hr
El Abbadi et al. (2024)

INSIGHT M
METHANE MANAGED

~40 kg/hr
Conrad et al. (2023) and
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We need to:

1) Assimilate data from all technologies, accounting for the fact that they each observe a different emission “population”

2) Account for emissions below the detection limit of all three technologies

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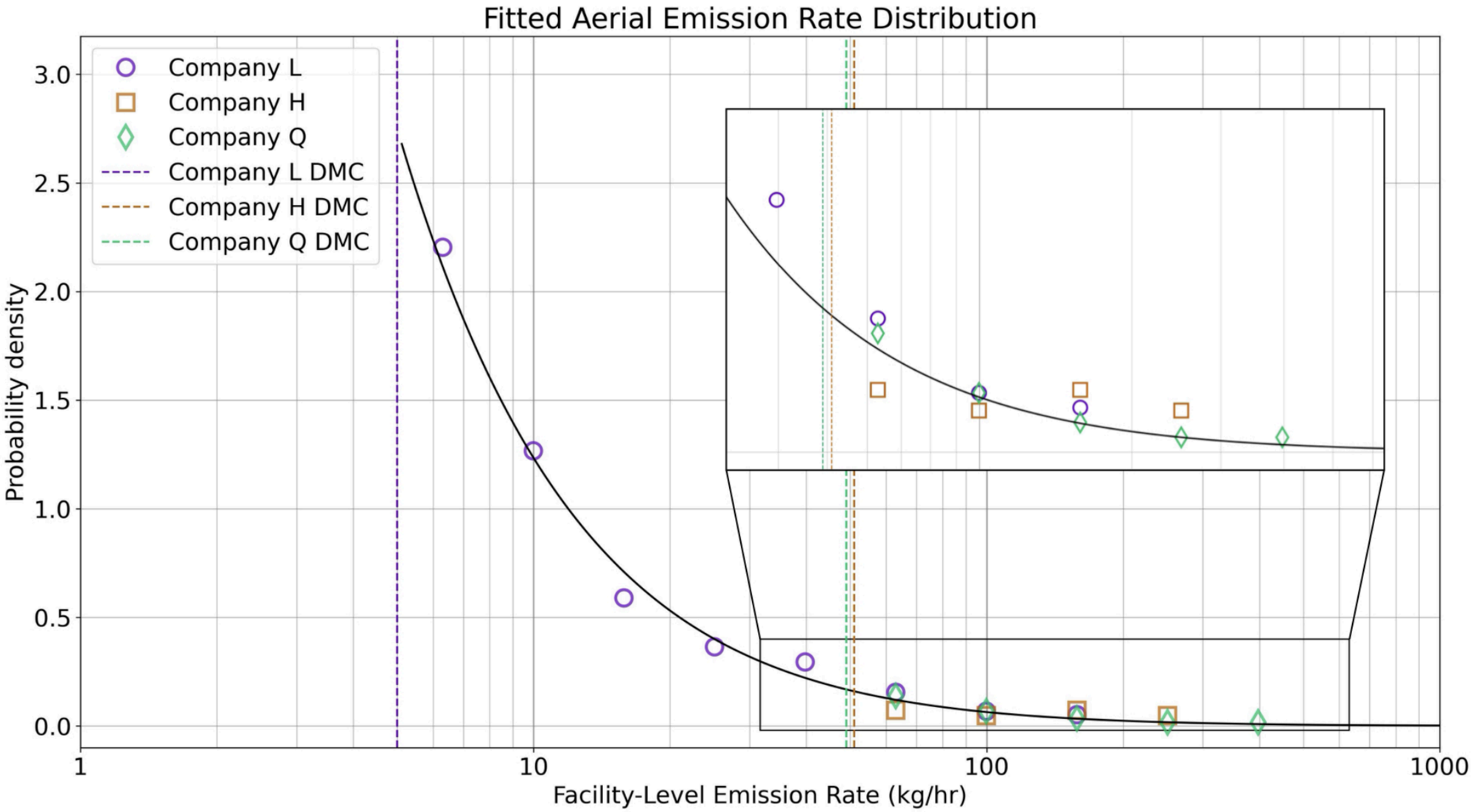
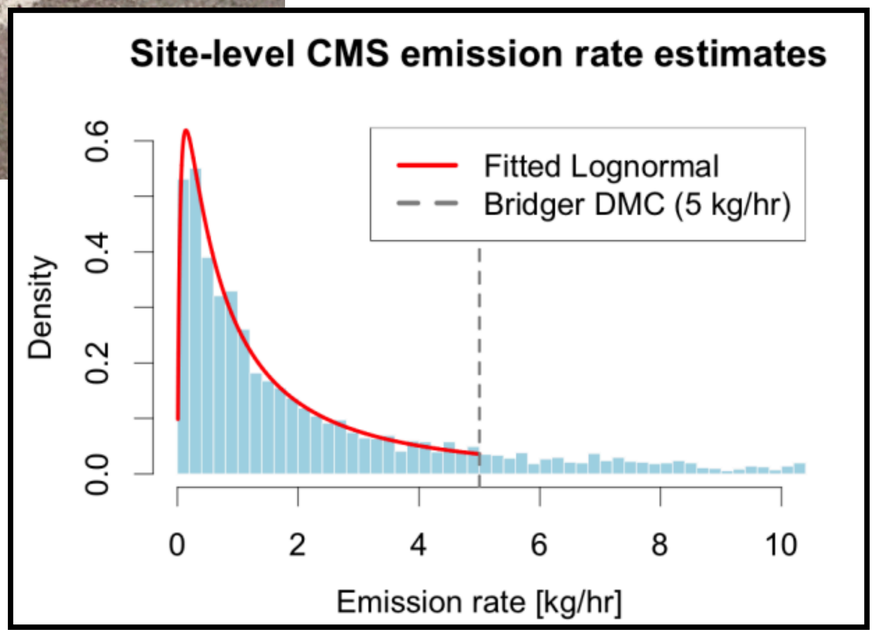


Distribution fitting led by Cal Okenberg!

2) Account for emissions below the detection limit of all three technologies

Use real-time emissions data from continuous monitoring systems (CMS)



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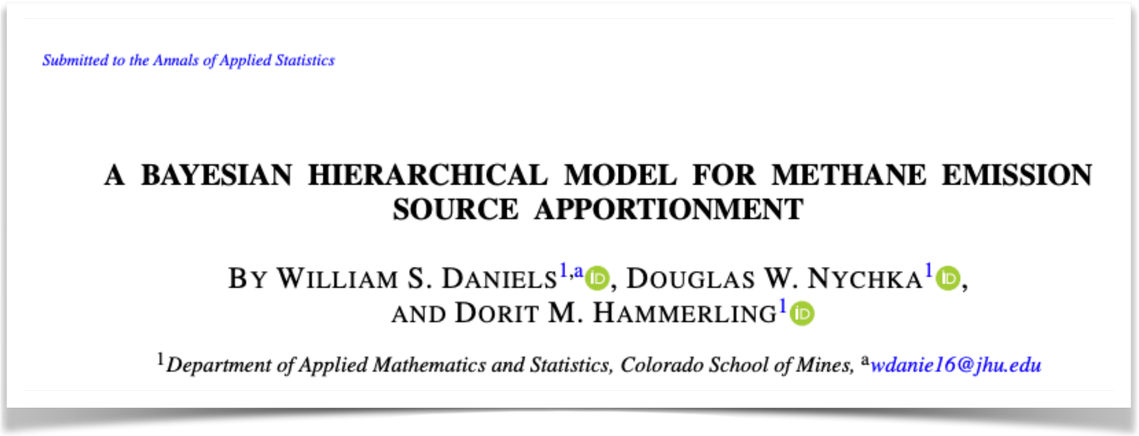
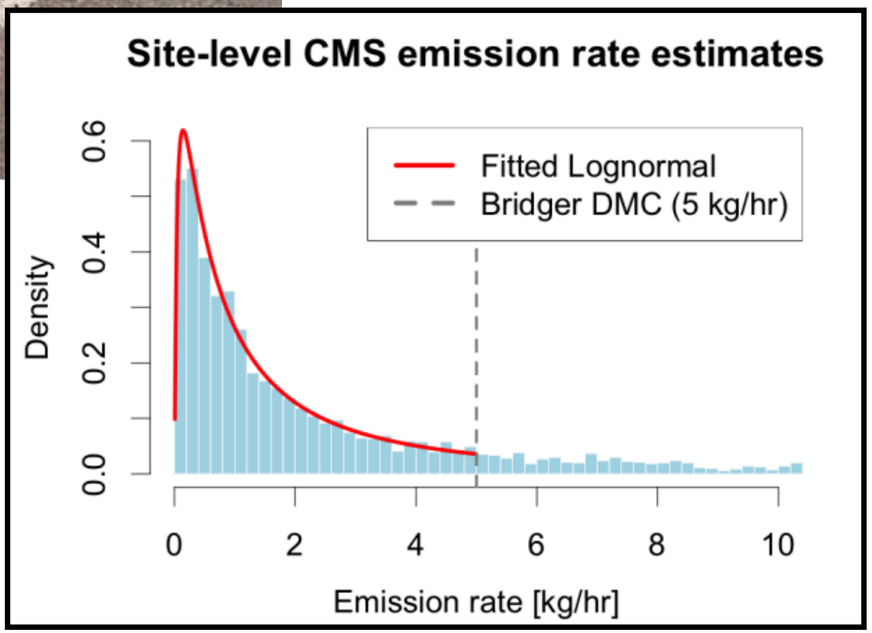


Submitted to the Annals of Applied Statistics

A BAYESIAN HIERARCHICAL MODEL FOR METHANE EMISSION SOURCE APPORTIONMENT

BY WILLIAM S. DANIELS[1,a], DOUGLAS W. NYCHKA[1], AND DORIT M. HAMMERLING[1]

[1]*Department of Applied Mathematics and Statistics, Colorado School of Mines,* [a]*wdanie16@jhu.edu*



2) Account for emissions below the detection limit of all three technologies

Not a lot of CMS data.. turn to the literature for backup options

Article | Open access | Published: 05 August 2021

Closing the methane gap in US oil and natural gas production emissions inventories

Jeffrey S. Rutherford, Evan D. Sherwin, Arvind P. Ravikumar, Garvin A. Heath, Jacob Englander, Daniel Cooley, David Lyon, Mark Omara, Quinn Langfitt & Adam R. Brandt

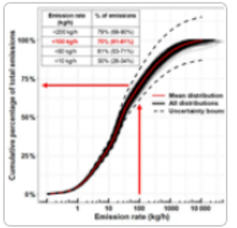
Nature Communications **12**, Article number: 4715 (2021) | Cite this article

"Bottom-up alternative #1"

"Bottom-up alternative #2"

Research article | 04 Feb 2025

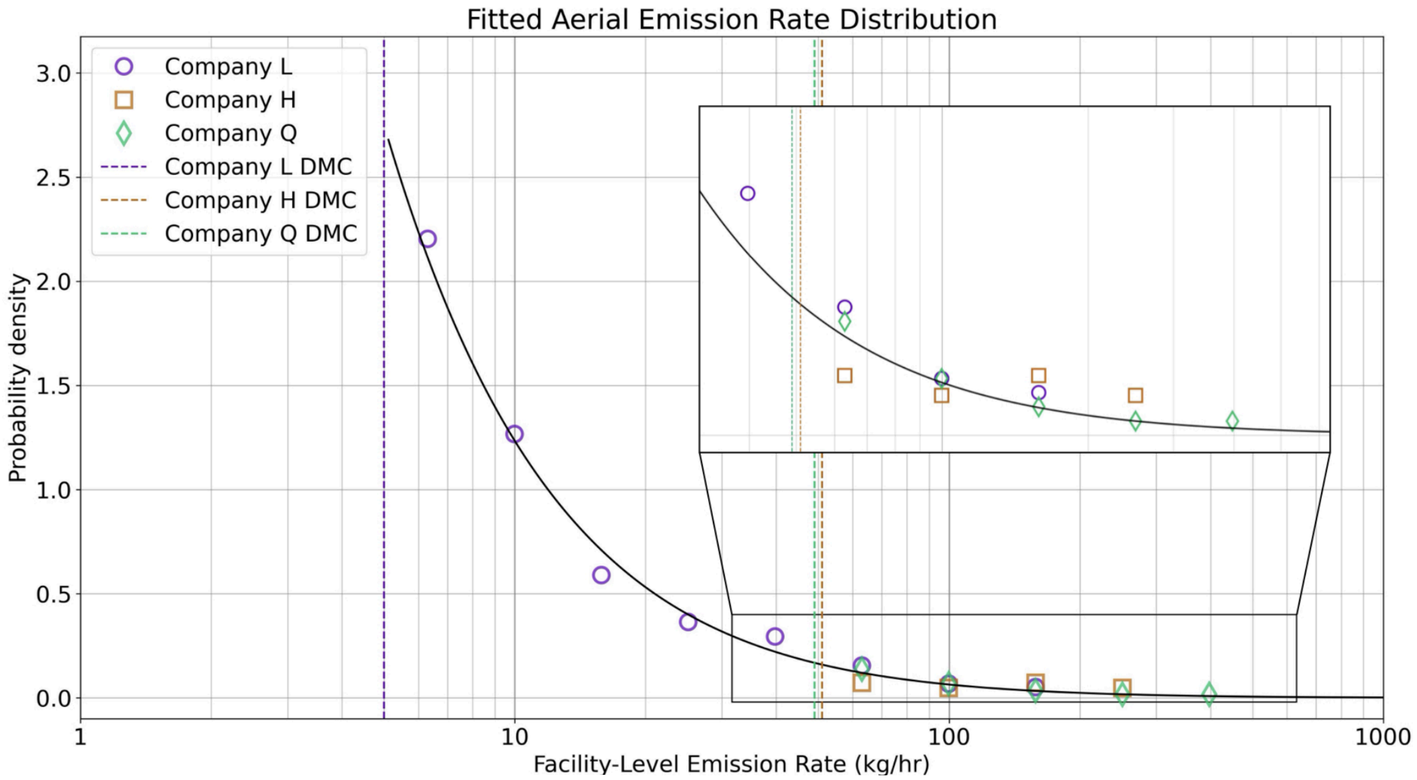
Small emission sources in aggregate disproportionately account for a large majority of total methane emissions from the US oil and gas sector



James P. Williams, Mark Omara, Anthony Himmelberger, Daniel Zavala-Araiza, Katlyn MacKay, Joshua Benmergui, Maryann Sargent, Steven C. Wofsy, Steven P. Hamburg, and Ritesh Gautam

Creating the state-level emission estimate

Emissions > 5 kg/hr



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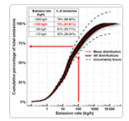

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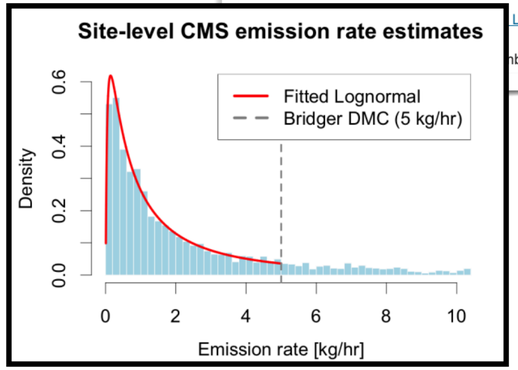
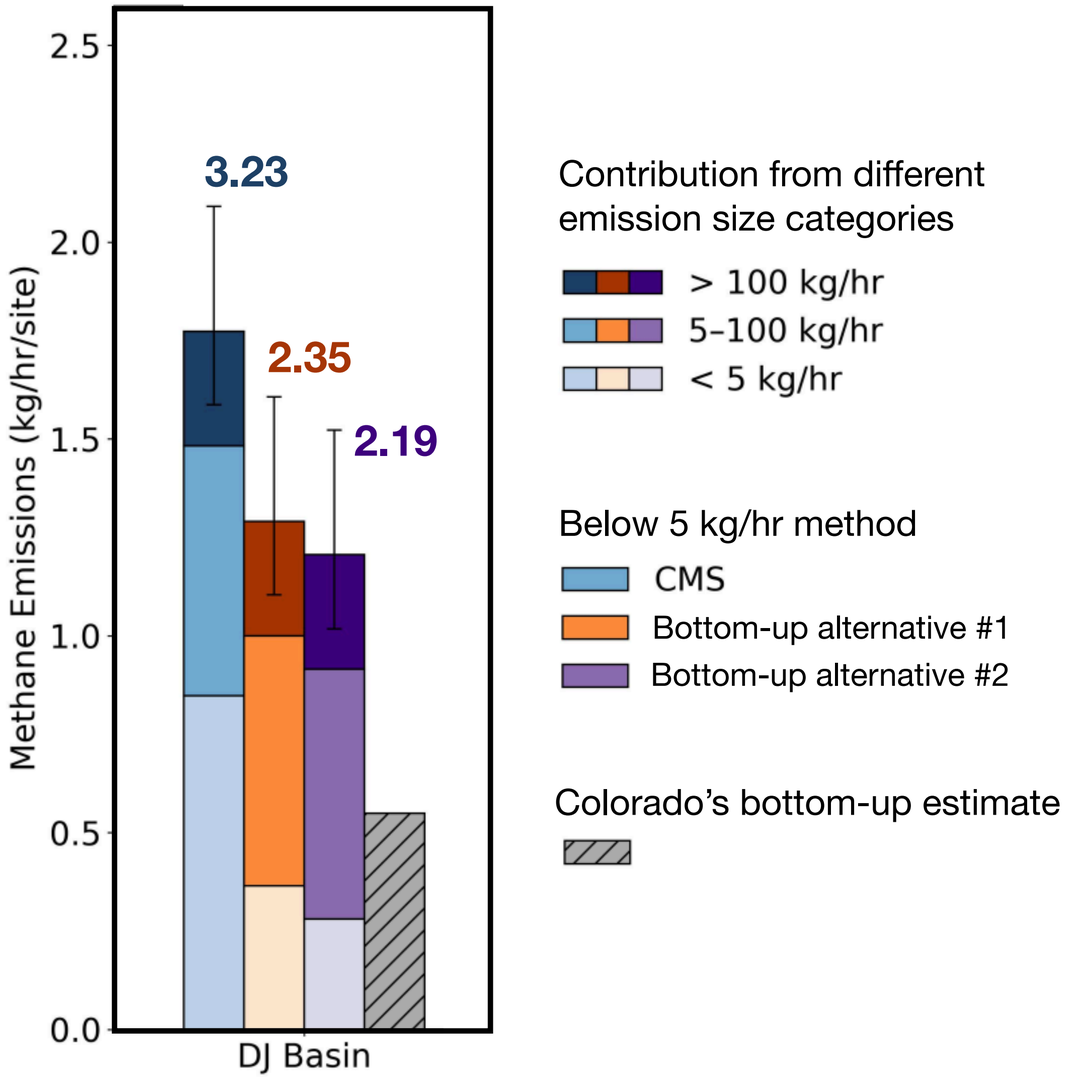


Sample from these distributions within a Markov Chain Monte Carlo (MCMC) framework to scale up to the state-level

End result: 2026 “Default Factor”



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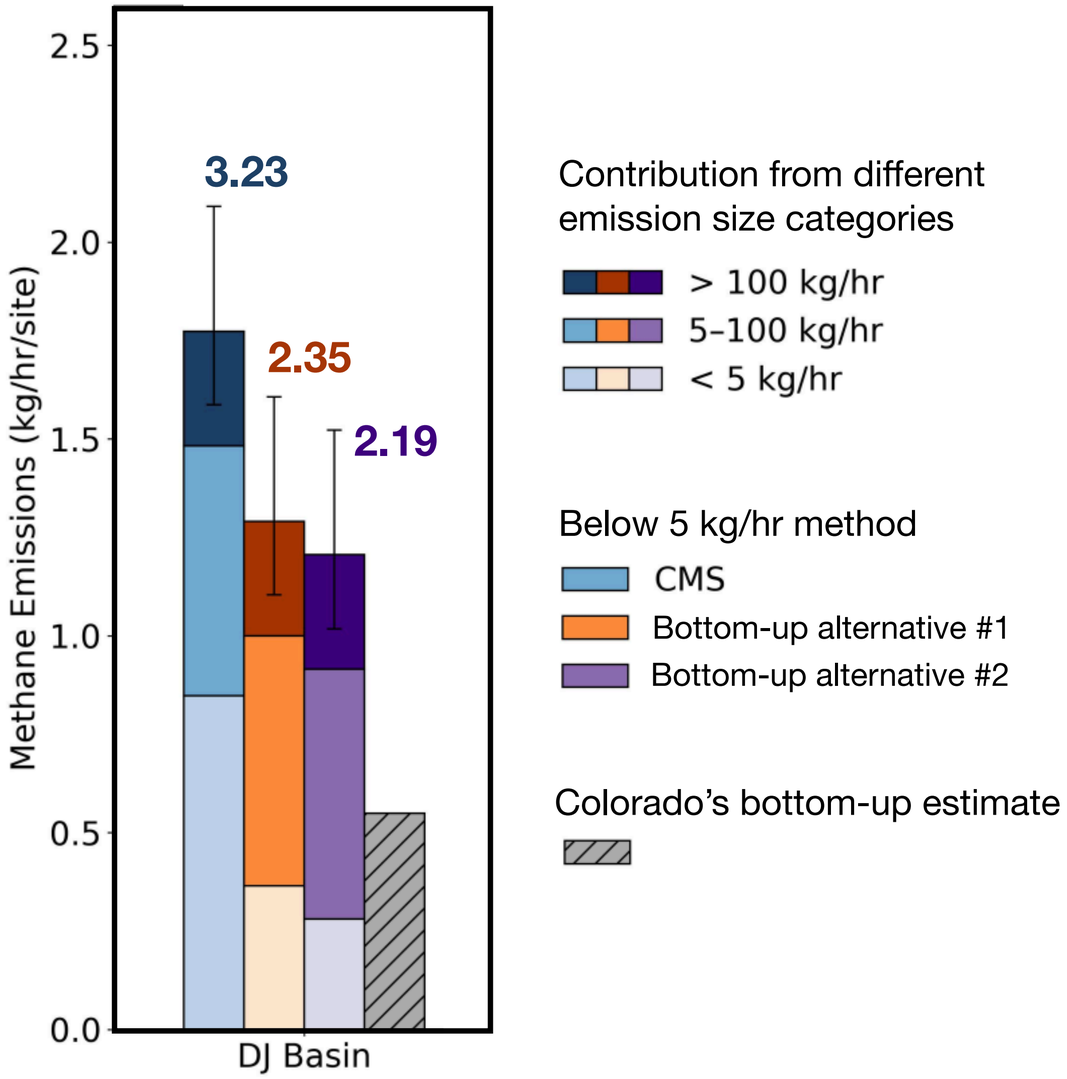

2025

COLORADO Department of Public Health & Environment = 1.164

2026

COLORADO SCHOOL OF MINES = (average) 2.59

COLORADO STATE UNIVERSITY = 1.58

COLORADO Department of Public Health & Environment = 2.2

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2025 — Default factor = **1.164**

2026 — Default factor = **2.2**

2027 — Default factor = **???**

Project extension already funded by CDPHE to set factor for next year!

Extension includes many more sites with CMS.

Goal = an entirely measurement-based inventory.


An Act

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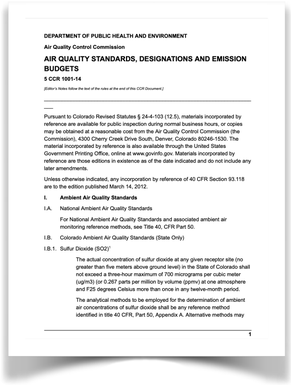
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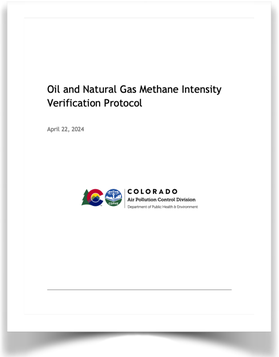
Oil and Natural Gas Methane Intensity Verification Protocol

April 22, 2024

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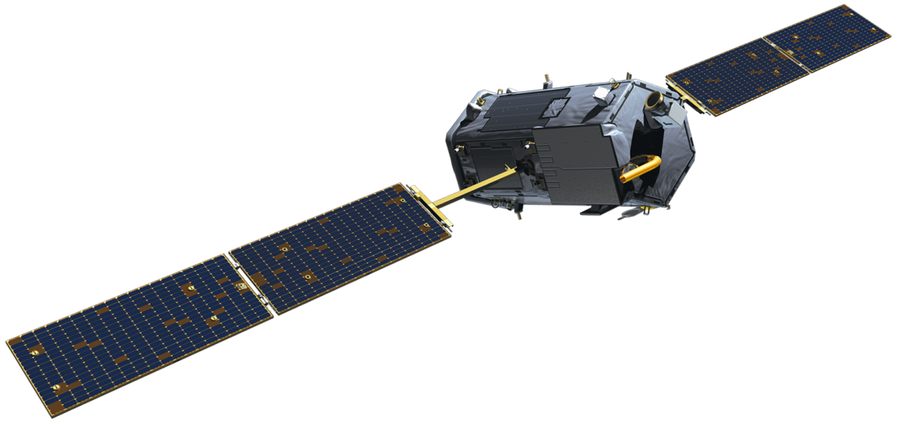
Department of Public Health & Environment

Project 3

Improve process-based understanding of the carbon cycle

JOHNS HOPKINS UNIVERSITY

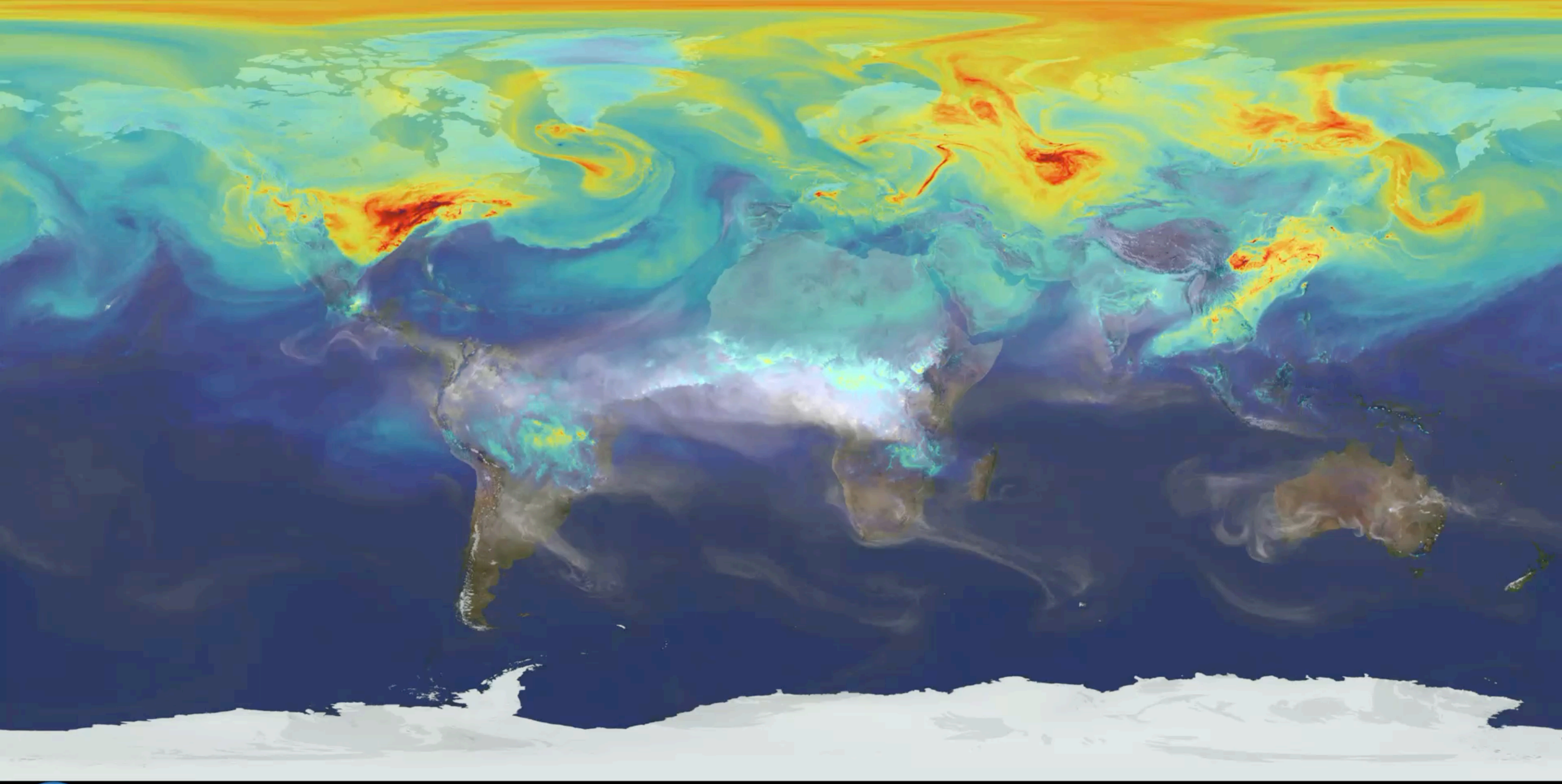
Jet Propulsion Laboratory
California Institute of Technology



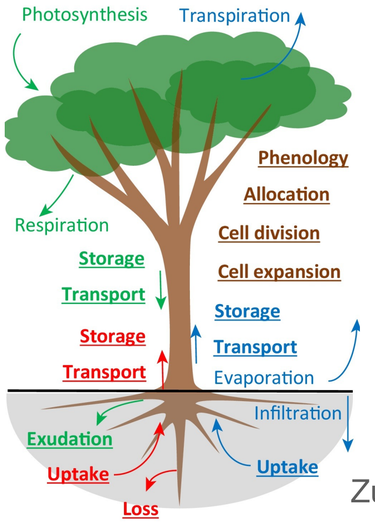
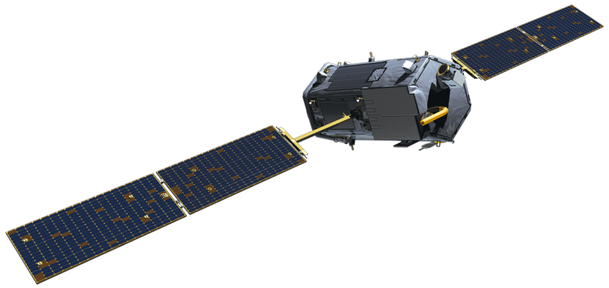
Improve process-based understanding of the carbon cycle

↓

Better process-based understanding = better future projections = more accurate emission reduction goals

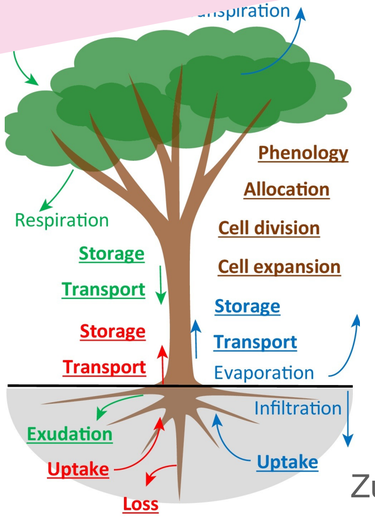
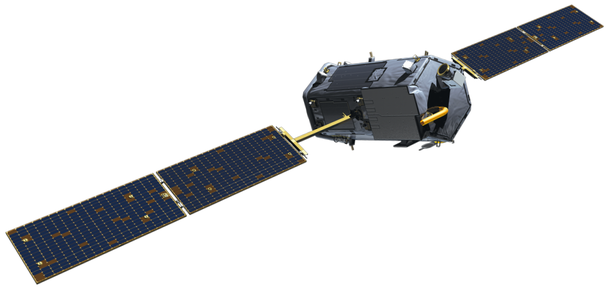

2006 / 01 / 01
Global Modeling and Assimilation Office
Carbon Monoxide Column Abundance [1.0e18 molec cm-2]
0.0 0.6 1.2 1.8 2.4 3.0 3.6 4.2 4.8 5.4 6.0
Carbon Dioxide Column Concentration [ppmv]
377 379 381 383 385 387 389 391 393 395

Similar bottom-up / top-down divide in carbon cycle science

	Bottom-up estimate	**Top-down estimate**
Methane emissions on oil and gas sites	**Bottom-up inventory estimate** = 1 wellhead x wellhead factor + 1 GPU x GPU factor + 1 tank x tank factor	 
The global carbon cycle		These are called: "Dynamic Global Vegetation Models" (DGVMs) The TRENDY models are one ensemble of DGVMs 

Zuidema et al. (2018)

Similar bottom-up / top-down divide in carbon cycle science

	Bottom-up estimate	**Top-down estimate**
Methane emissions on oil and gas sites	**Bottom-up inventory estimate** = 1 wellhead x wellhead fac… 1 GPU …	
The global carbon cycle	 These are called: "Dynamic Global Vegetation Models" (DGVMs) The TRENDY models are one ensemble of DGVMs Zuidema et al. (2018)	

Do the bottom-up TRENDY models agree with the top-down satellite inversions?

Similar bottom-up / top-down divide in carbon cycle science

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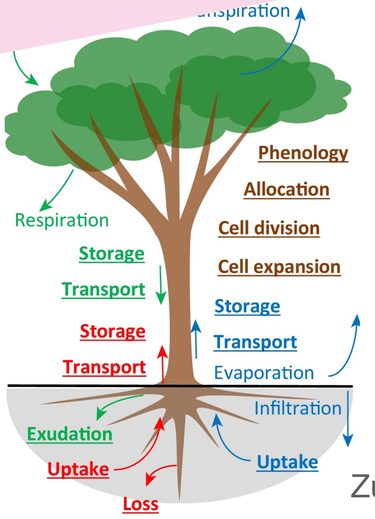
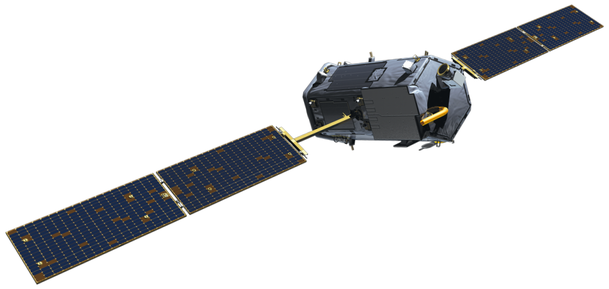
The global carbon cycle	 These are called: "Dynamic Global Vegetation Models" (DGVMs) The TRENDY models are one ensemble of DGVMs Zuidema et al. (2018)	

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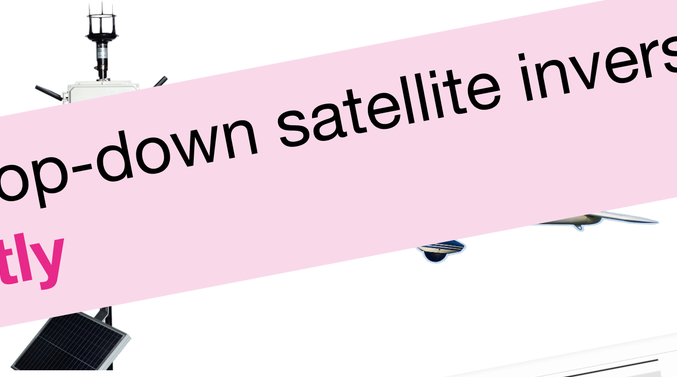
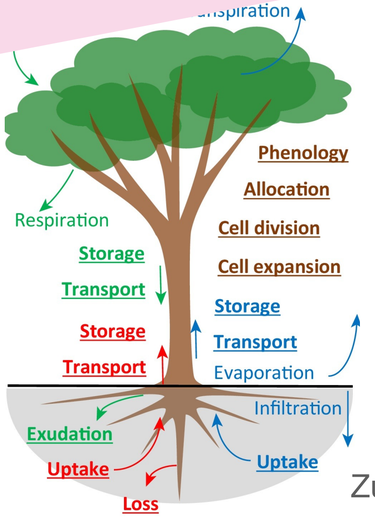
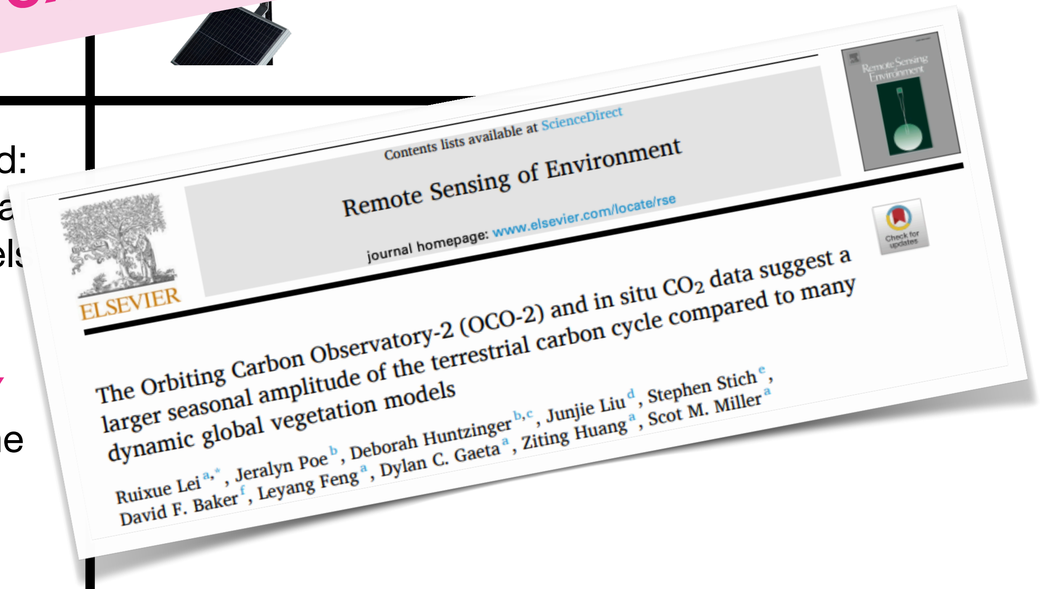
Methane emissions on oil and gas sites	**Bottom-up inventory estimate** = 1 wellhead x wellhead fac… 1 GPU …	
The global carbon cycle	 These are called: "Dynamic Globa… Vegetation Models (DGVMs) The TRENDY models are one ensemble of DGVMs	

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Zuidema et al. (2018)

Where, when, and why do TRENDY models disagree with satellite inversions?

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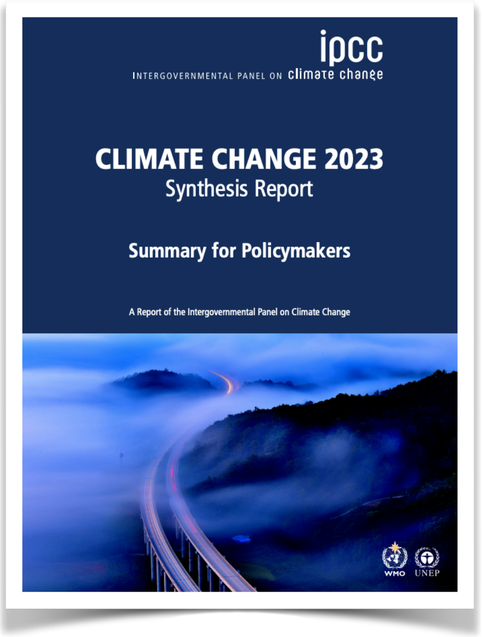
Why are we doing this again?

Projections of future climate scenarios rely on bottom-up, process-based models of the global carbon cycle



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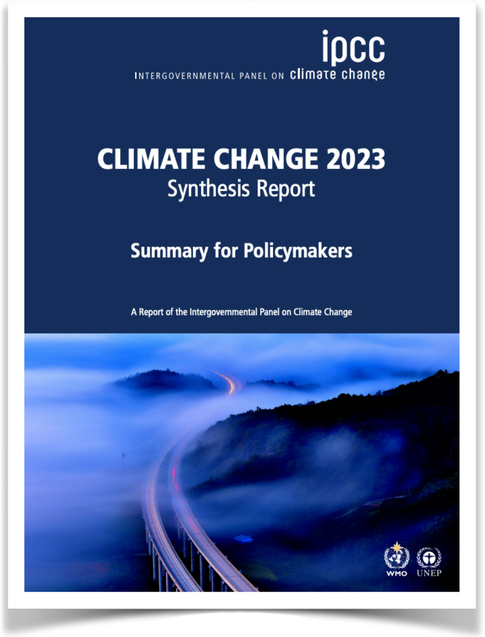
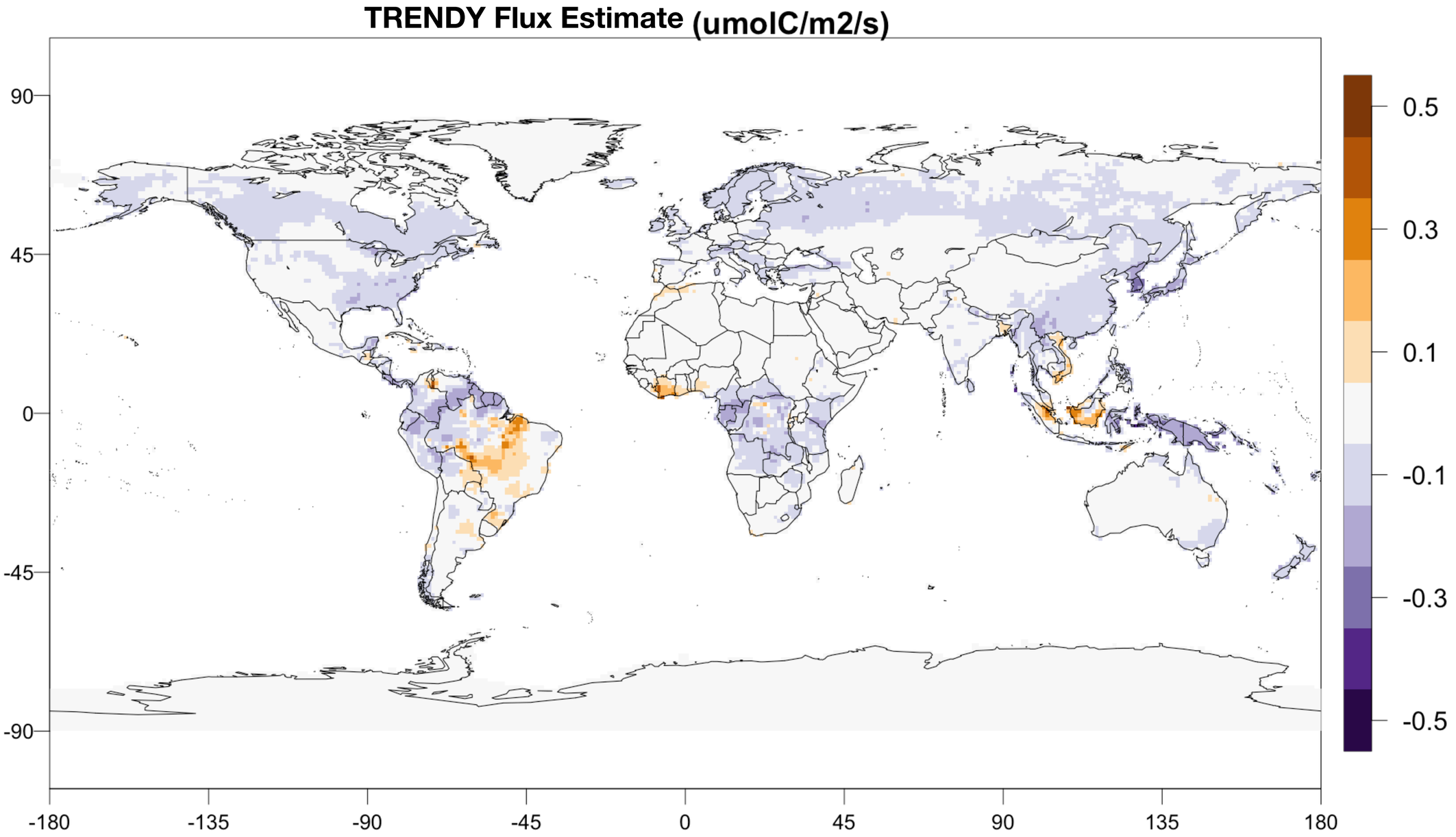


- Use satellite data to “check” predictions of the current climate from the TRENDY models.
- Improved predictions of the current climate = better projections of the future climate.
- Better projections of future climate = more accurate emission reduction targets.

Where, when, and why do TRENDY models disagree with satellite inversions?



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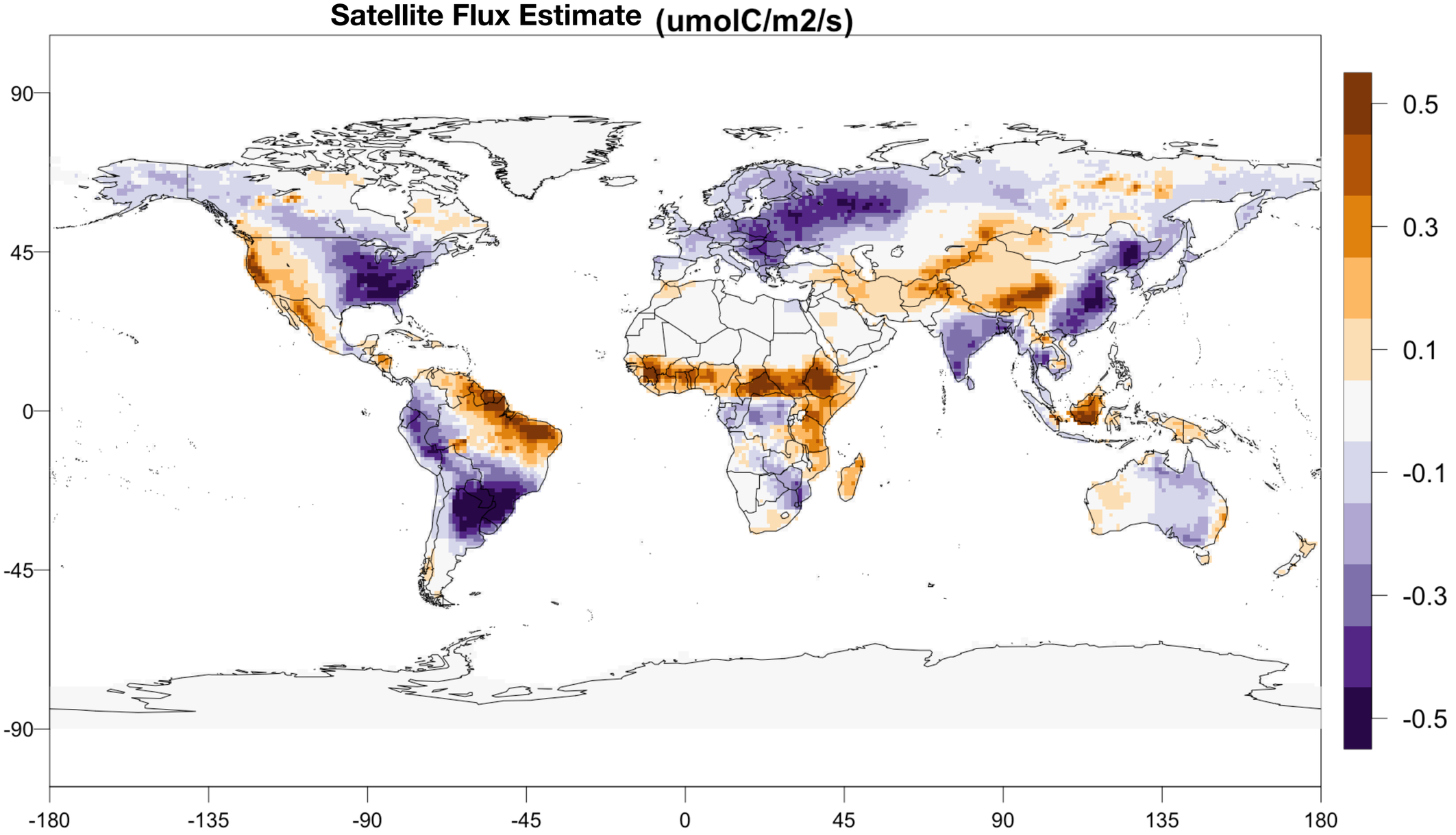

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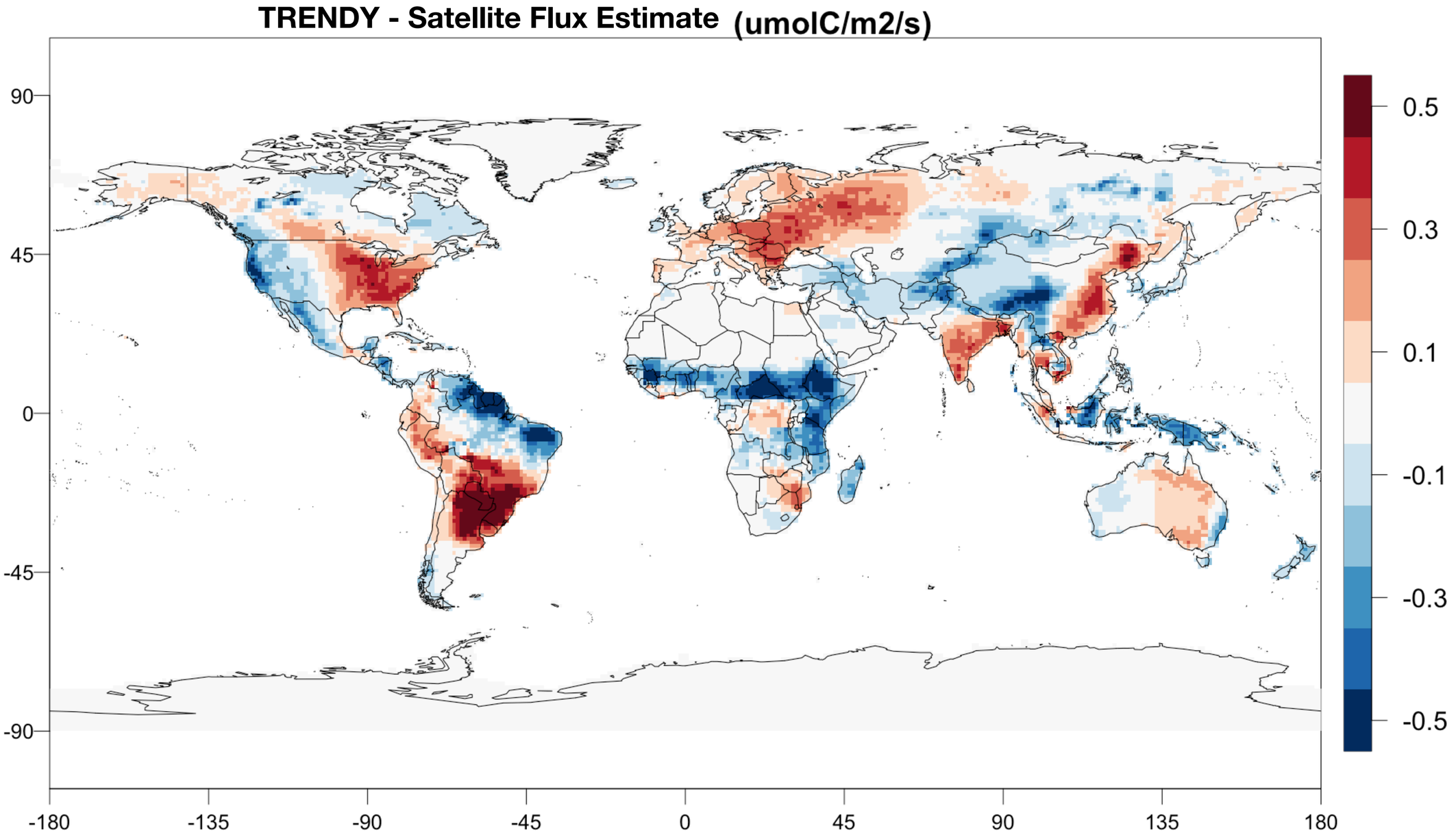
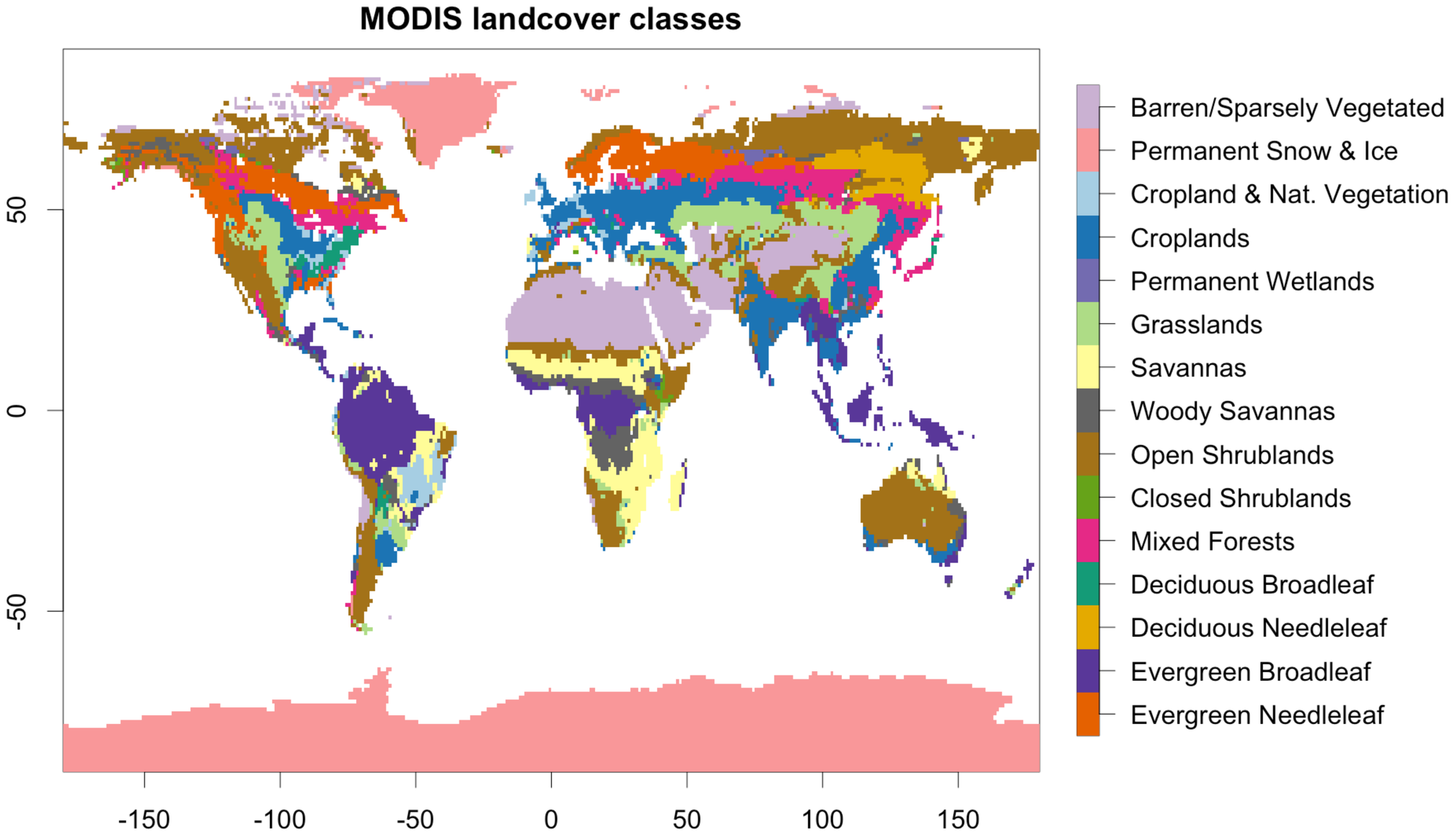


Does landcover class explain some of the differences?



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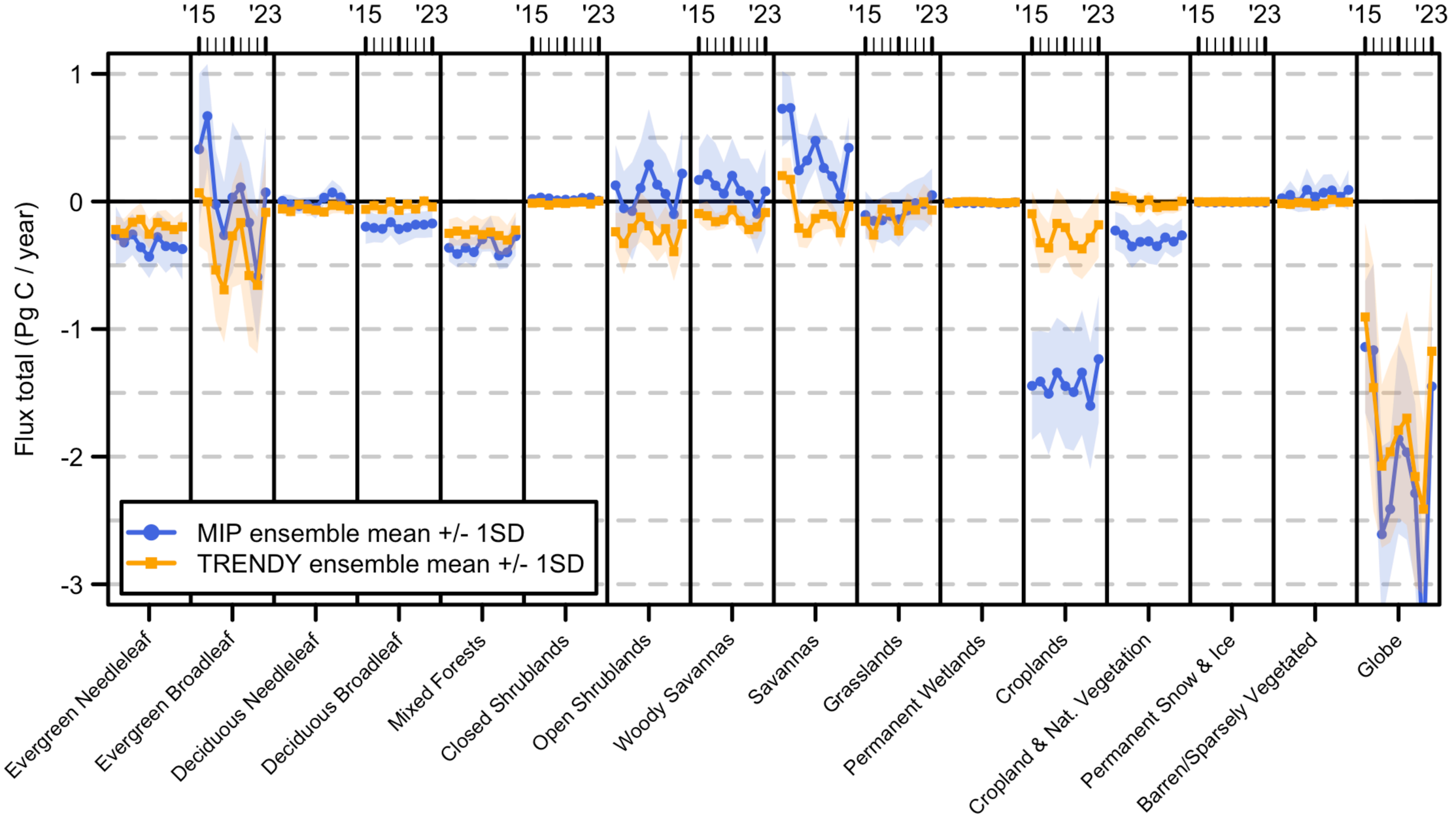

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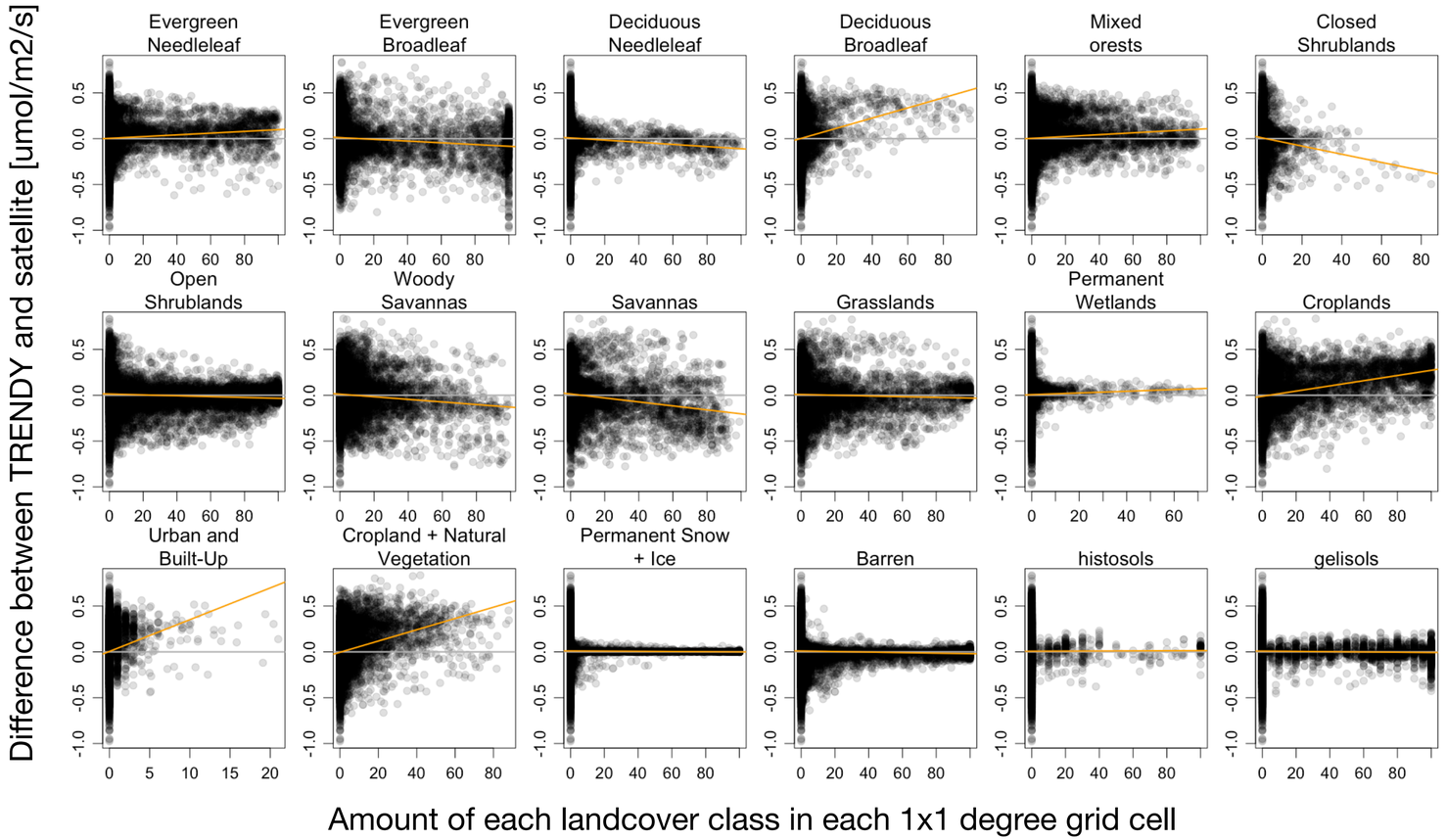

$$y = X\beta$$

Difference between TRENDY and satellite

MODIS landcover class

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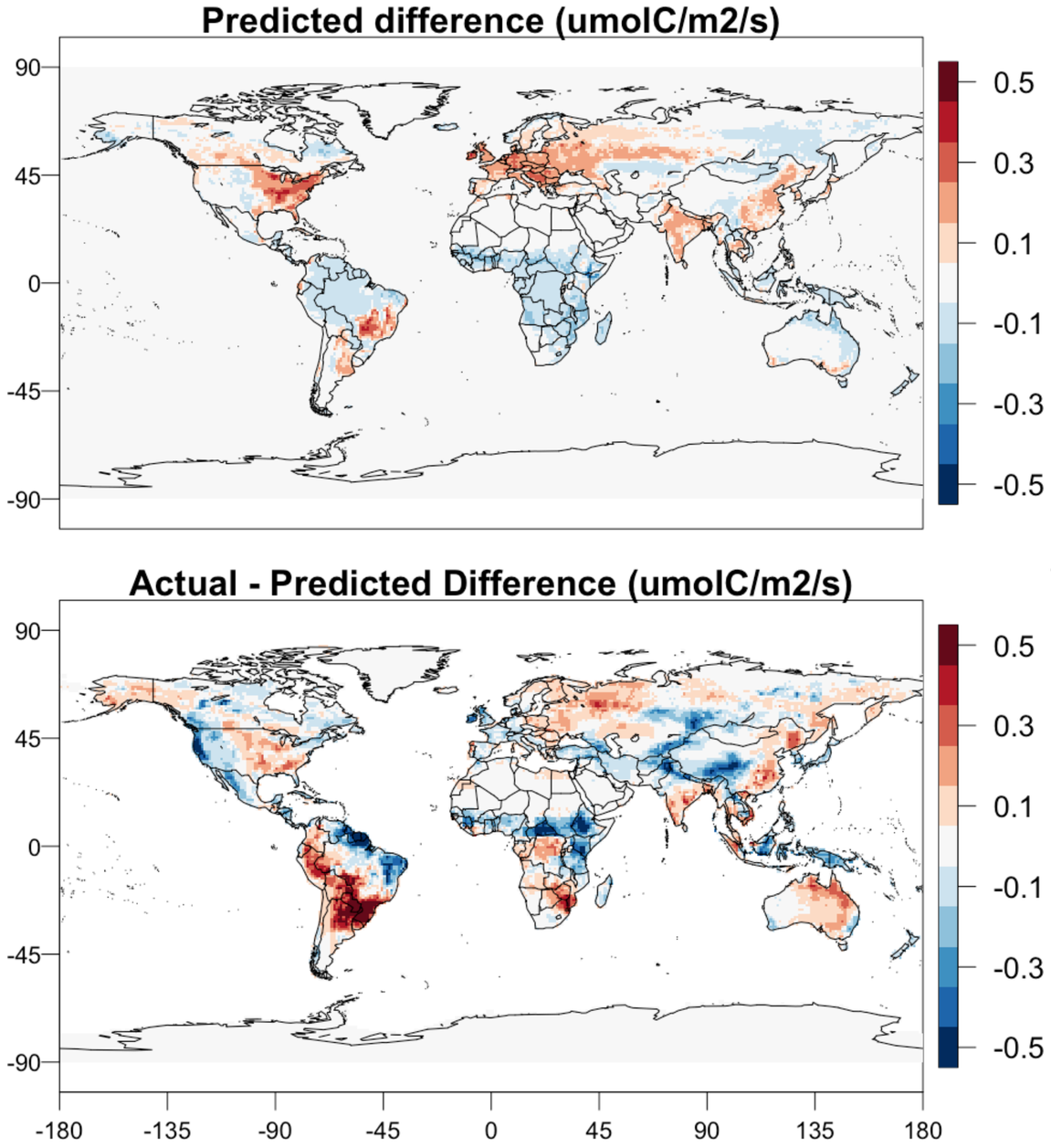

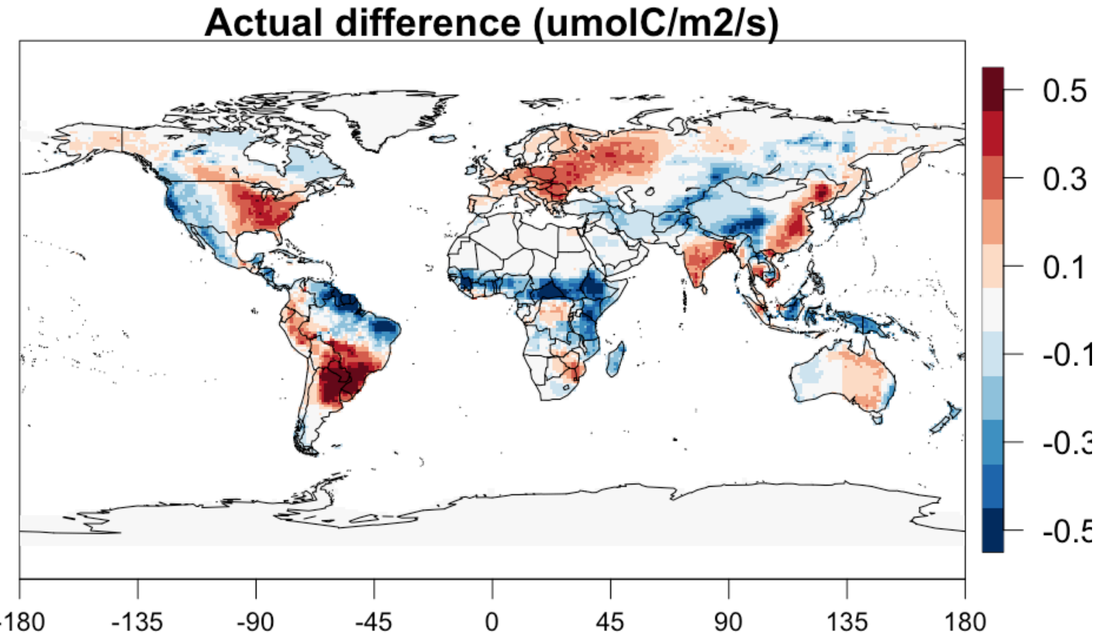

Landcover explains some of the difference, but definitely not all of it!

Next step:

Don’t just model the difference using landcover classes, but how each TRENDY model “views” the world within each class

We have many variables that can help with this:

Near-Surface Air Temperature
Precipitation
Total Soil Moisture Content
Total Runoff
Total Evapo-Transpiration
Carbon in Vegetation
Carbon in Above-ground Litter Pool
Carbon in Soil (including below-ground litter)
Carbon in Products of Land Use Change
Fractional Land Cover of PFT
Fractional Ocean Cover
Burnt Area Fraction
Leaf Area Index
Carbon in Leaves
Carbon in Wood
Carbon in Roots
Carbon in Coarse Woody Debris
Carbon in individual soil pools
Total Carbon Flux from Vegetation to Litter

Carbon Flux from Leaves to Litter
Carbon Flux from Wood to Litter
Carbon Flux from Roots to Litter
Total Carbon Flux from Litter to Soil
Total Carbon Flux from Vegetation Directly to Soil
Carbon Flux from individual soil pools
Temperature of Soil
Evaporation from Canopy
Water Evaporation from Soil
Transpiration
soil moisture
Tree heights
CO2 Flux to Atmosphere from Grazing
CO2 Flux to Atmosphere from Crop Harvesting
Irrigation
Nitrogen in Vegetation
Nitrogen in Above-ground Litter Pool
Nitrogen in Soil (including below-ground litter)

Difference between TRENDY and satellite

$$y = X\beta$$

Thank you!
Questions?

wdanie16@jhu.edu

Find and quantify equipment leaks

↓

Boots-on-the-ground emission mitigation

Set state-wide emissions regulations

↓

Economic incentives for emission reduction

Improve process-based understanding of the carbon cycle

↓

Better process-based understanding = better future projections = more accurate emission reduction goals

COLORADO SCHOOL OF MINES

JOHNS HOPKINS UNIVERSITY

EEMDL Energy Emissions Modeling and Data Lab

U.S. DEPARTMENT OF ENERGY

NASA