# Characterizing methane emissions on oil and gas sites

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# Agenda

**Introduction:**
Methane emissions, oil and gas sites, measurement technologies

**Chapter 1:**
Single-source emission detection, localization, and quantification

→ **Chapter 2:**
Reconciling aerial measurements and bottom-up inventories

→ **Chapter 3:**
Intercomparison of CMS solutions

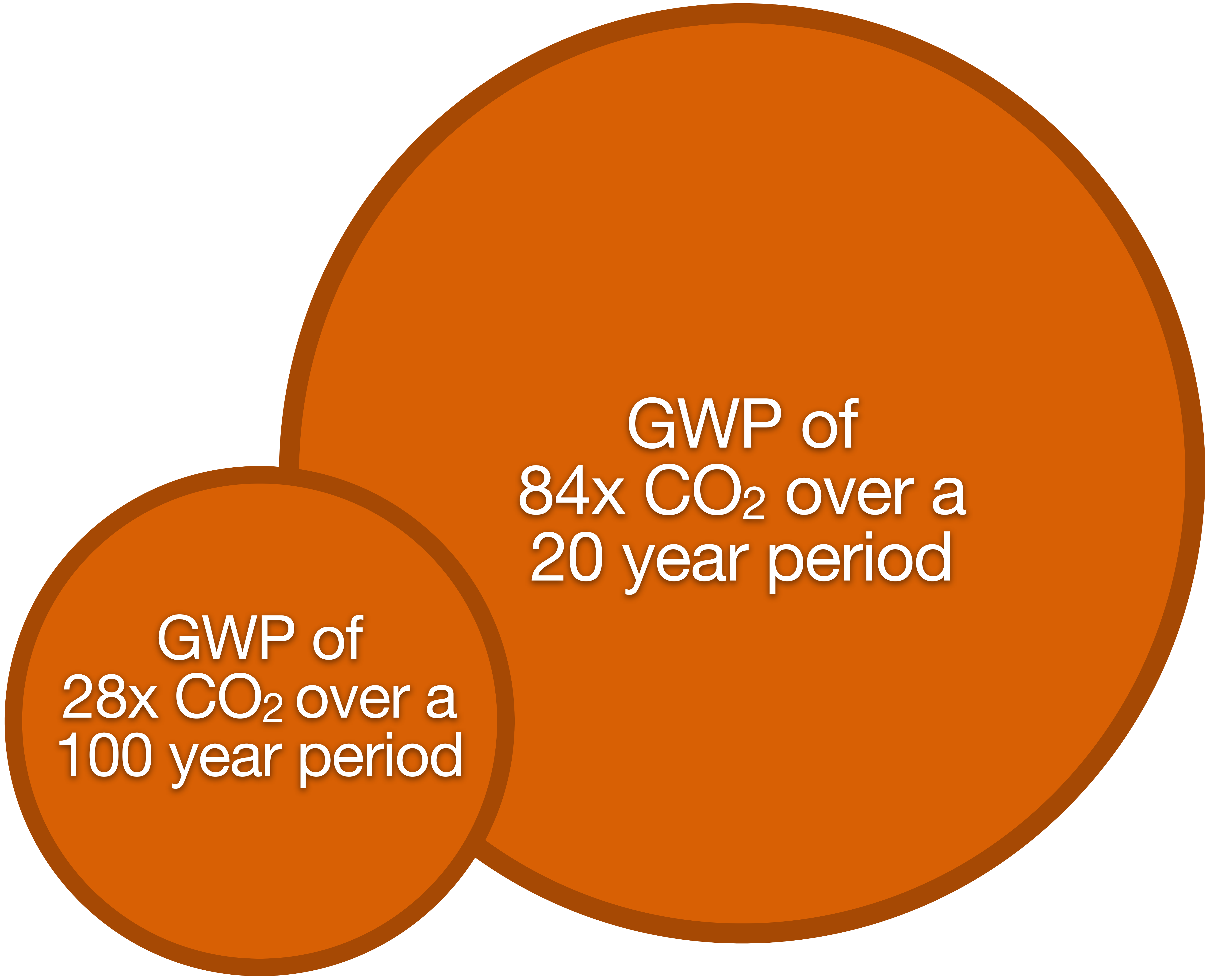
**Chapter 4:**
Multi-source emission detection, localization, and quantification

**Chapter 5:**
Robust duration estimates

# Why do we care about methane?

GWP:
global warming
potential

Methane is a potent greenhouse gas



# Why do we care about methane?

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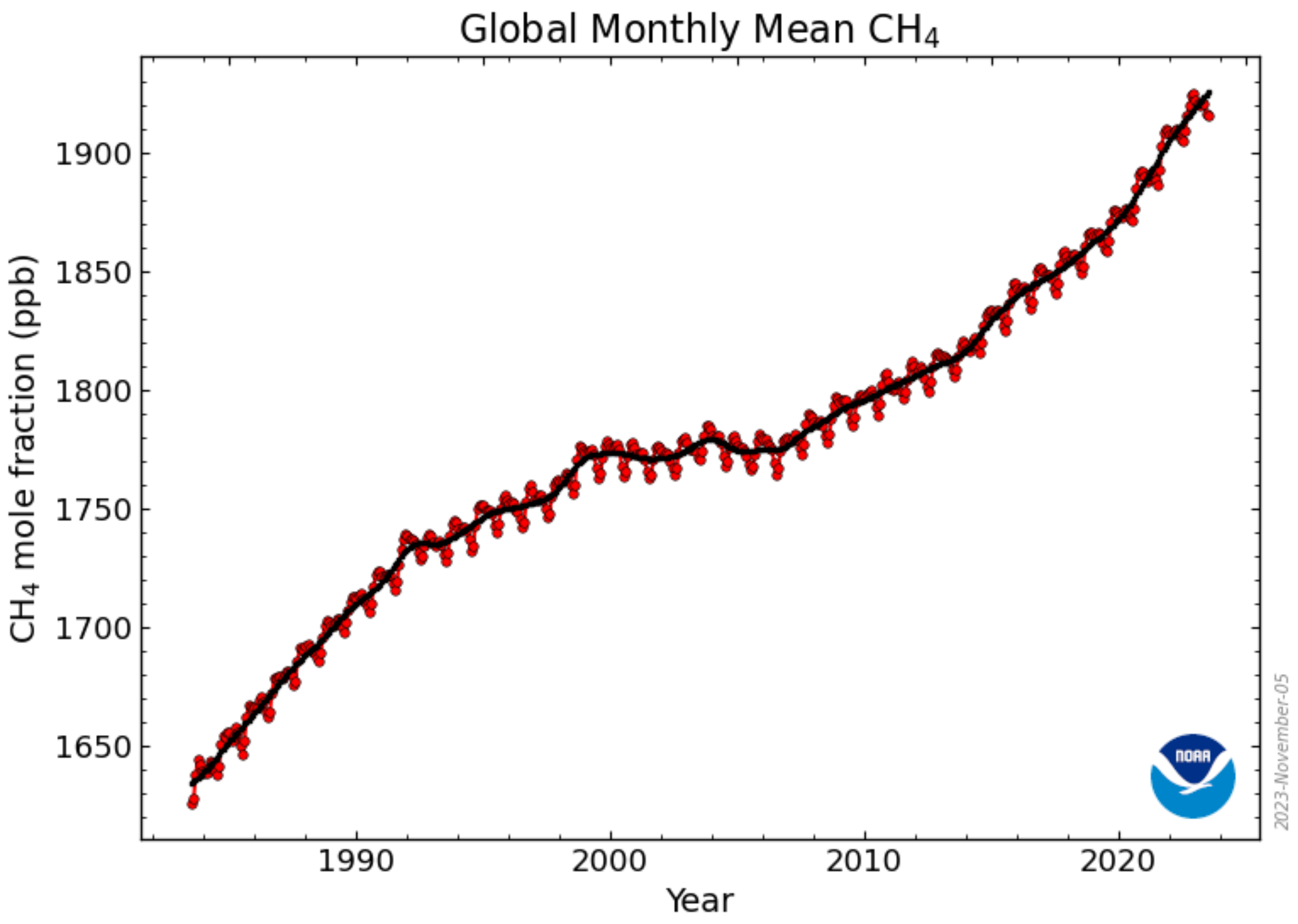
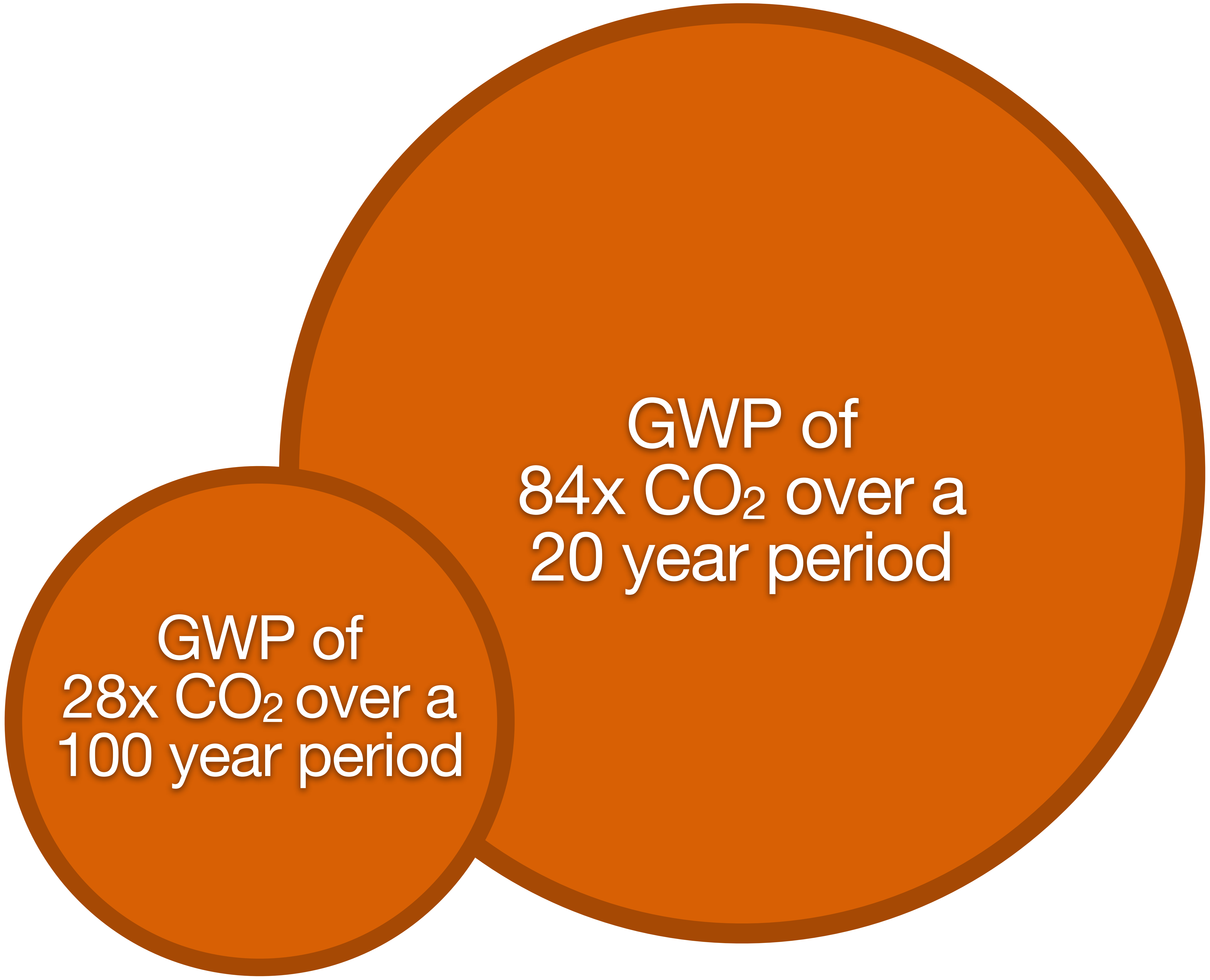
potential

Methane is a potent greenhouse gas

Global concentrations are increasing



# Why do we care about methane?

GWP:
global warming
potential

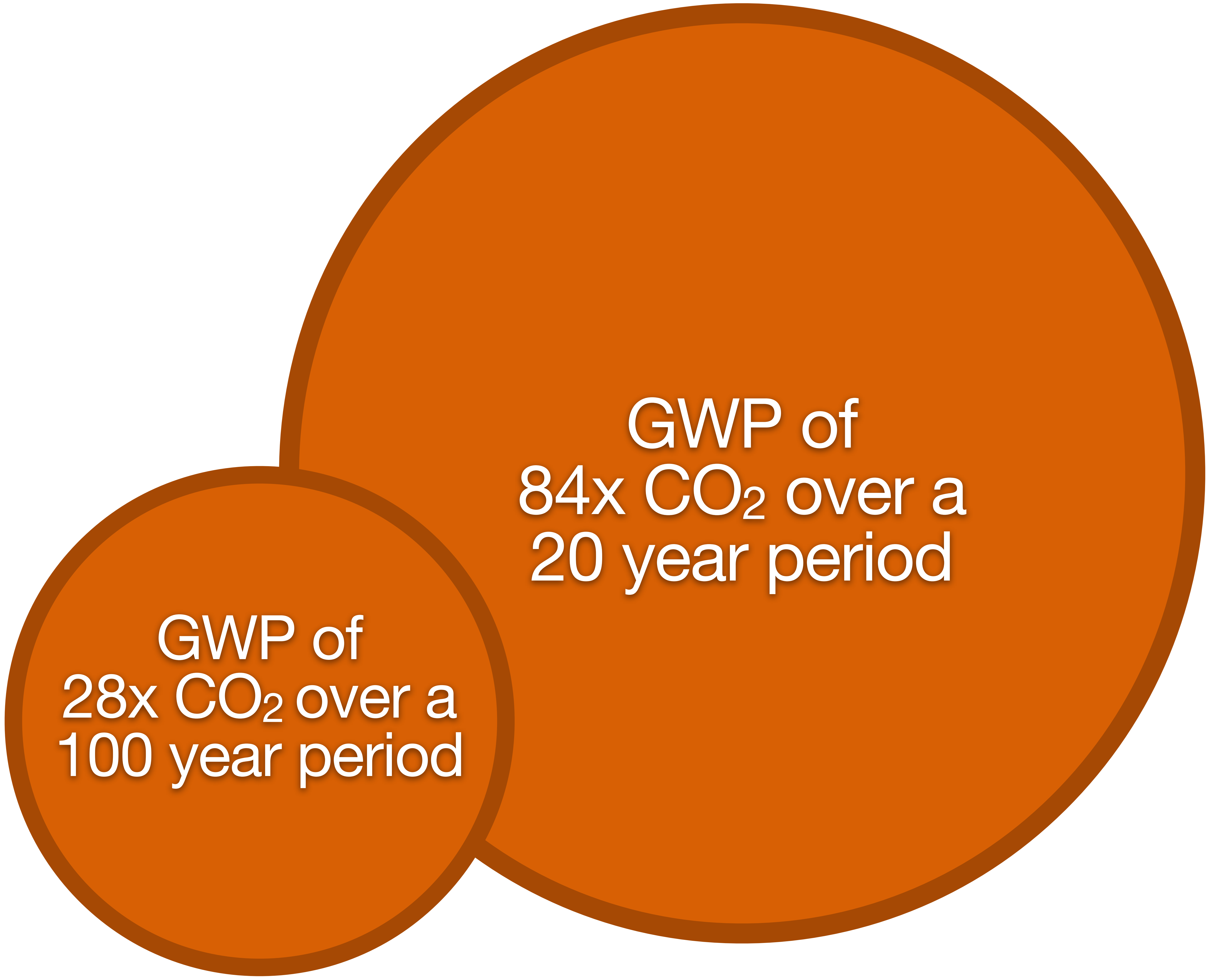
Methane is a potent greenhouse gas

Global concentrations are increasing

Relatively short lifetime

CH4 lifetime = **9** years
CO2 lifetime = **300-1000** years

Effect of CH4 emission reductions will be felt within our lifetimes!



# Why do we care about methane?

Methane is a potent greenhouse gas

Global concentrations are increasing

Relatively short lifetime

Recent regulatory push

## United States

**H. R. 5376 (Inflation Reduction Act)**

SEC. 136. (a) The Administrator shall impose and collect a fee from the owner or operator of **each applicable facility** that is required to report methane emissions …

SEC. 136. (g)(2) … calculation of fees under subsection (c) of this section, are based on **empirical data** and accurately reflect the total methane emissions from the applicable facilities.

# Why do we care about methane?

Methane is a potent greenhouse gas

Global concentrations are increasing

Relatively short lifetime

Recent regulatory push

**Amendments adopted by the European Parliament on 9 May 2023 on the proposal for a regulation of the European Parliament**

… importers must provide a report with the following information for **each site** from which the import to the Union has taken place …

… information specifying the exporter's, or where relevant, the producer's **direct measurements of site-level methane emissions**, conducted by independent service provider …

European Union

# Why do we care about methane?

Methane is a potent greenhouse gas

Global concentrations are increasing

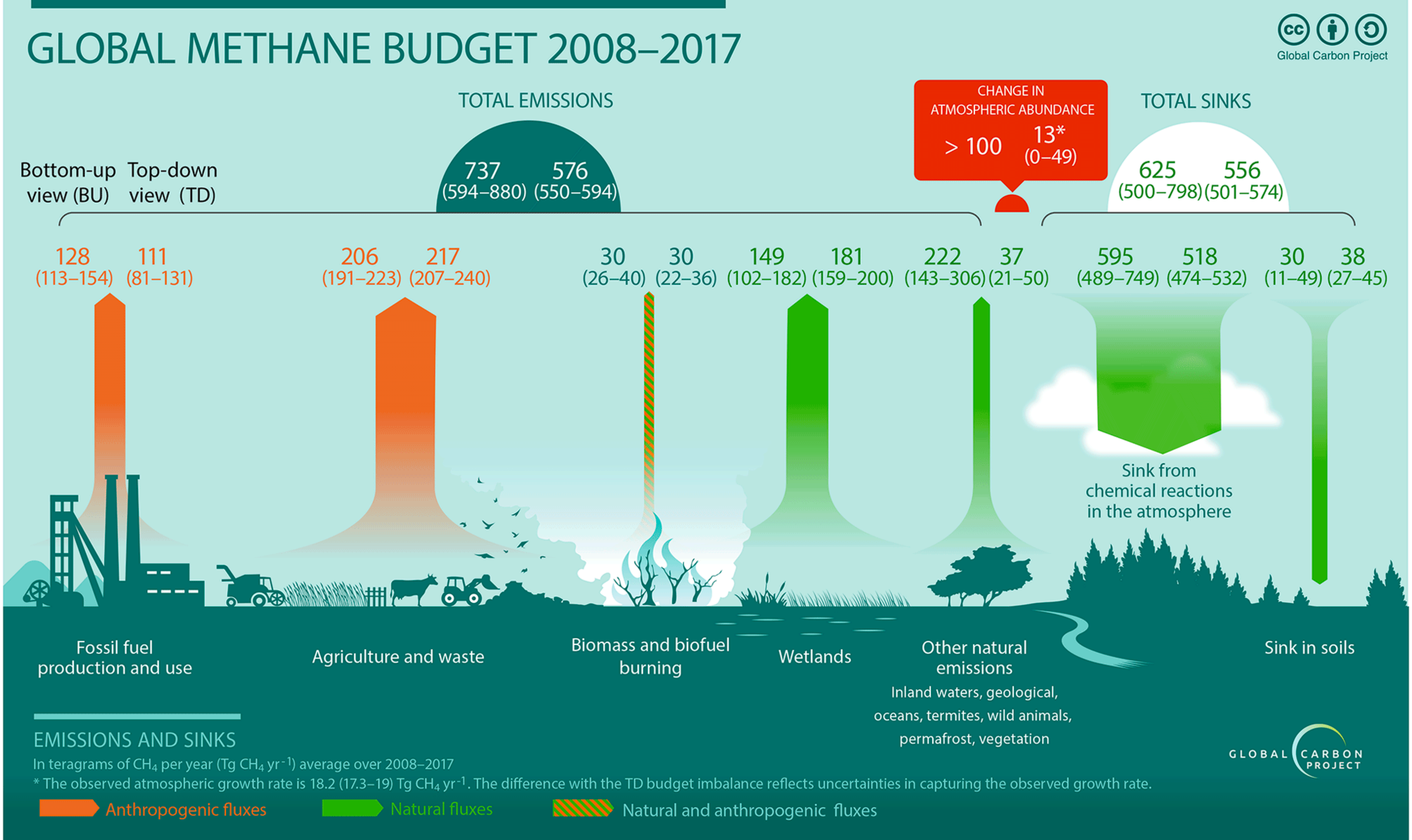
Relatively short lifetime

Recent regulatory push

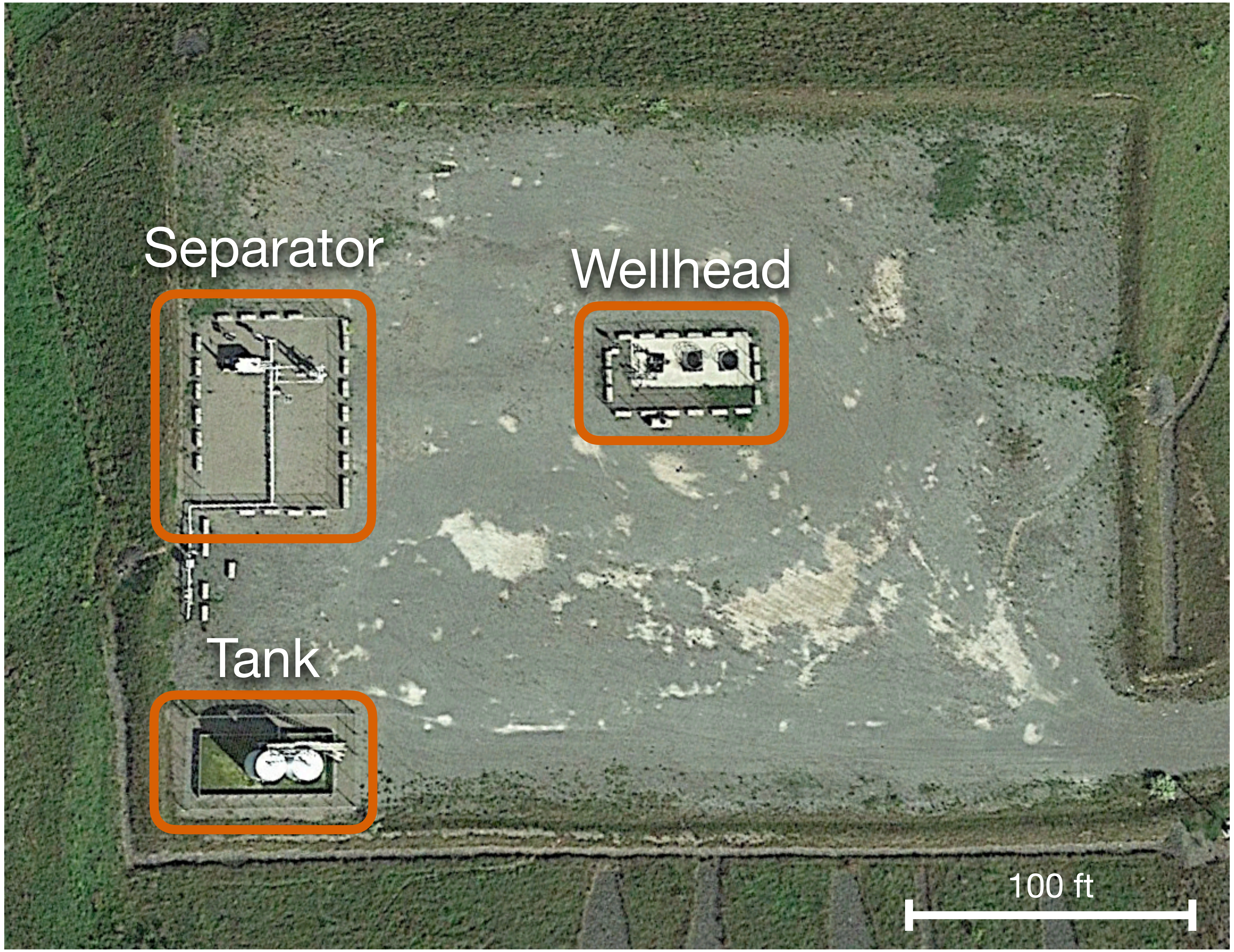
**The Oil & Gas Methane Partnership 2.0 (OGMP 2.0)**

Level 5 — Emissions reported similarly to Level 4, but with the addition of **site-level measurements** (measurements that characterize site-level emissions distribution for a statistically representative population)

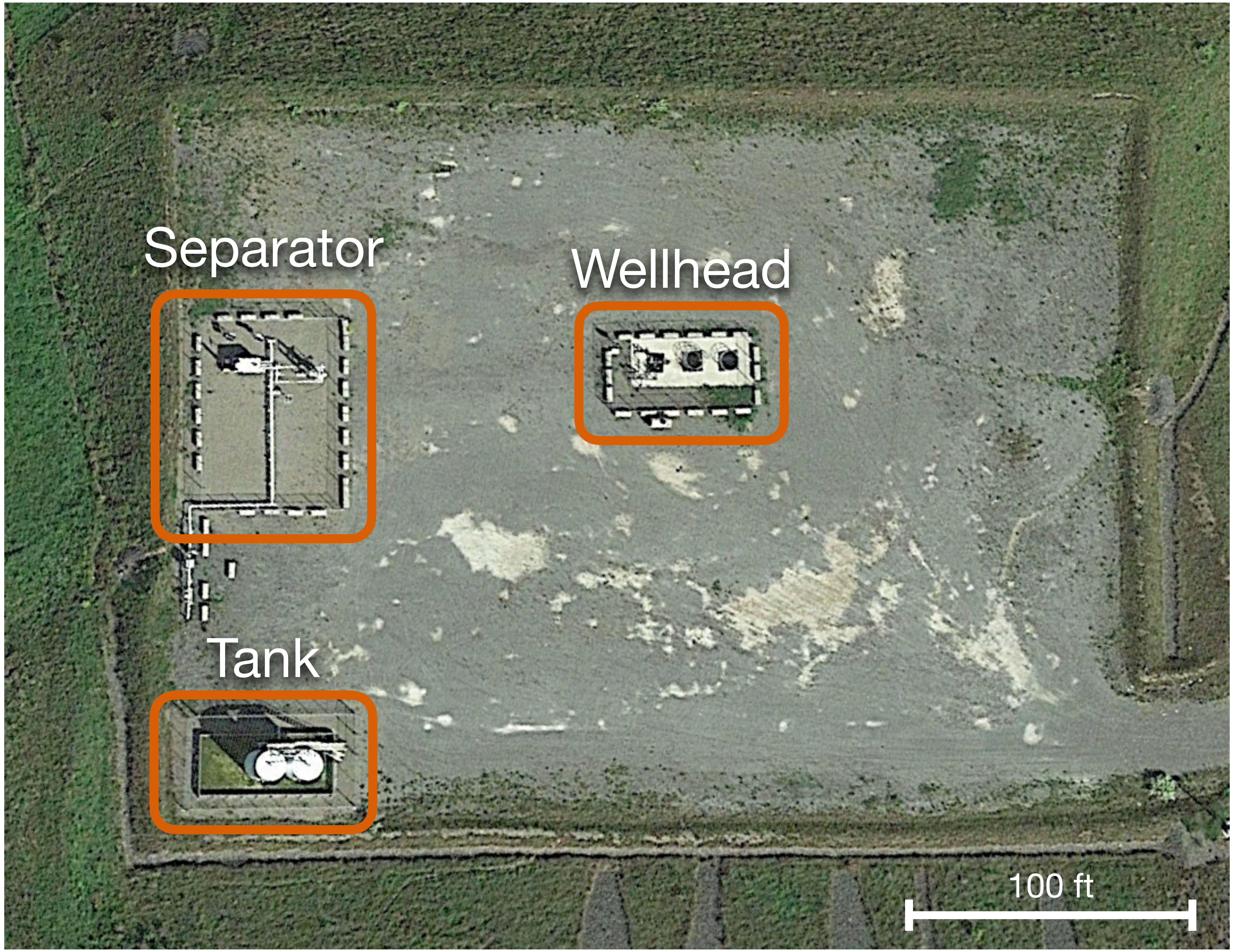
Global Initiatives


GLOBAL METHANE BUDGET 2008–2017
Global Carbon Project
TOTAL EMISSIONS
737
(594–880)
576
(550–594)
CHANGE IN ATMOSPHERIC ABUNDANCE
> 100
13*
(0–49)
TOTAL SINKS
625
(500–798)
556
(501–574)
Bottom-up view (BU)
Top-down view (TD)
128 (113–154)
111 (81–131)
206 (191–223)
217 (207–240)
30 (26–40)
30 (22–36)
149 (102–182)
181 (159–200)
222 (143–306)
37 (21–50)
595 (489–749)
518 (474–532)
30 (11–49)
38 (27–45)
Sink from chemical reactions in the atmosphere
Fossil fuel production and use
Agriculture and waste
Biomass and biofuel burning
Wetlands
Other natural emissions
Inland waters, geological, oceans, termites, wild animals, permafrost, vegetation
Sink in soils
EMISSIONS AND SINKS
In teragrams of CH4 per year (Tg CH4 yr-1) average over 2008–2017
* The observed atmospheric growth rate is 18.2 (17.3–19) Tg CH4 yr-1. The difference with the TD budget imbalance reflects uncertainties in capturing the observed growth rate.
Anthropogenic fluxes
Natural fluxes
Natural and anthropogenic fluxes
GLOBAL CARBON PROJECT

# Example production oil and gas site

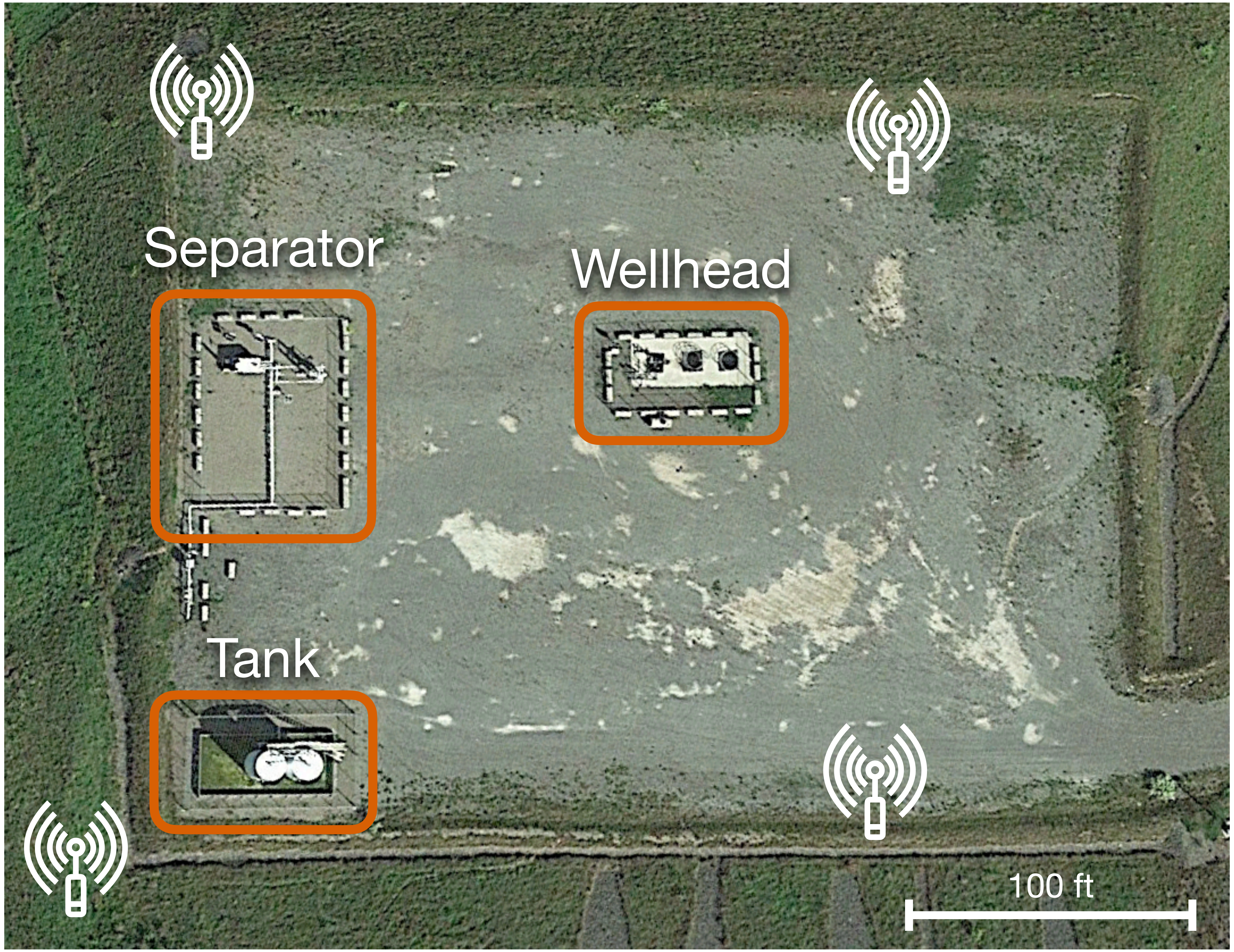


# Example production oil and gas site



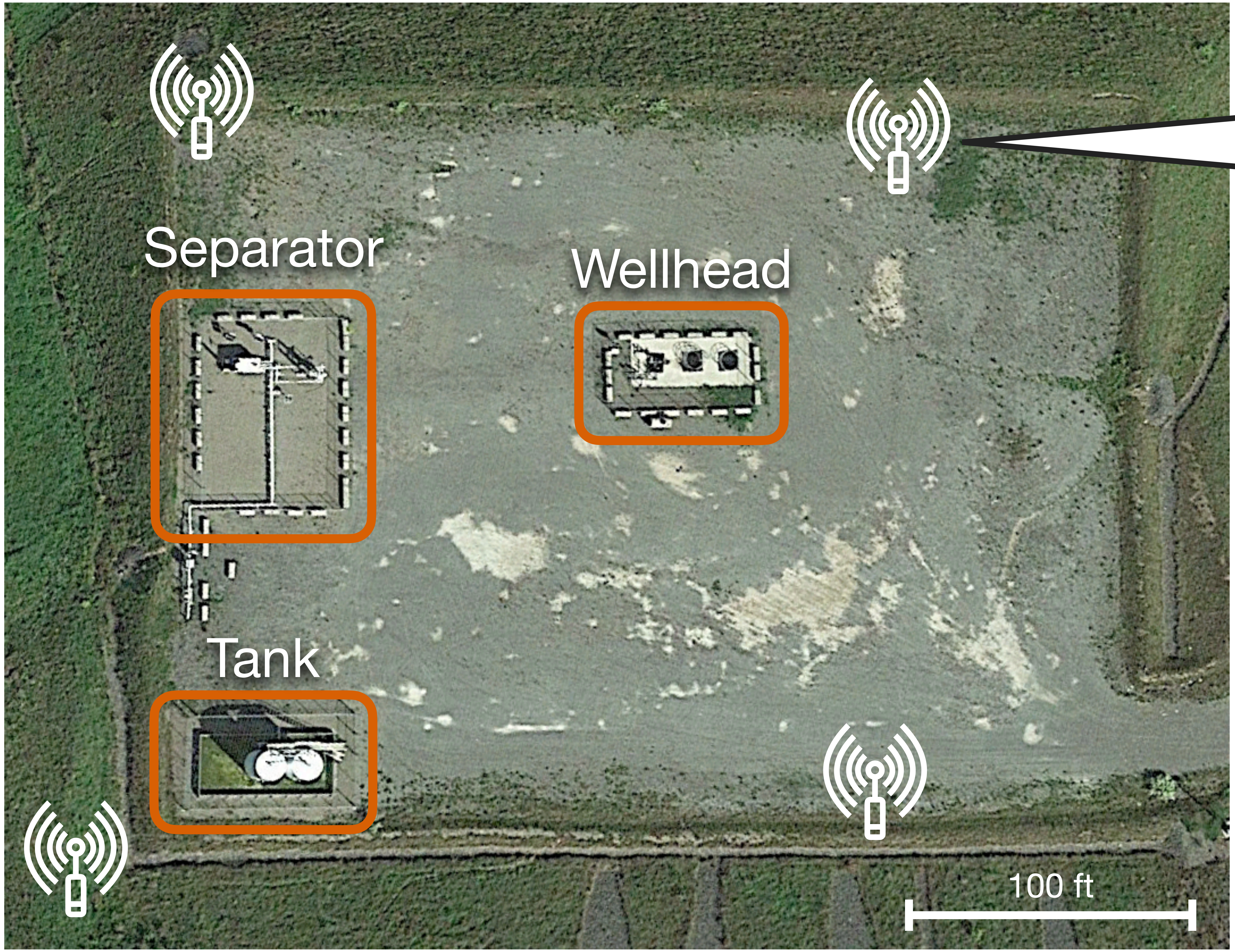

## Continuous monitoring system (CMS)

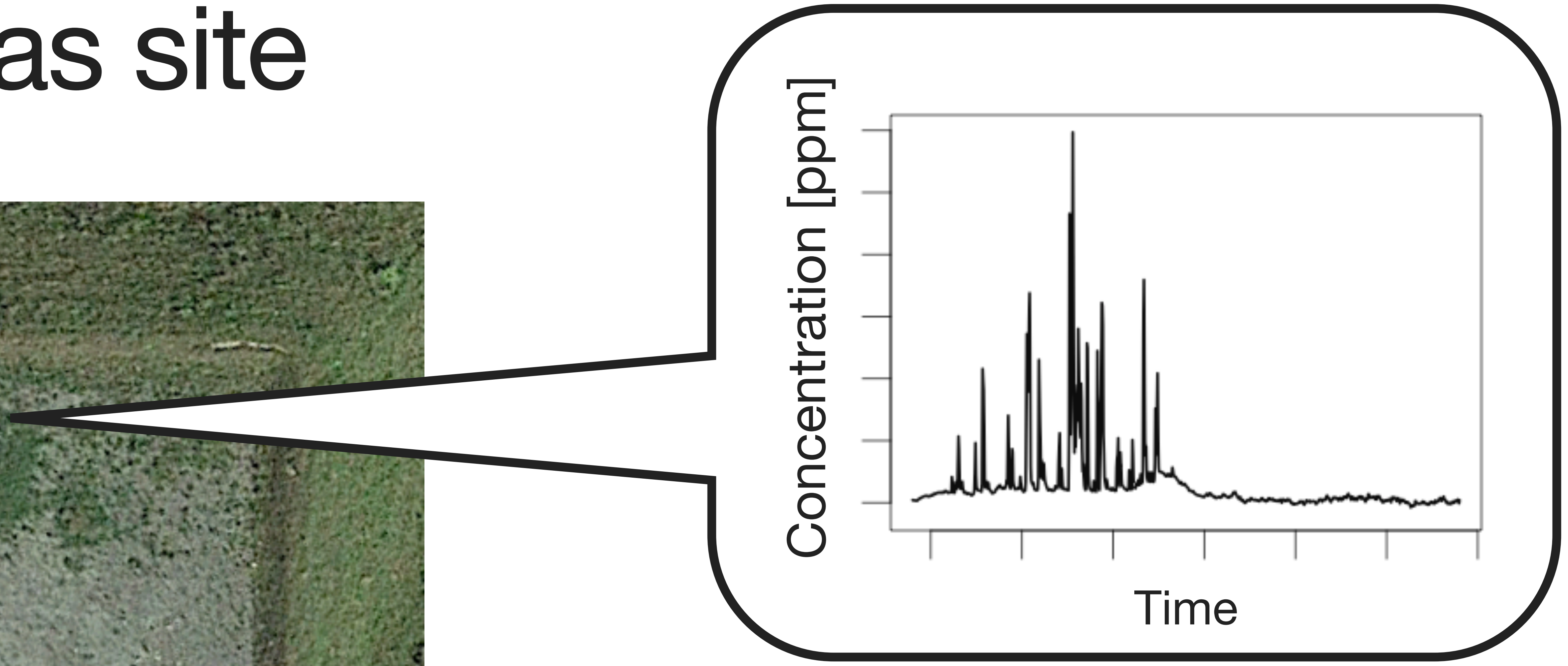
# Example production oil and gas site



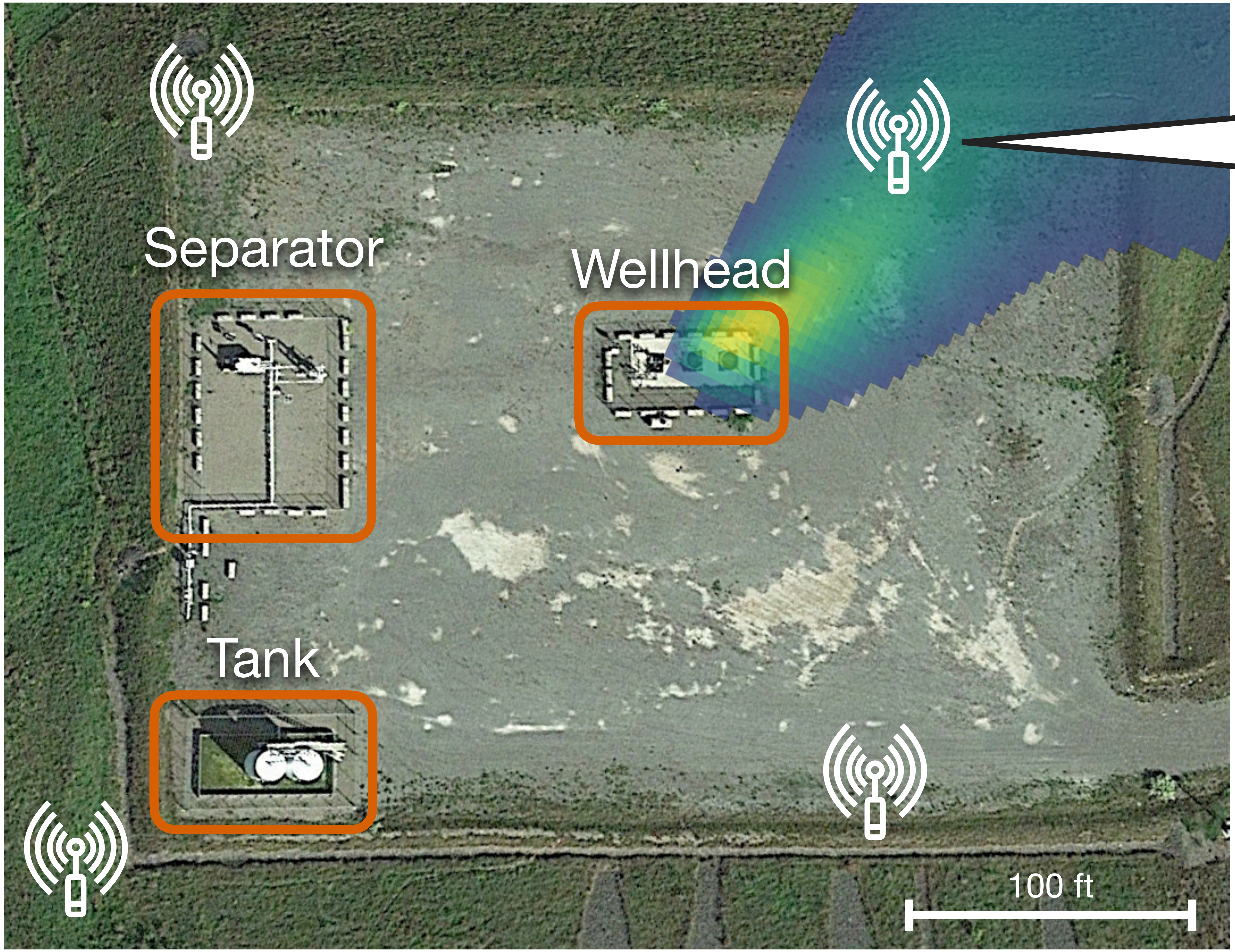

## Continuous monitoring system (CMS)

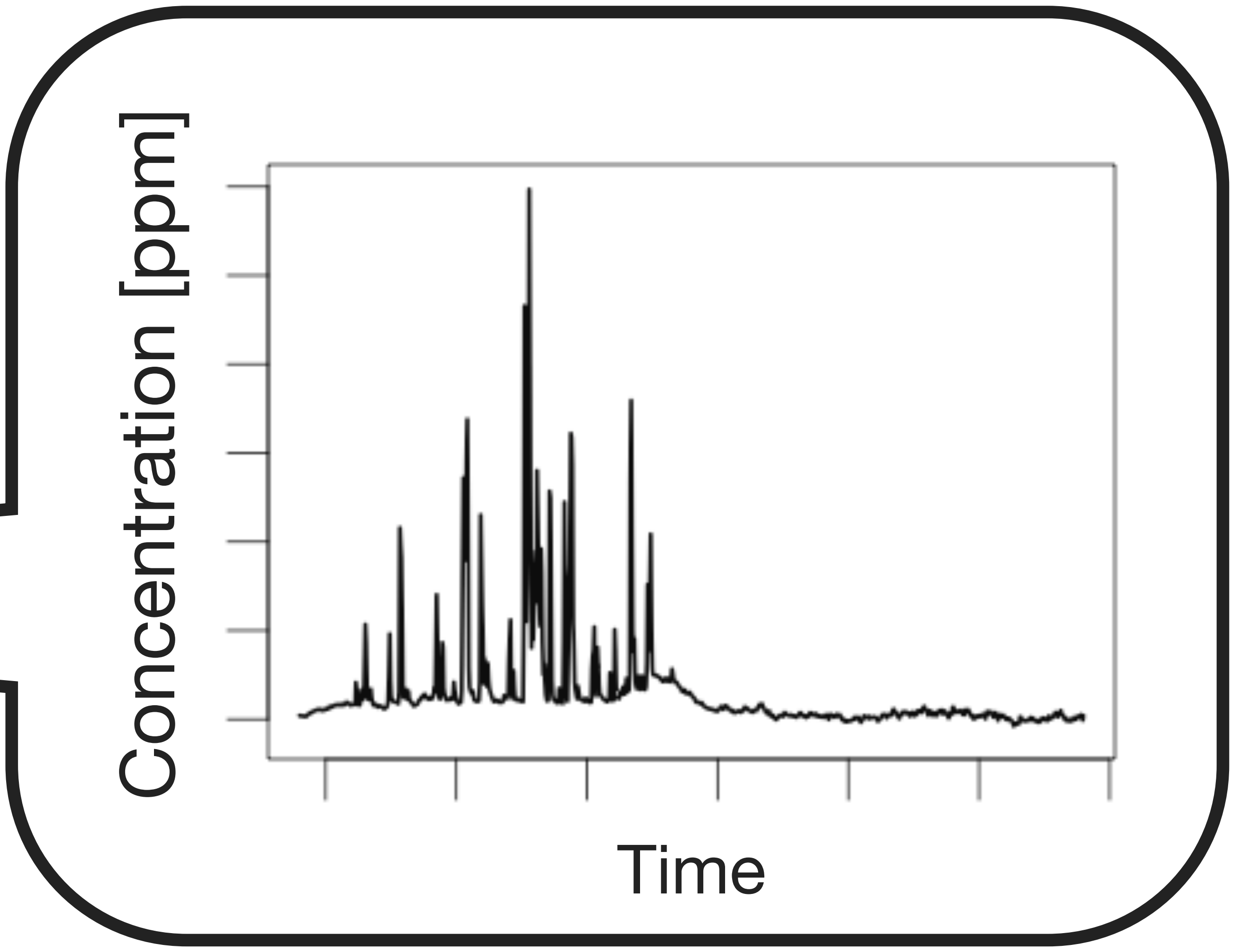
# Example production oil and gas site



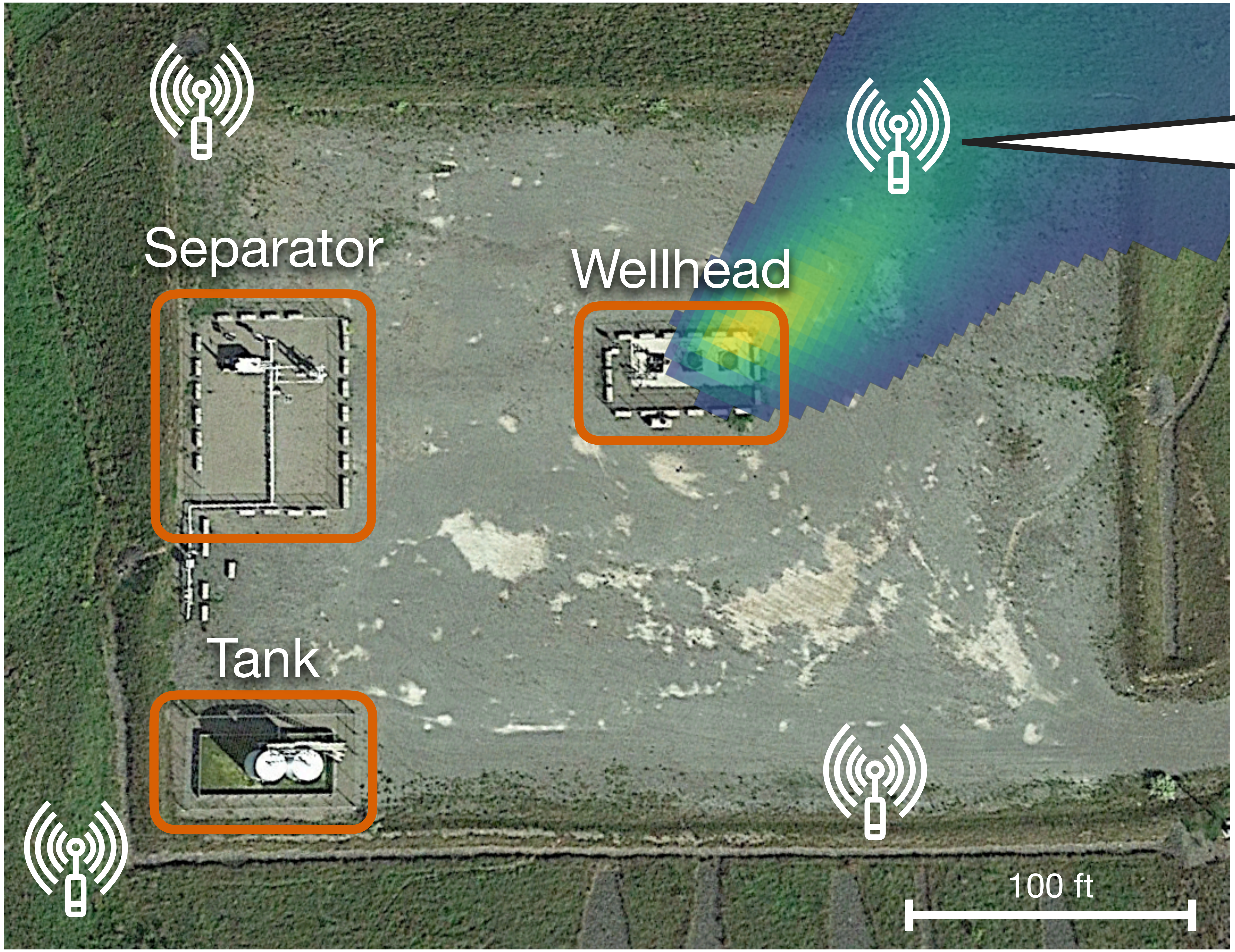
# Example production oil and gas site

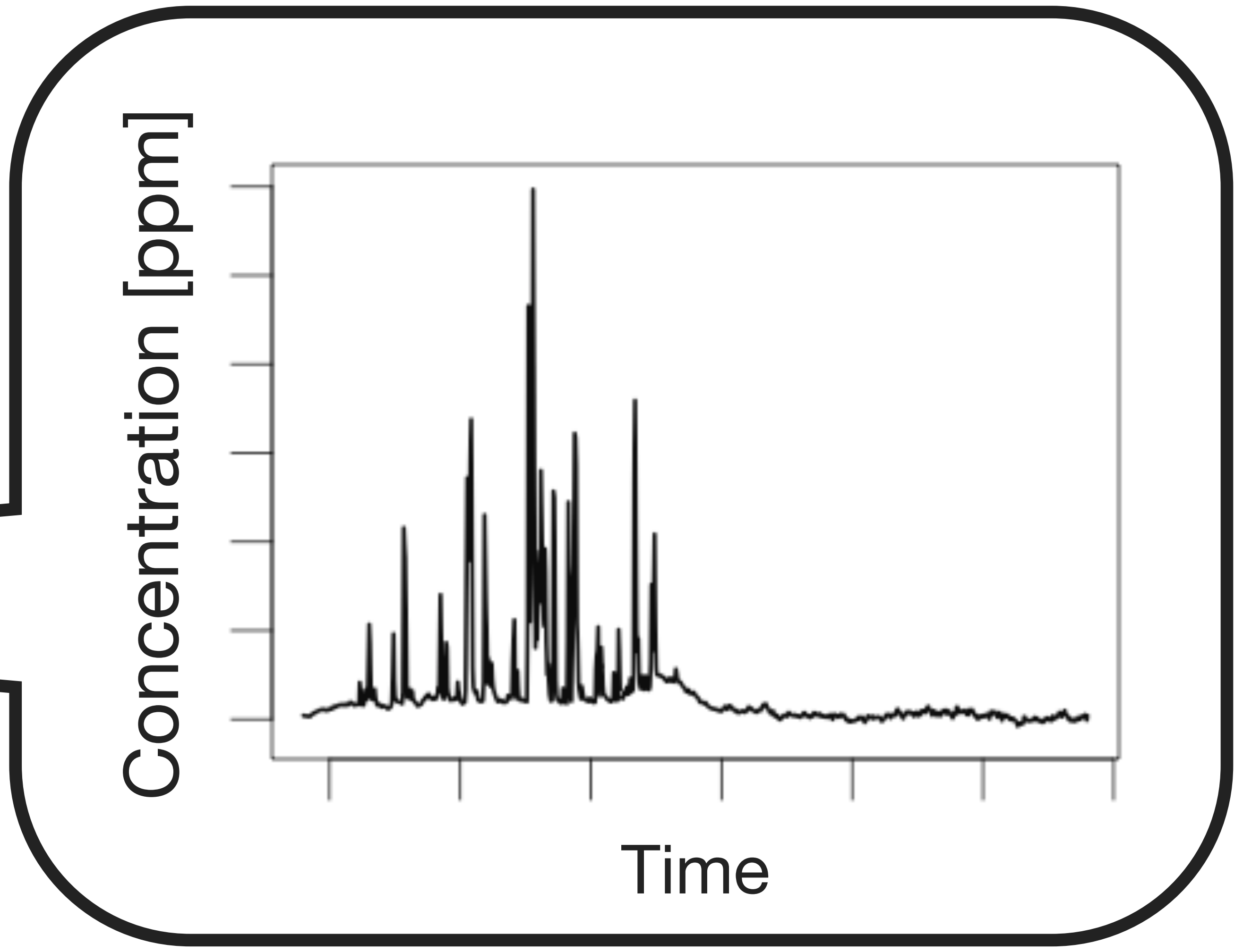



Aerial measurement technology

# Example production oil and gas site



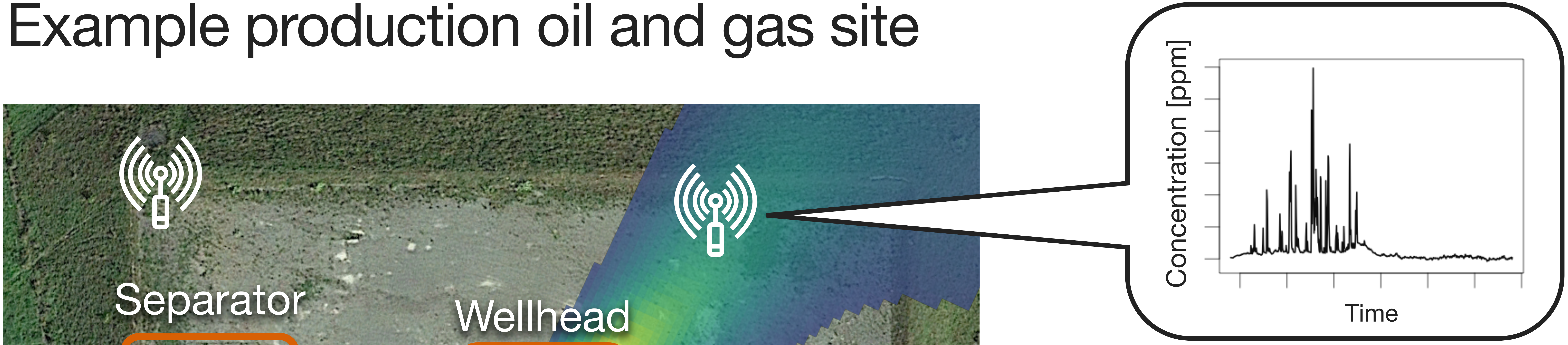




Aerial measurement technology

**Bottom-up inventory estimate** =

1 wellhead x wellhead emission factor +
1 separator x separator emission factor +
1 tank x tank emission factor

# Example production oil and gas site




Event detection:
When is an emission happening?

Localization:
Where is the emission coming from?

Quantification:
How much is being emitted?

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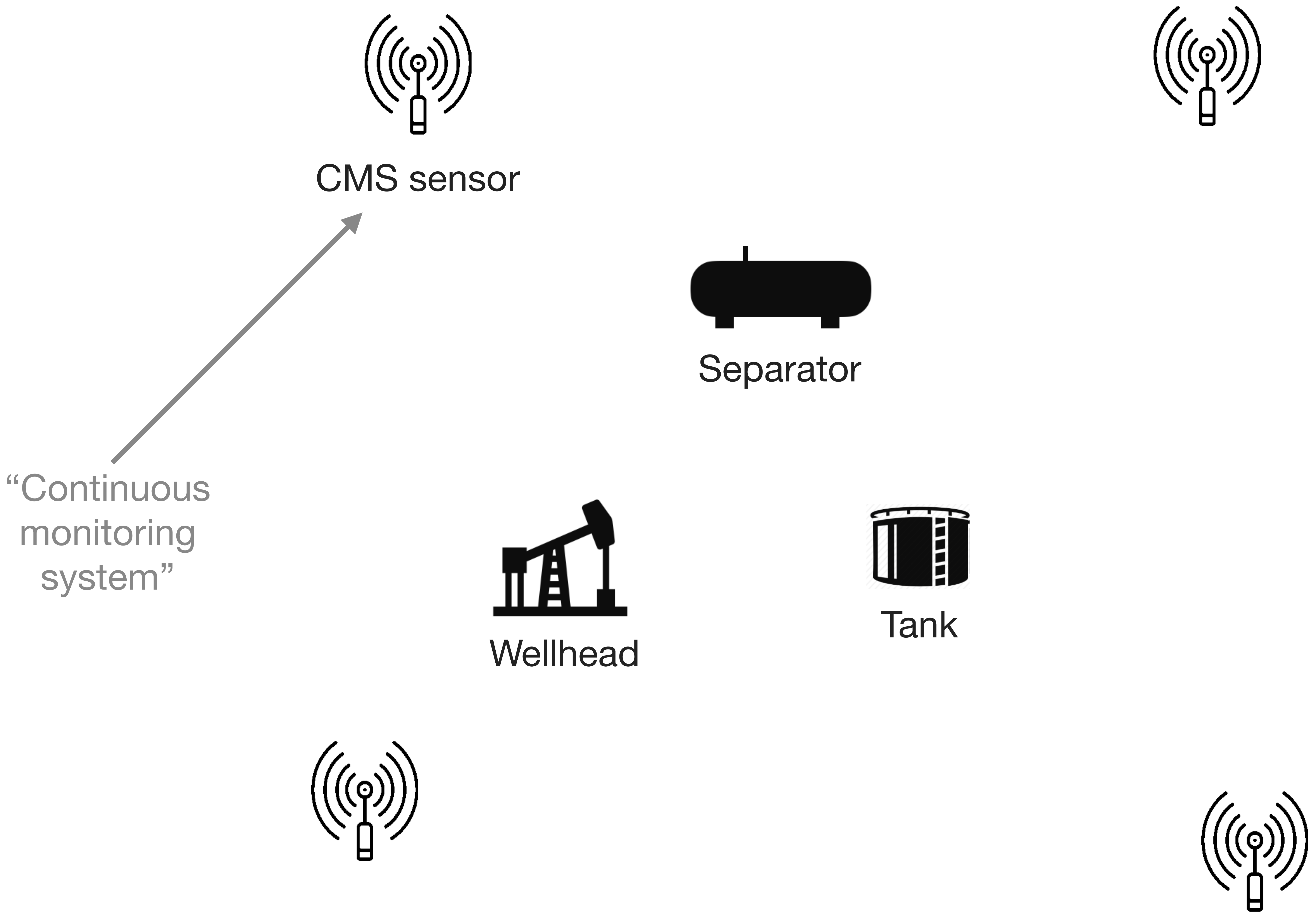
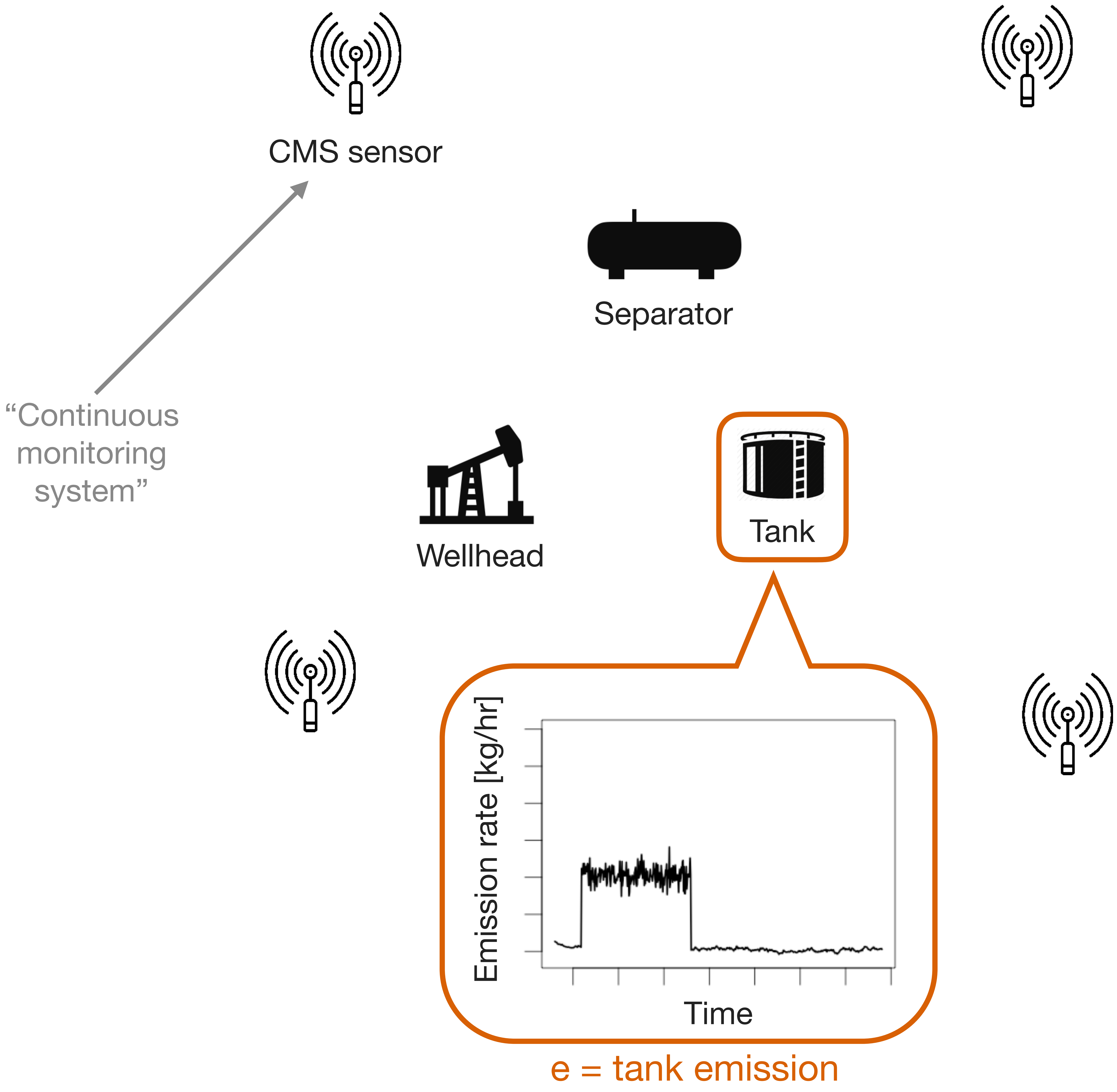
Robust duration estimates

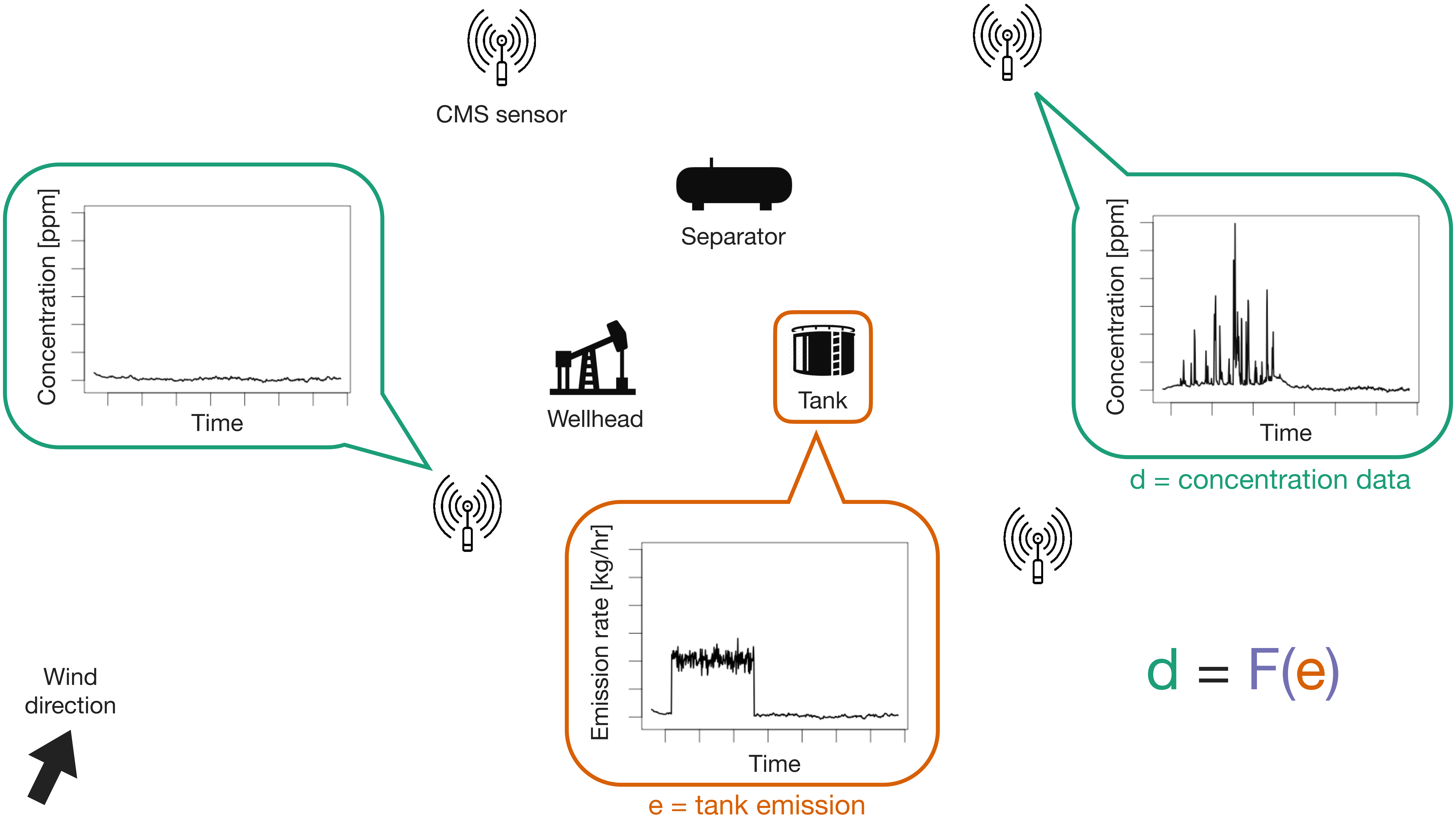
# Chapter 1:

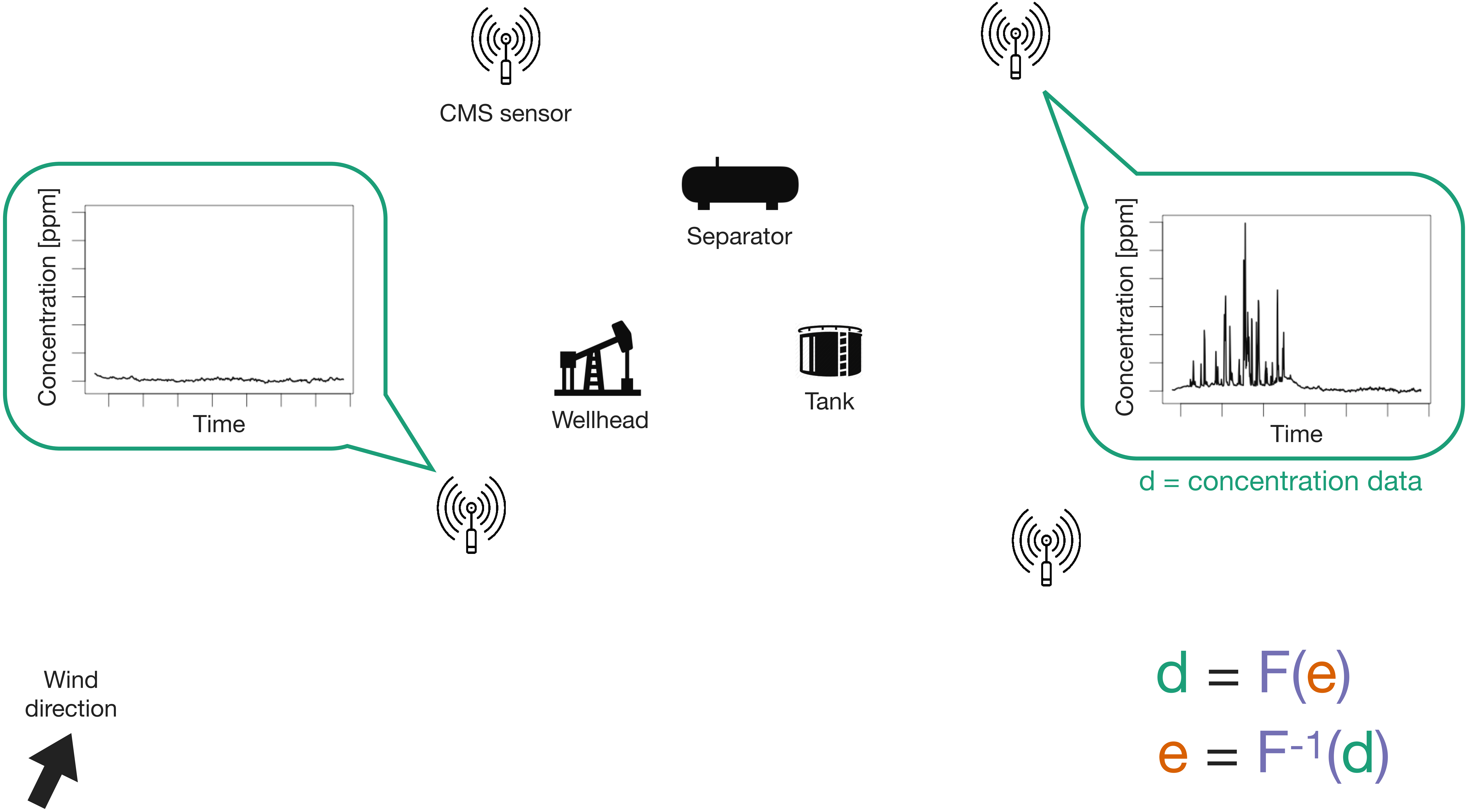
## Single-source emission detection, localization, and quantification




# The continuous monitoring inverse problem


CMS sensor
Separator
"Continuous
monitoring
system"
Wellhead
Tank
Emission rate [kg/hr]
Time
e = tank emission


CMS sensor
Separator
Concentration [ppm]
Time
Wellhead
Tank
Concentration [ppm]
Time
d = concentration data
Emission rate [kg/hr]
Time
e = tank emission
Wind
direction
d = F(e)



CMS sensor
Separator
Concentration [ppm]
Time
Wellhead
Tank
Concentration [ppm]
Time
d = concentration data
Wind
direction


$$d = F(e)$$

$$e = F^{-1}(d)$$

# Open source framework for solving inverse problem

STEP 1:
Background removal
and event detection

→

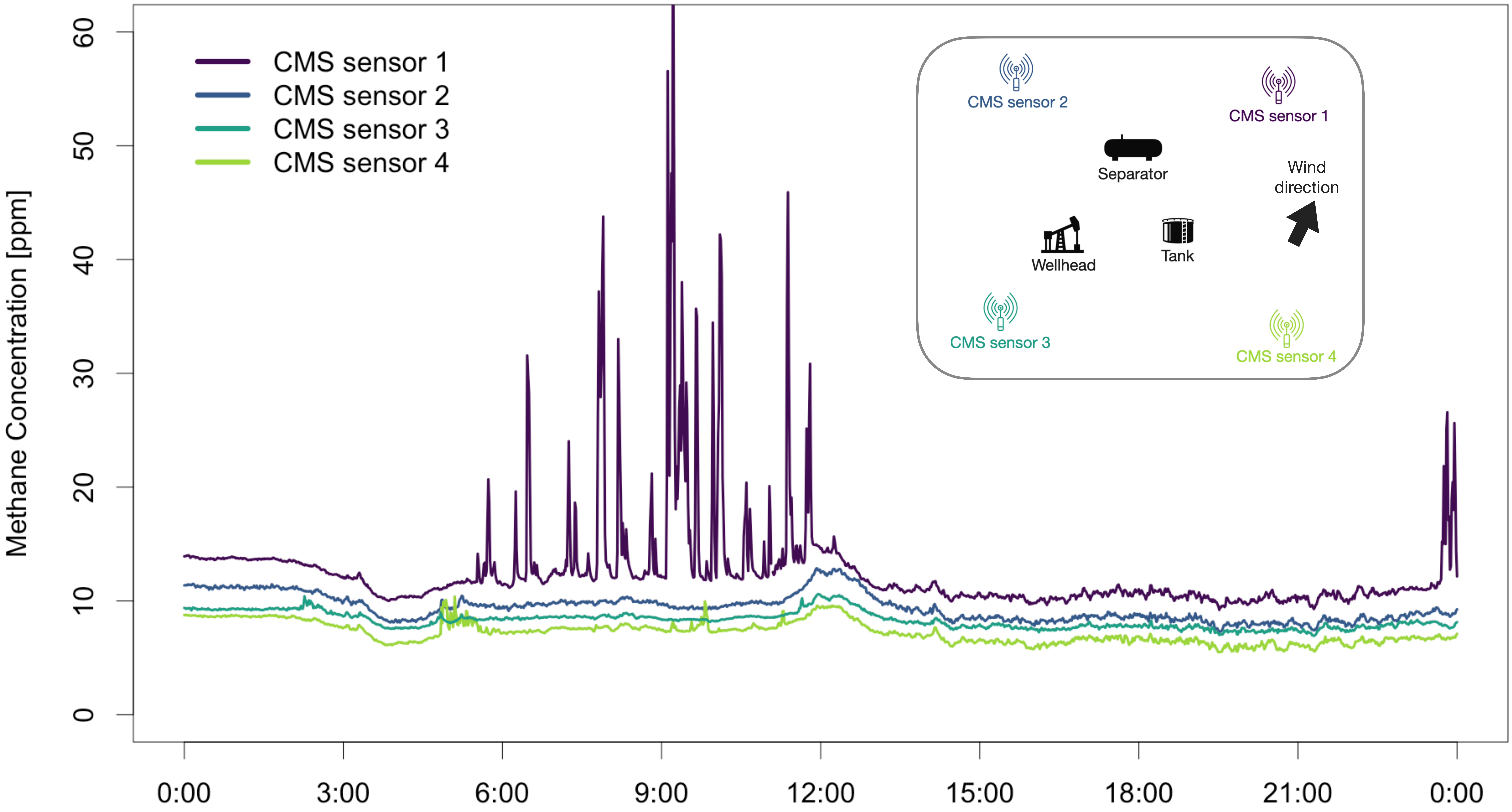
STEP 2:
Simulation

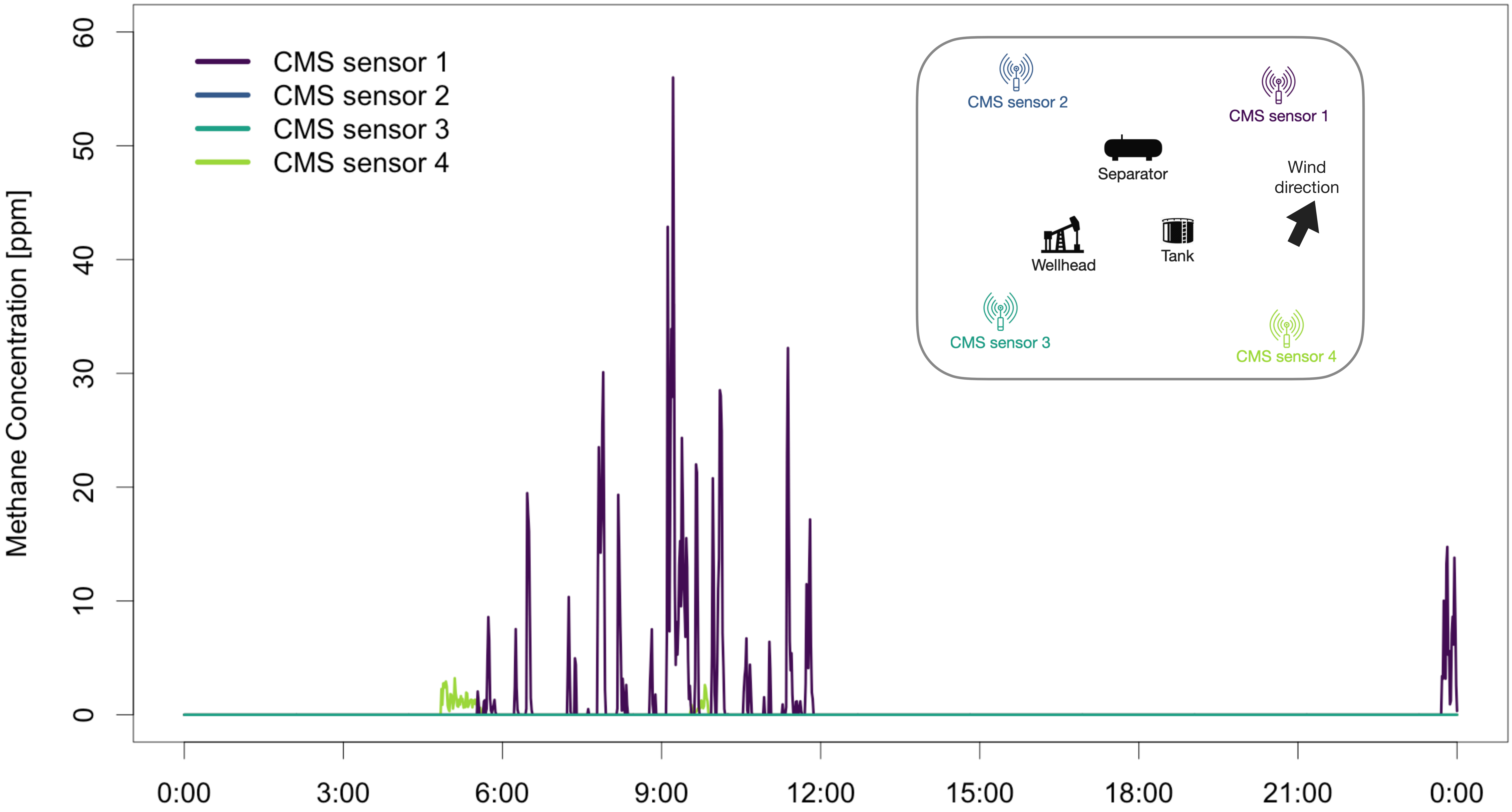
→

STEP 3:
Localization

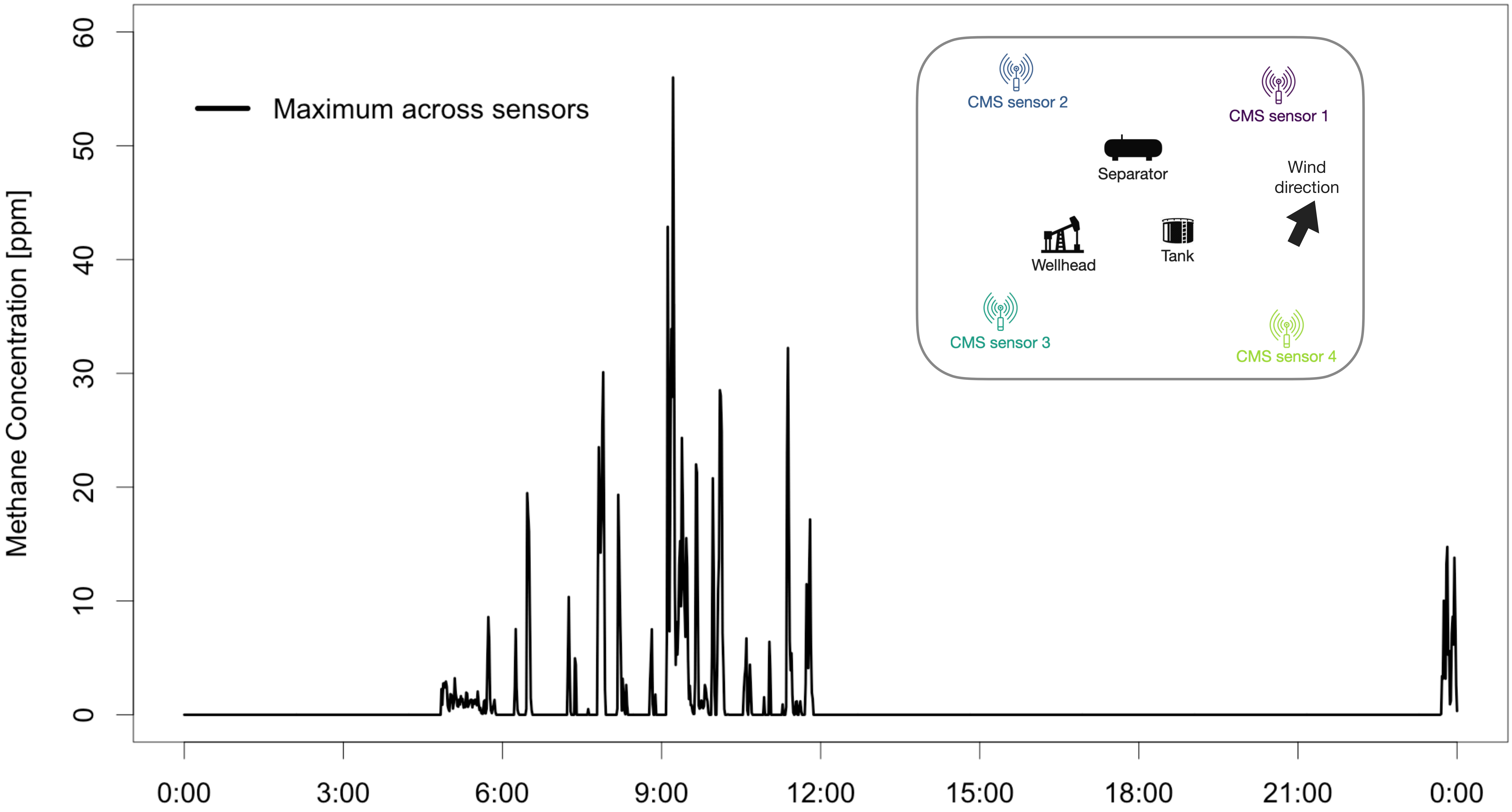
→

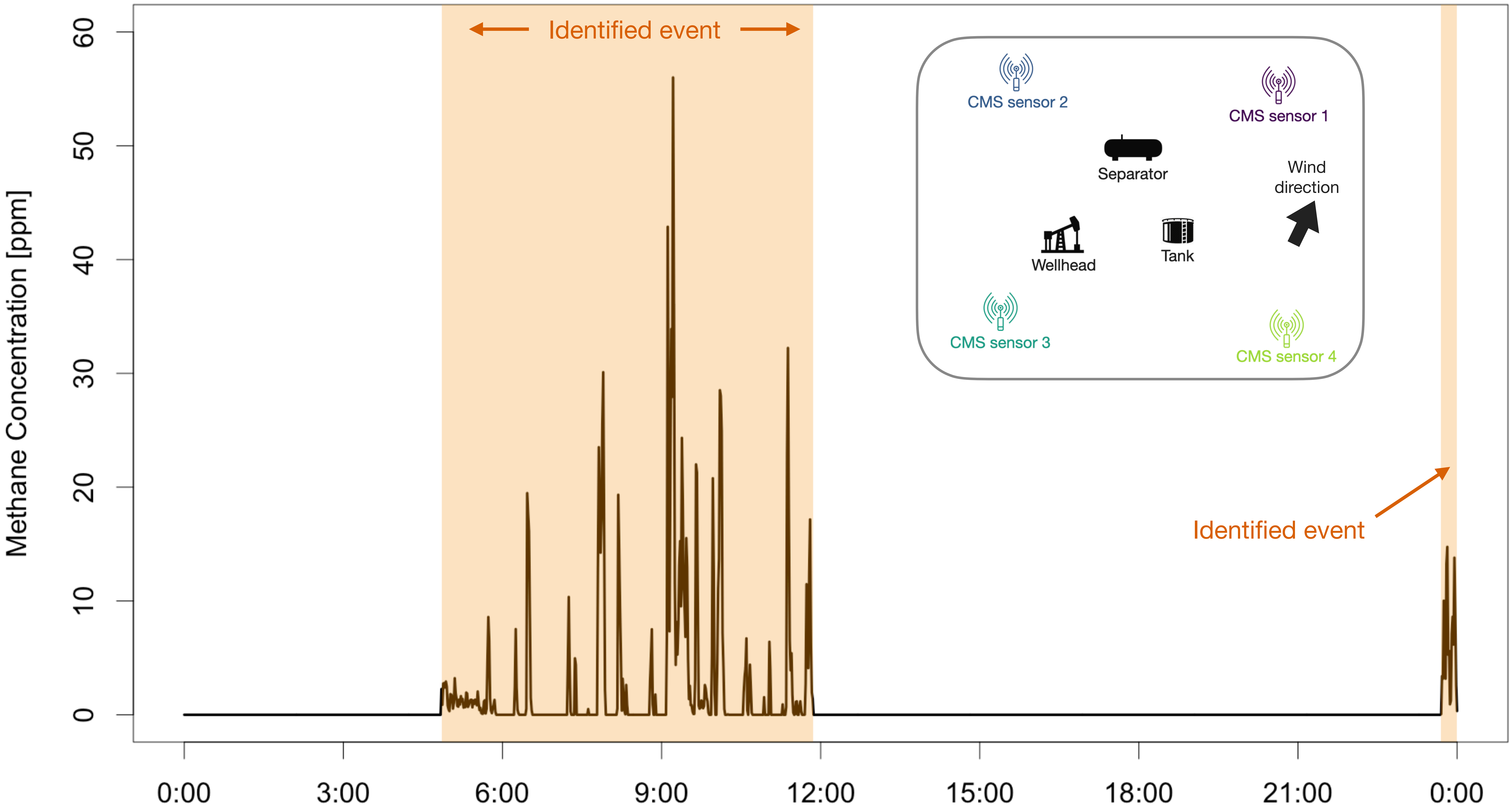
STEP 4:
Quantification


CMS sensor 1
CMS sensor 2
CMS sensor 3
CMS sensor 4
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
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



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 1
CMS sensor 2
CMS sensor 3
CMS sensor 4
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
CMS sensor 3
CMS sensor 4


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


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

STEP 1:
Background removal
and event detection

→

STEP 2:
Simulation

→

STEP 3:
Localization

→

STEP 4:
Quantification

# 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 concentration at $(x, y, z, t)$

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

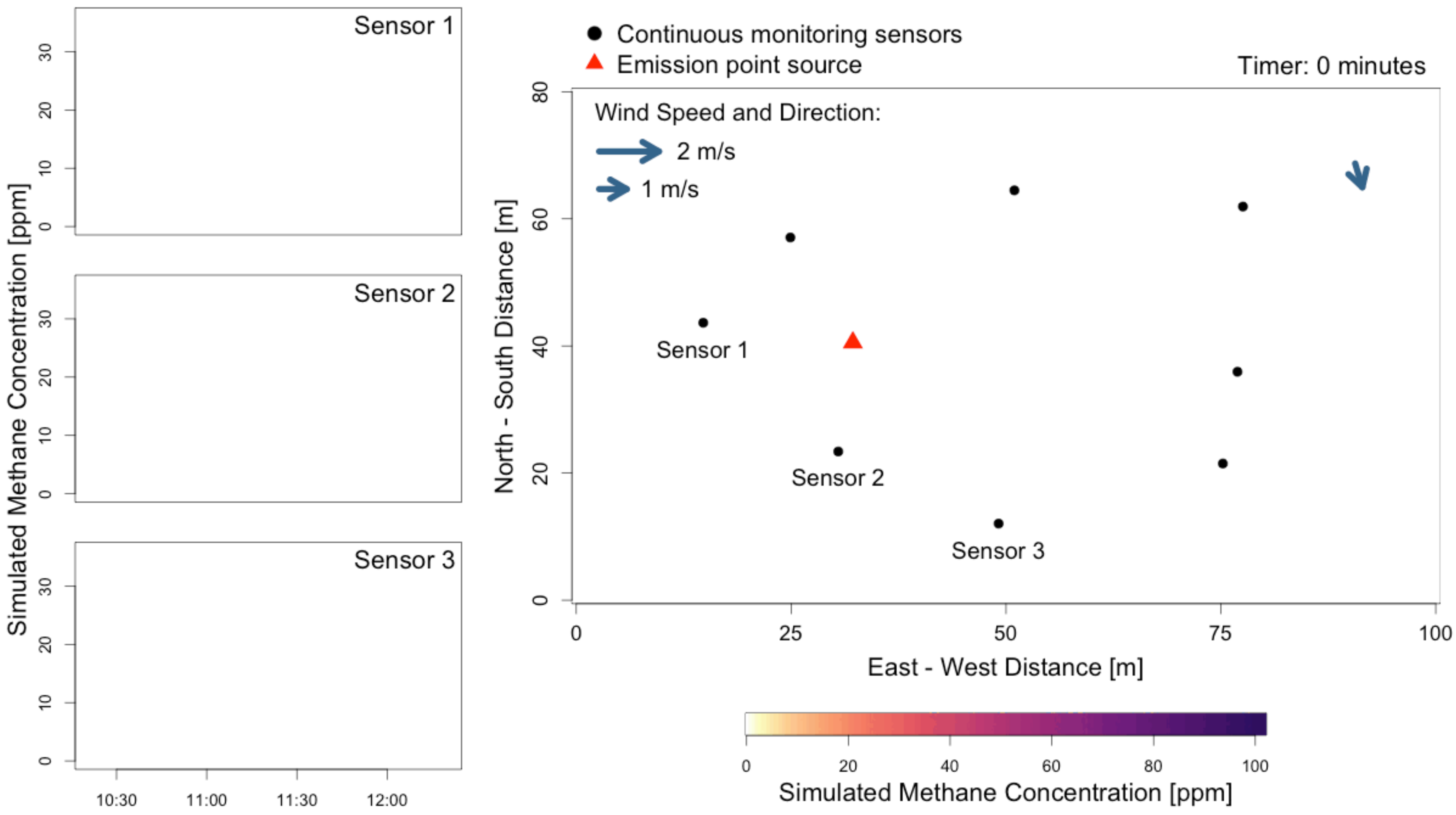
Total volume of methane contained in puff $p$

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

Concentration contribution of puff $p$

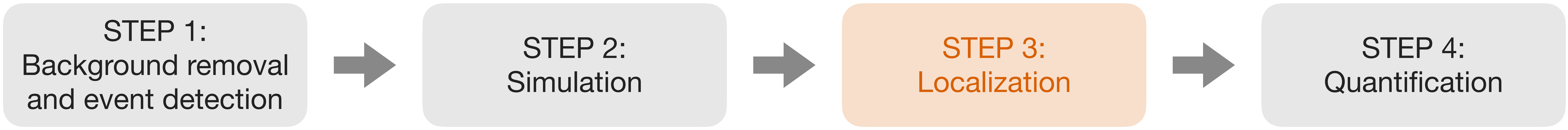
Decay in puff concentration in horizontal plane $(x, y)$

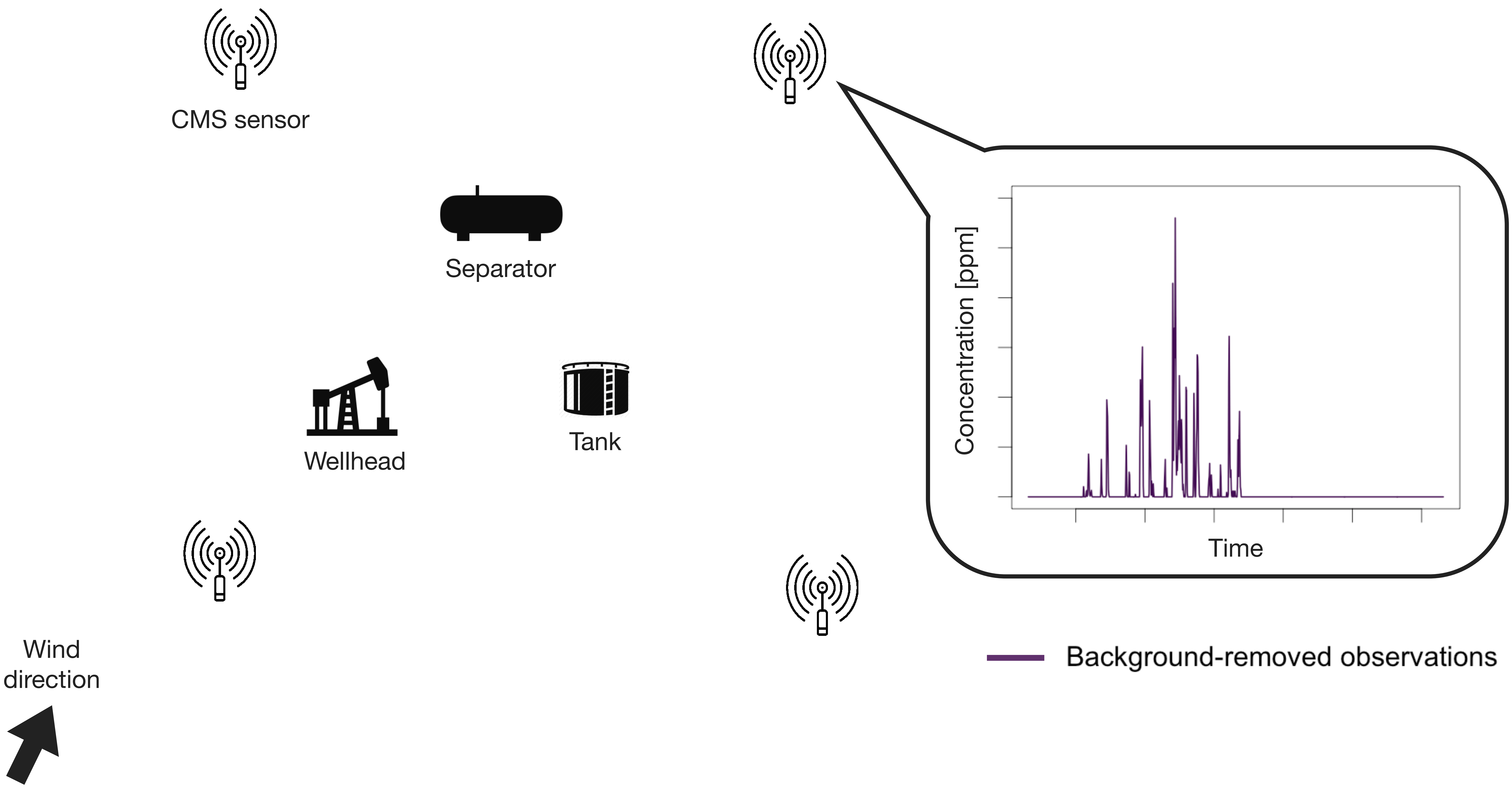
Decay in puff concentration in vertical dimension $(z)$


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]
East - West Distance [m]
0
20
40
60
80
25
50
75
100
Simulated Methane Concentration [ppm]

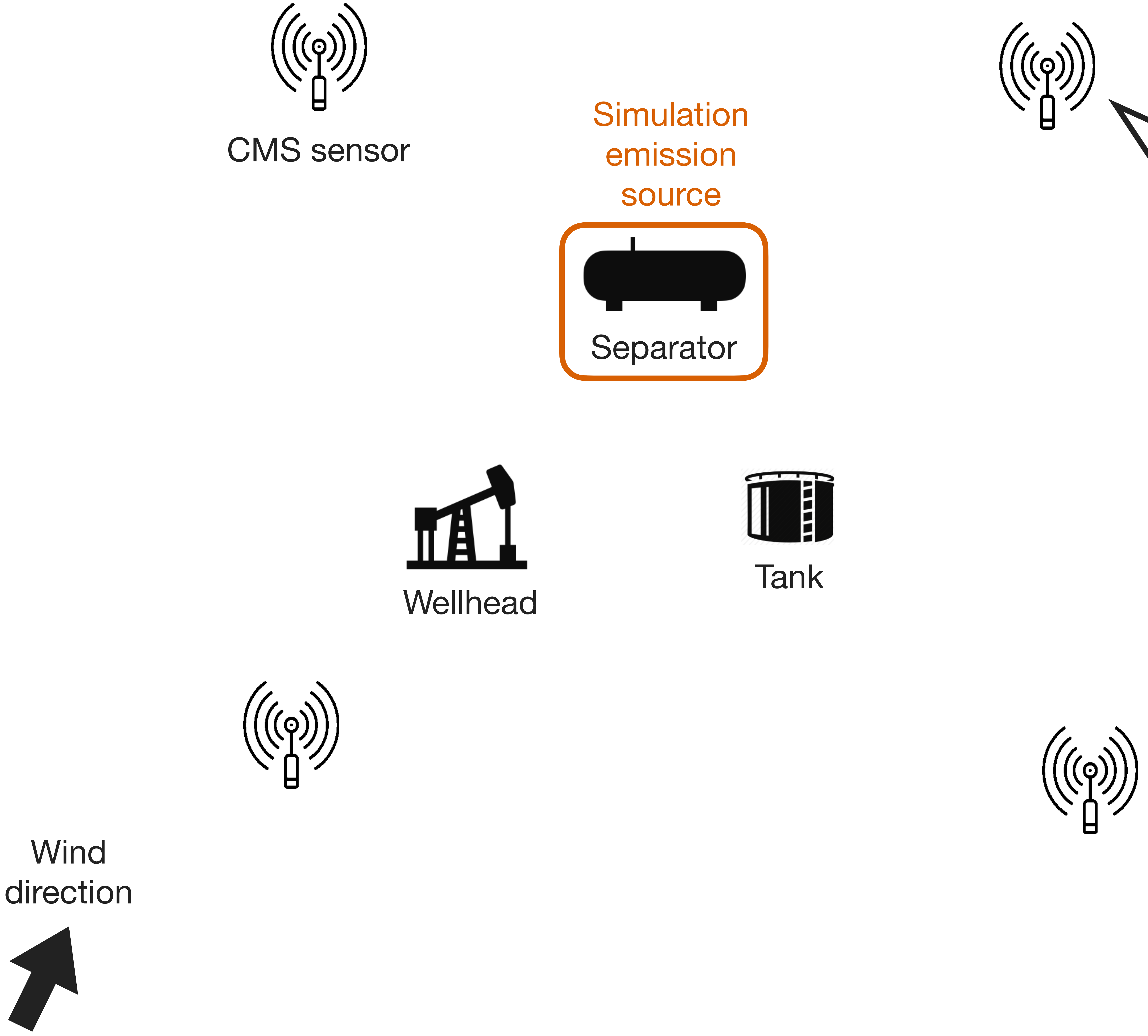

# Repeat this for all other potential sources!

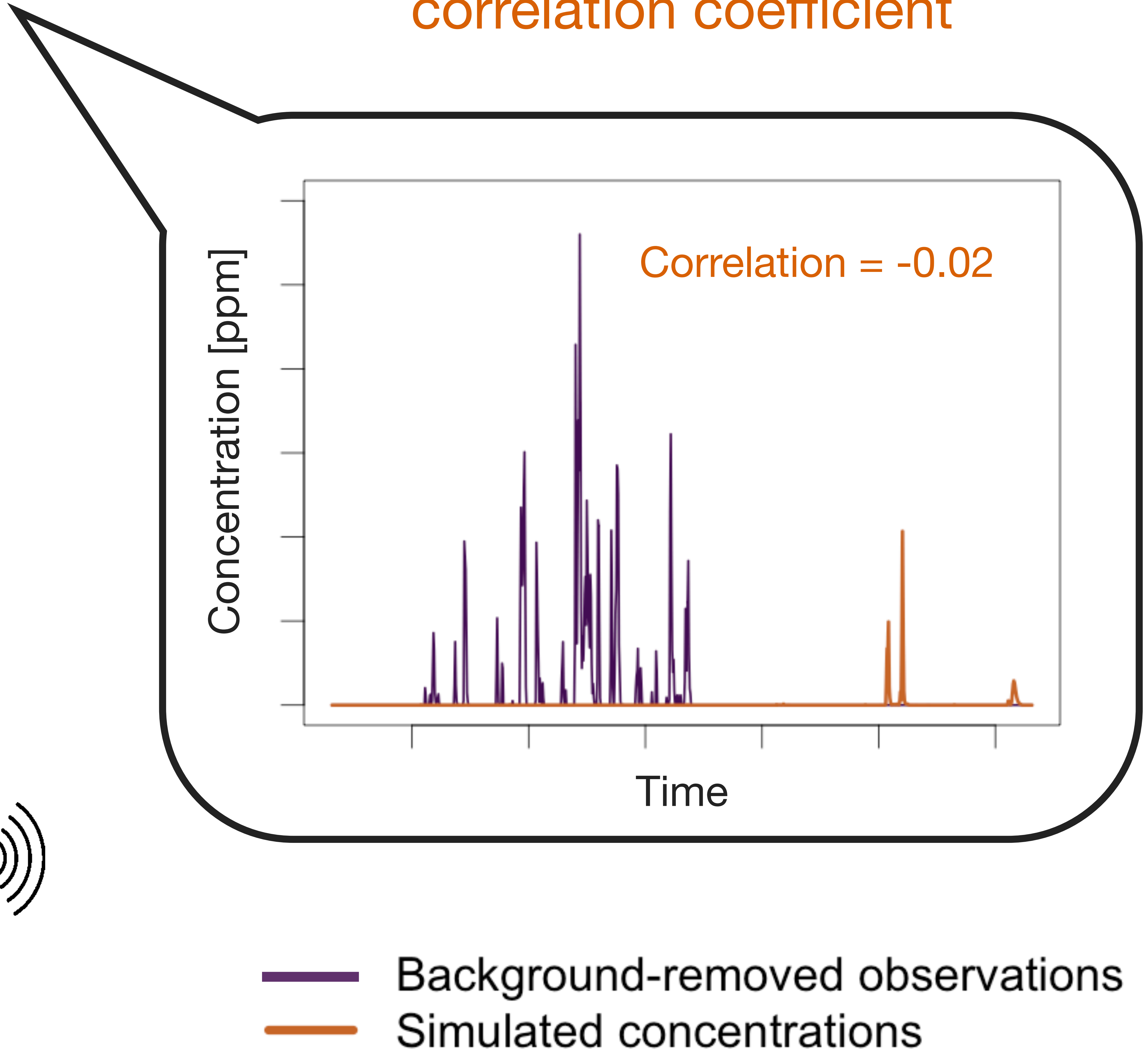
# Open source framework for solving inverse problem

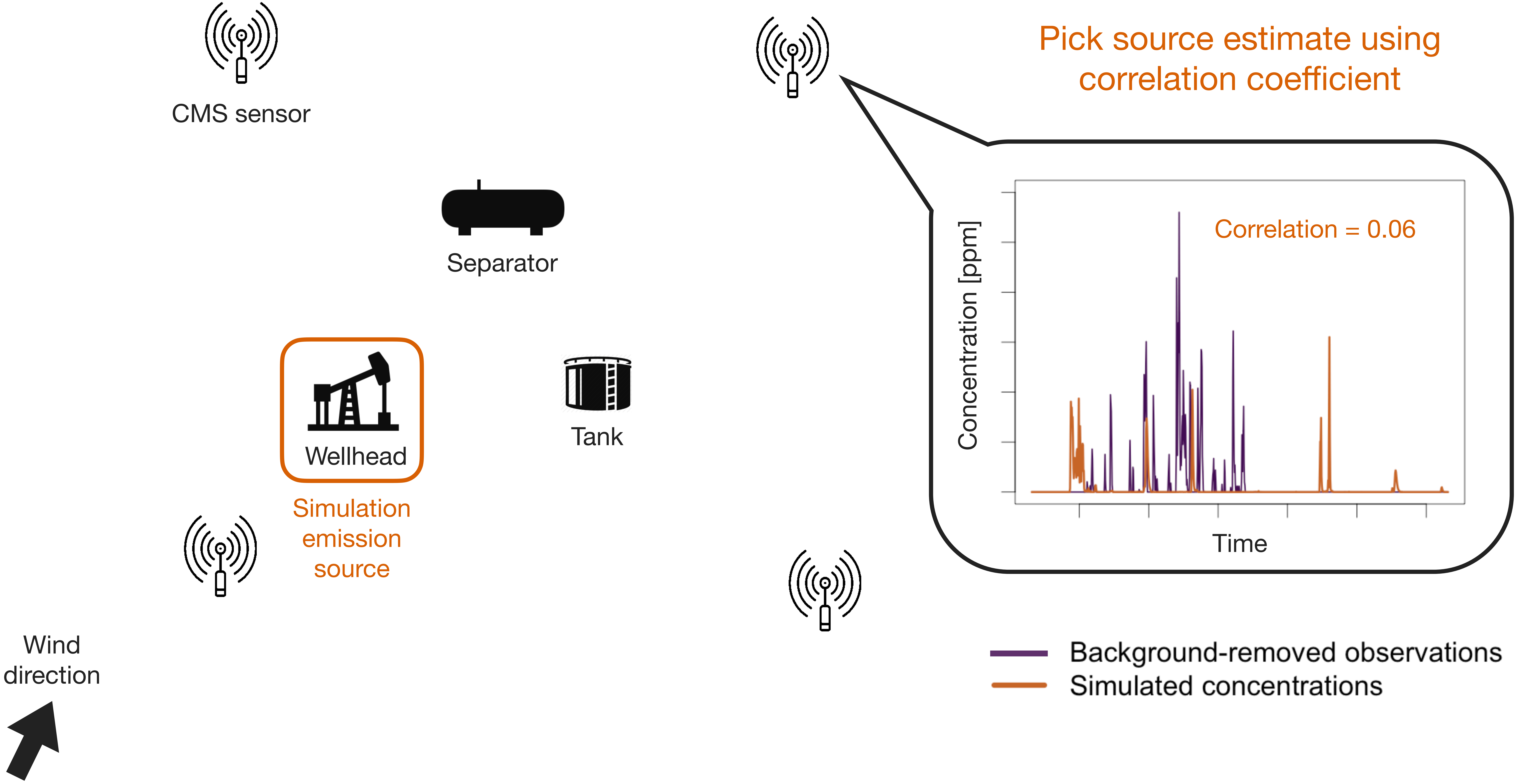


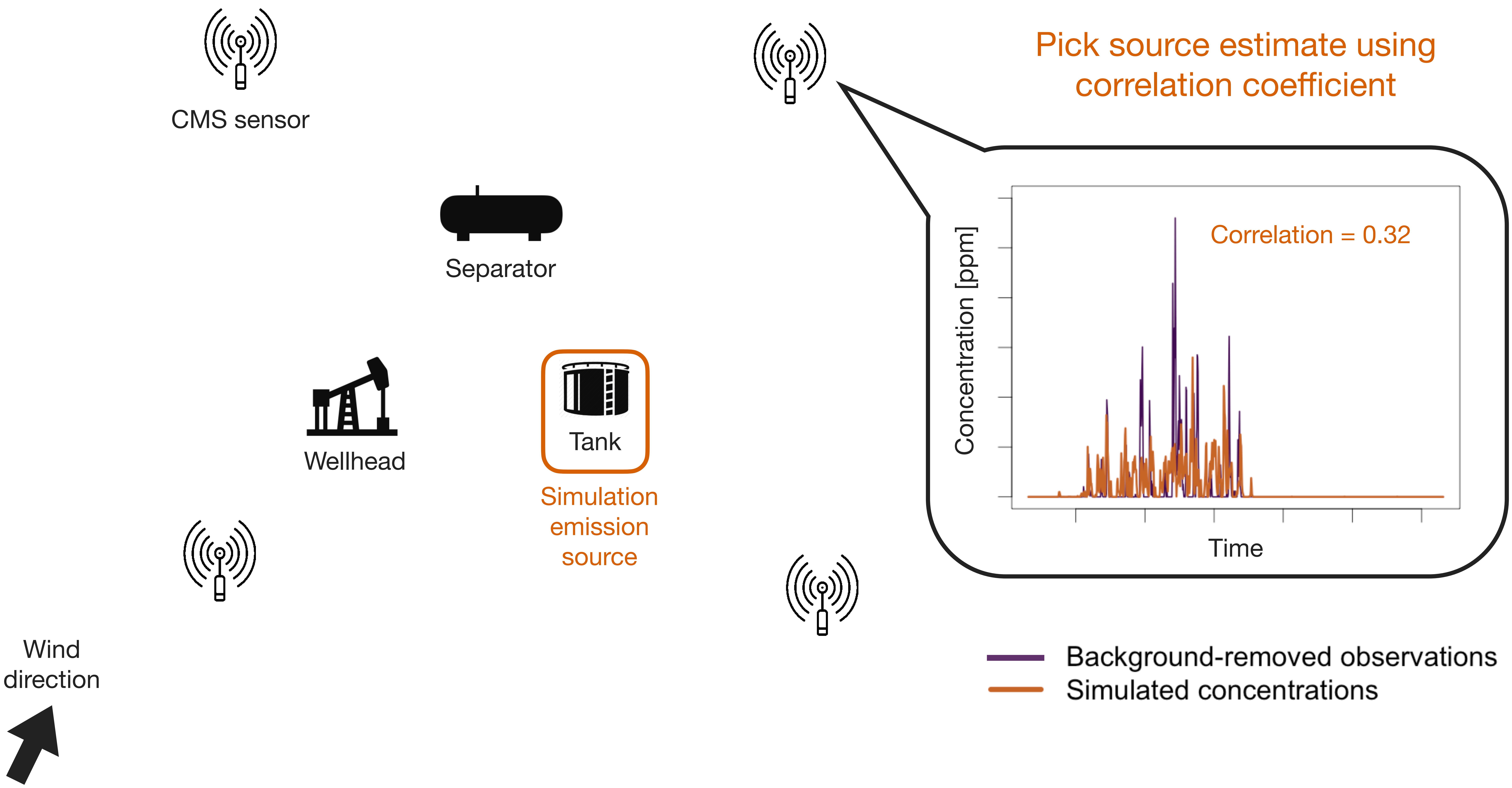

CMS sensor
Separator
Wellhead
Tank
Wind
direction
Concentration [ppm]
Time
Background-removed observations

## Pick source estimate using correlation coefficient




Pick source estimate using correlation coefficient
CMS sensor
Separator
Wellhead
Tank
Simulation emission source
Wind direction
Correlation = 0.06
Concentration [ppm]
Time
Background-removed observations
Simulated concentrations



CMS sensor
Separator
Wellhead
Tank
Simulation emission source
Wind direction
Pick source estimate using correlation coefficient
Correlation = 0.32
Concentration [ppm]
Time
Background-removed observations
Simulated concentrations

# 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

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 $p$

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

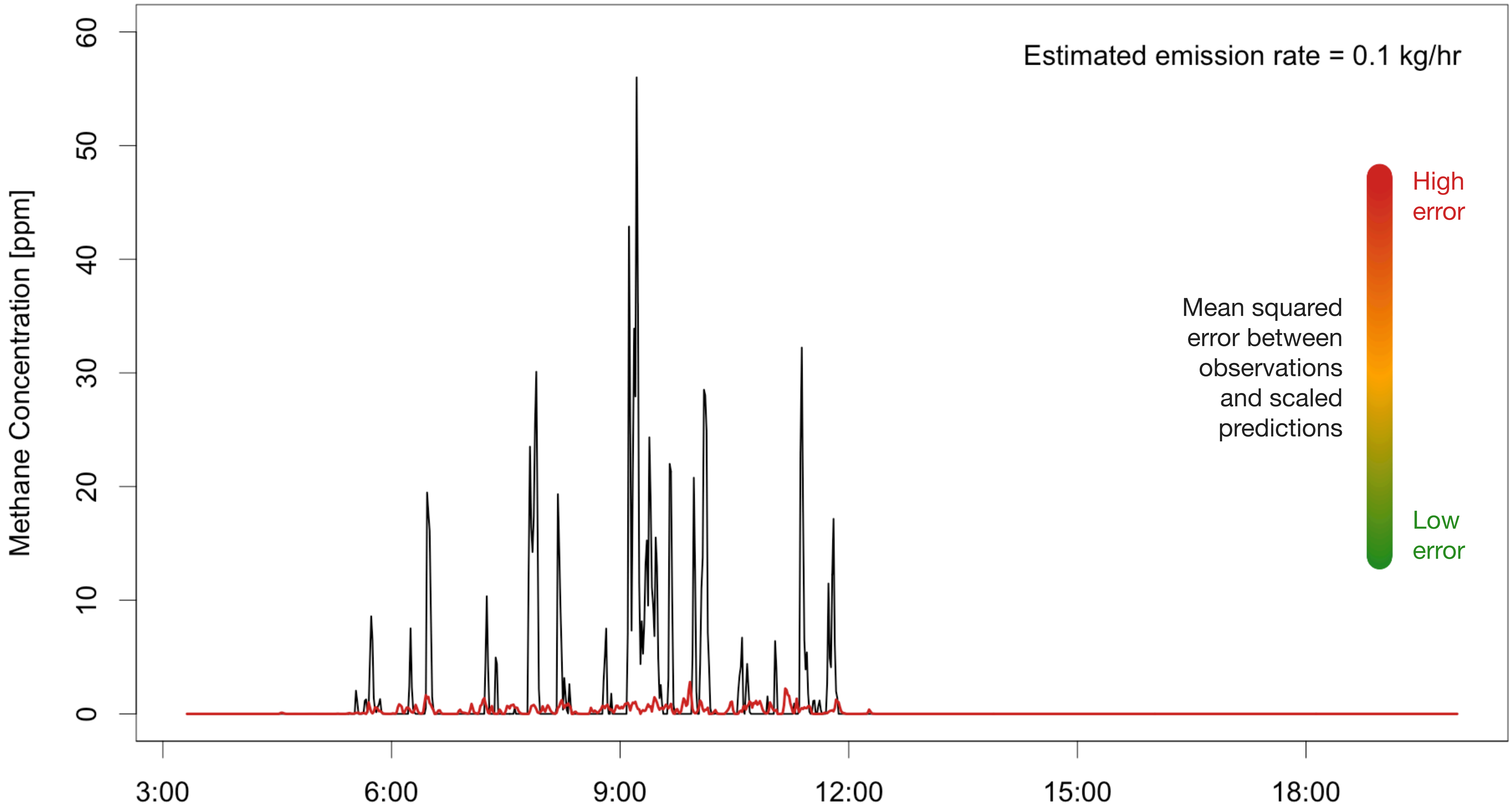
Total concentration at $(x, y, z, t)$

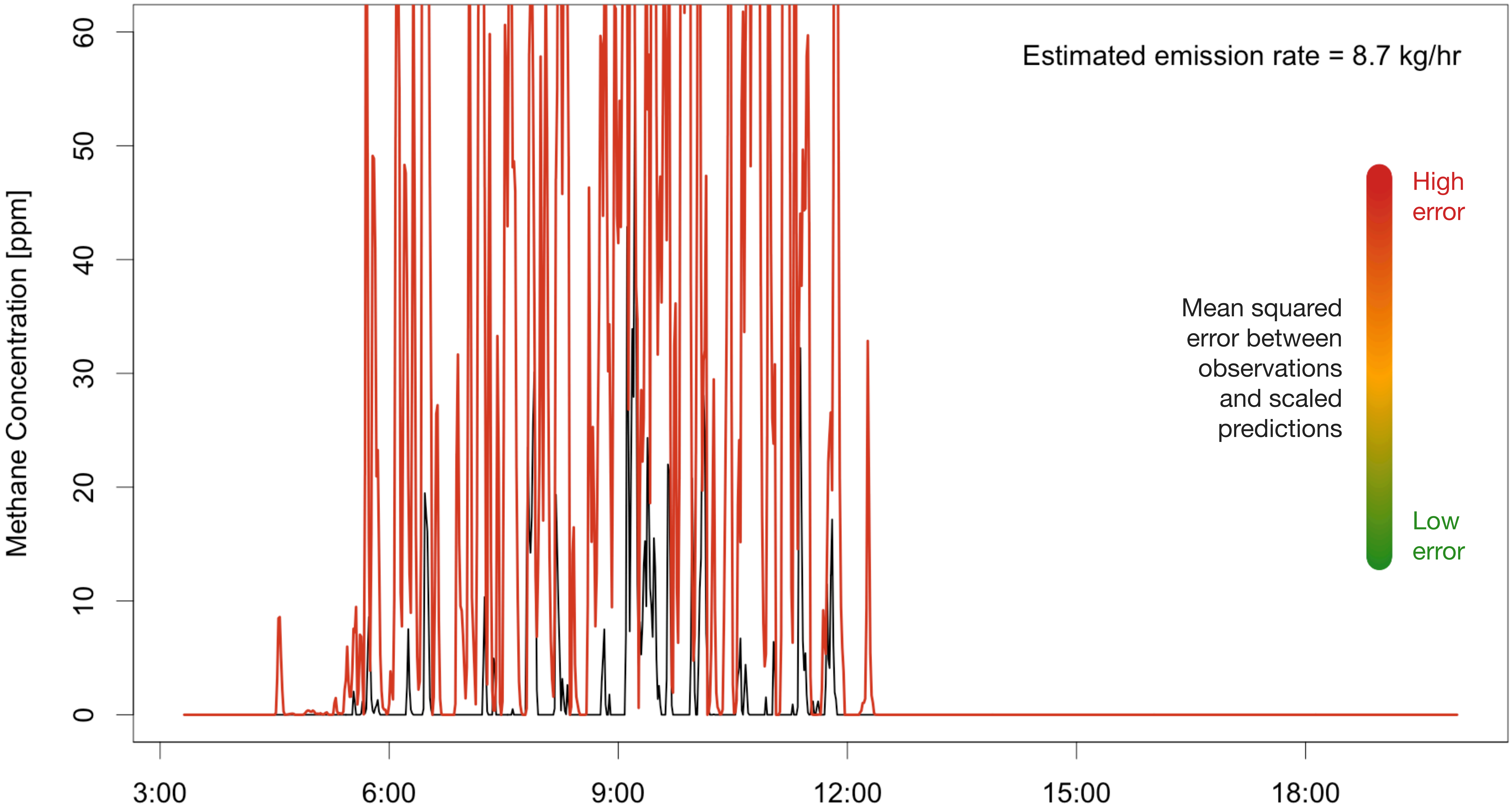
Concentration data

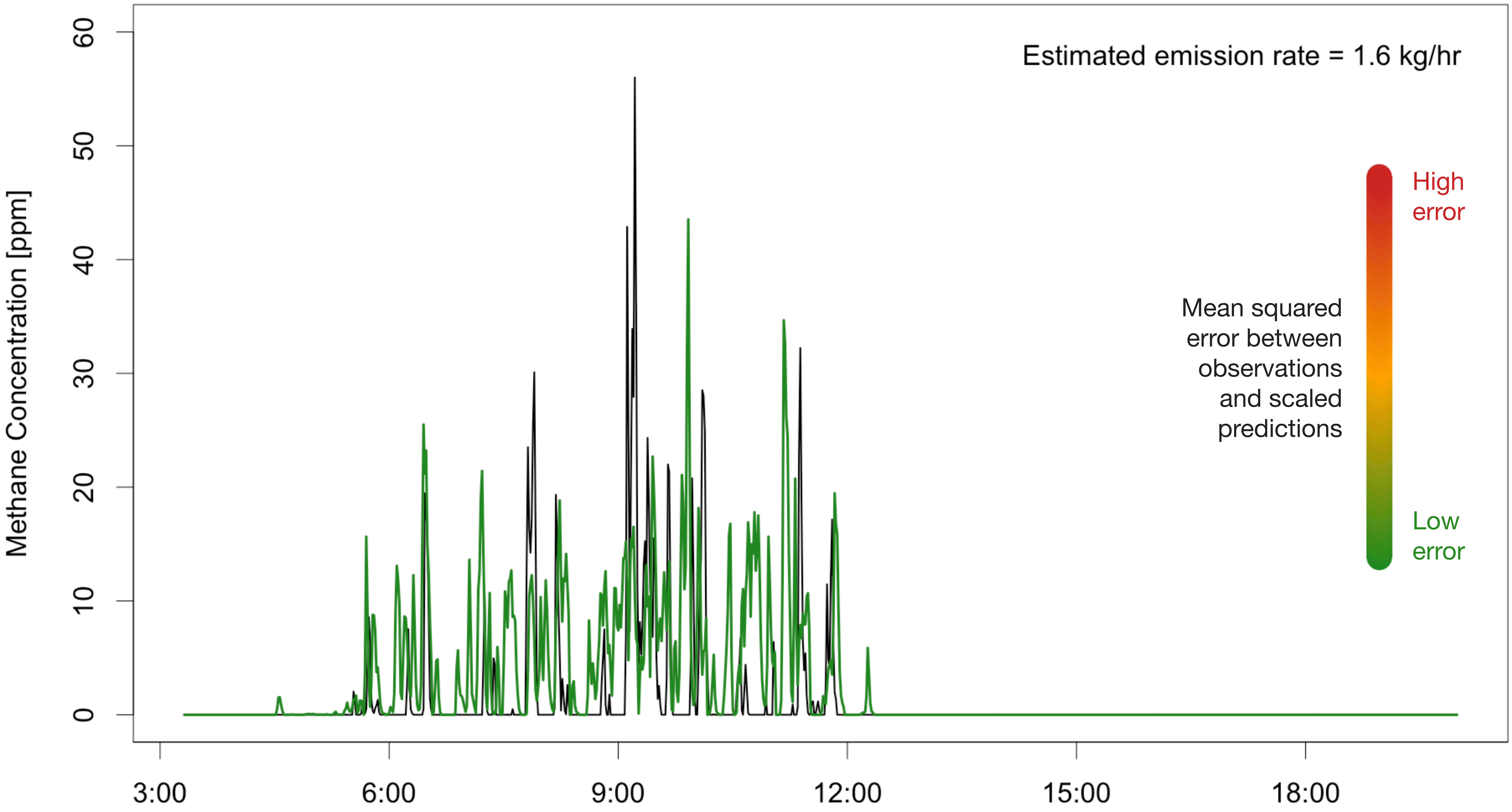
$$\hat{Q} = \underset{Q}{\operatorname{argmin}} \left\{ \frac{1}{n} \sum_{t=1}^{n} \big(d(x, y, z, t) - c(x, y, z, t, Q)\big)^2 \right\}$$

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
Mean squared error between observations and scaled predictions
High error
Low error
Methane Concentration [ppm]
0
10
20
30
40
50
60
3:00
6:00
9:00
12:00
15:00
18:00


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

→

STEP 2:
Simulation

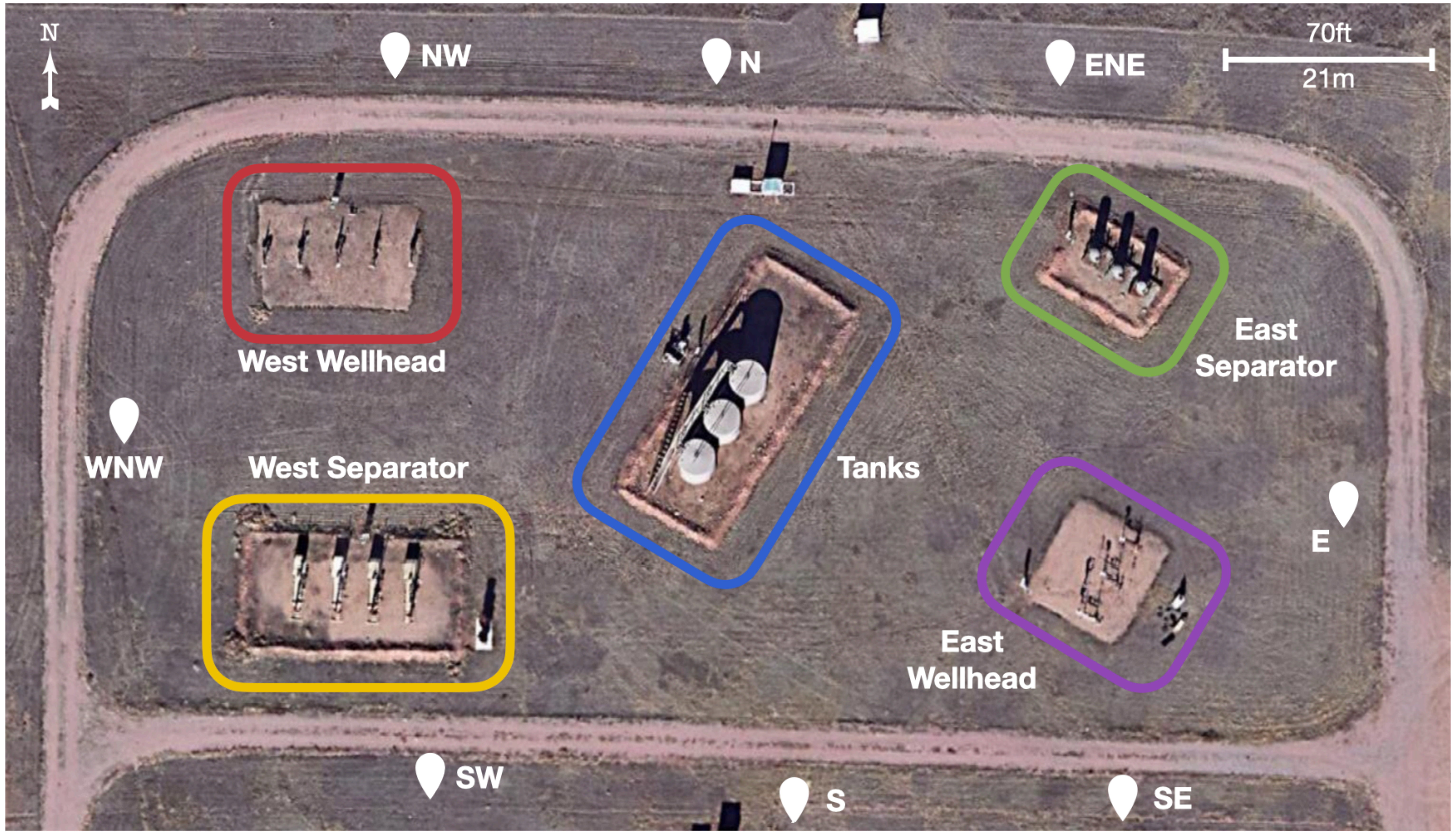
→

STEP 3:
Localization

→

STEP 4:
Quantification

# Evaluation on single-source controlled releases




Methane Emissions Technology Evaluation Center (METEC)

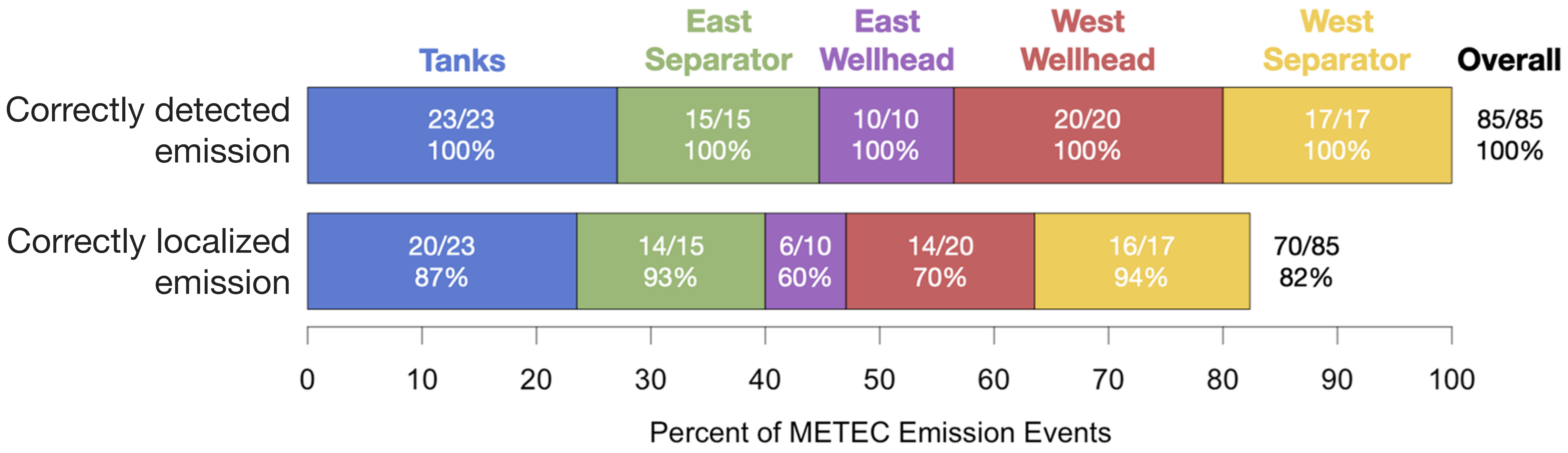
85 single-source controlled releases

Emission rates range from **0.2** to **6.4** kg/hr

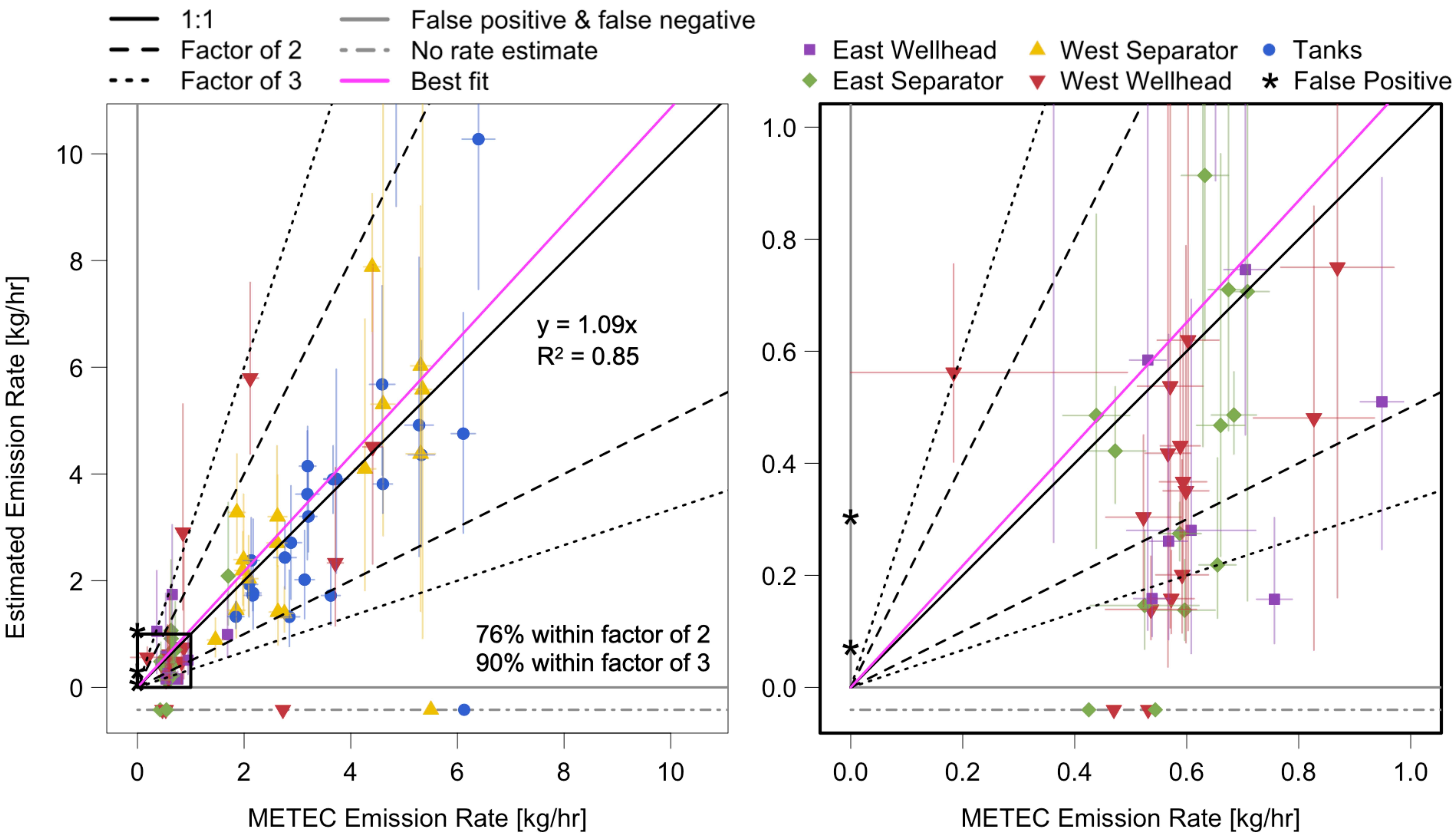
Emission durations range from **0.5** to **8.25** hours

# Evaluation on single-source controlled releases

Event-level false positive rate: 5.5%



# Evaluation on single-source controlled releases



Concluding thoughts:

- Framework is already being used by some CMS technology vendors.

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

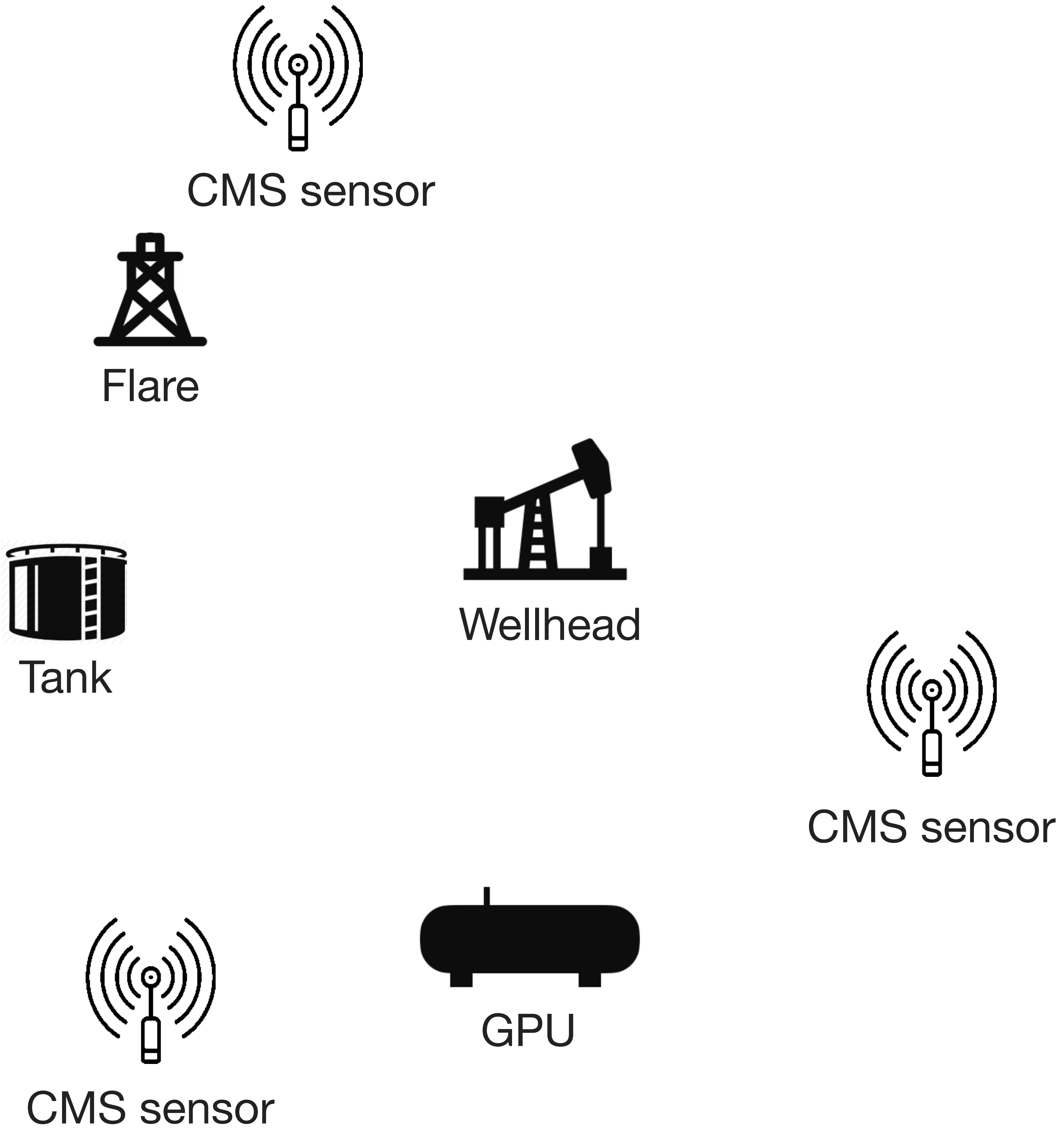
**William Daniels**, Meng Jia, Dorit Hammerling.
*Elementa: Science of the Anthropocene,* 12 (1), 00110, (2024).

Filling a critical need: a lightweight and fast Gaussian puff model implementation.

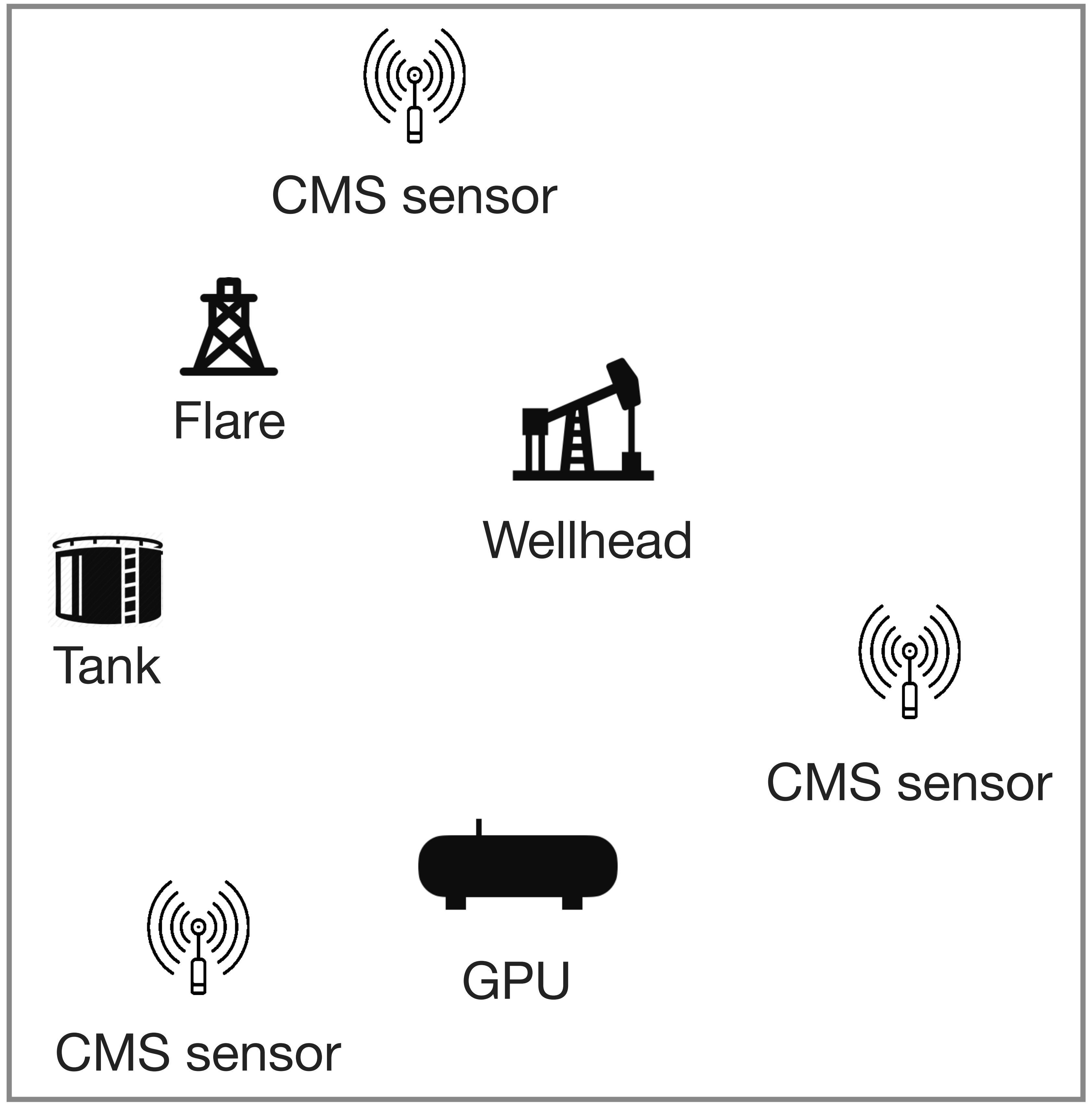
Meng Jia, Ryker Fish, **William Daniels**, Brennan Sprinkle, Dorit Hammerling.
*Scientific Reports*, in revision, (2024).

# Chapter 2:

## Reconciling aerial measurements and bottom-up inventories

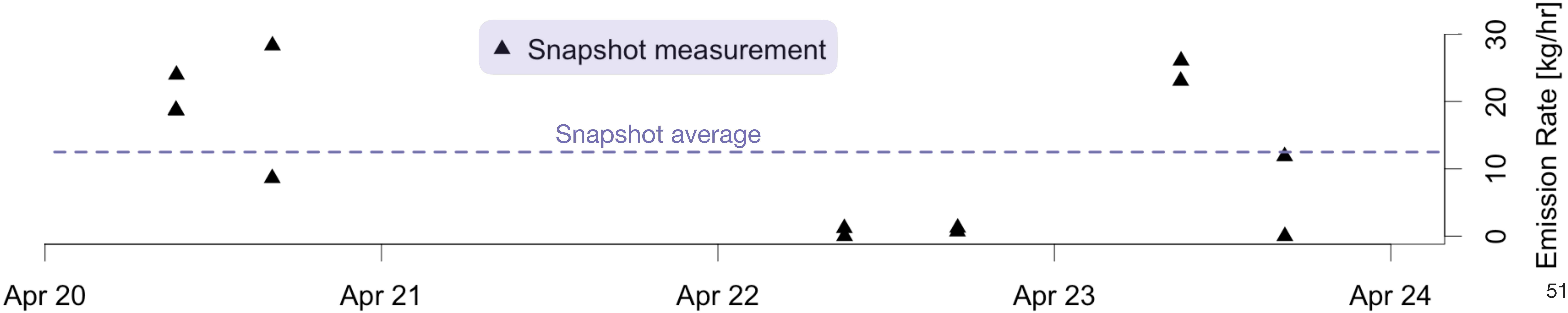


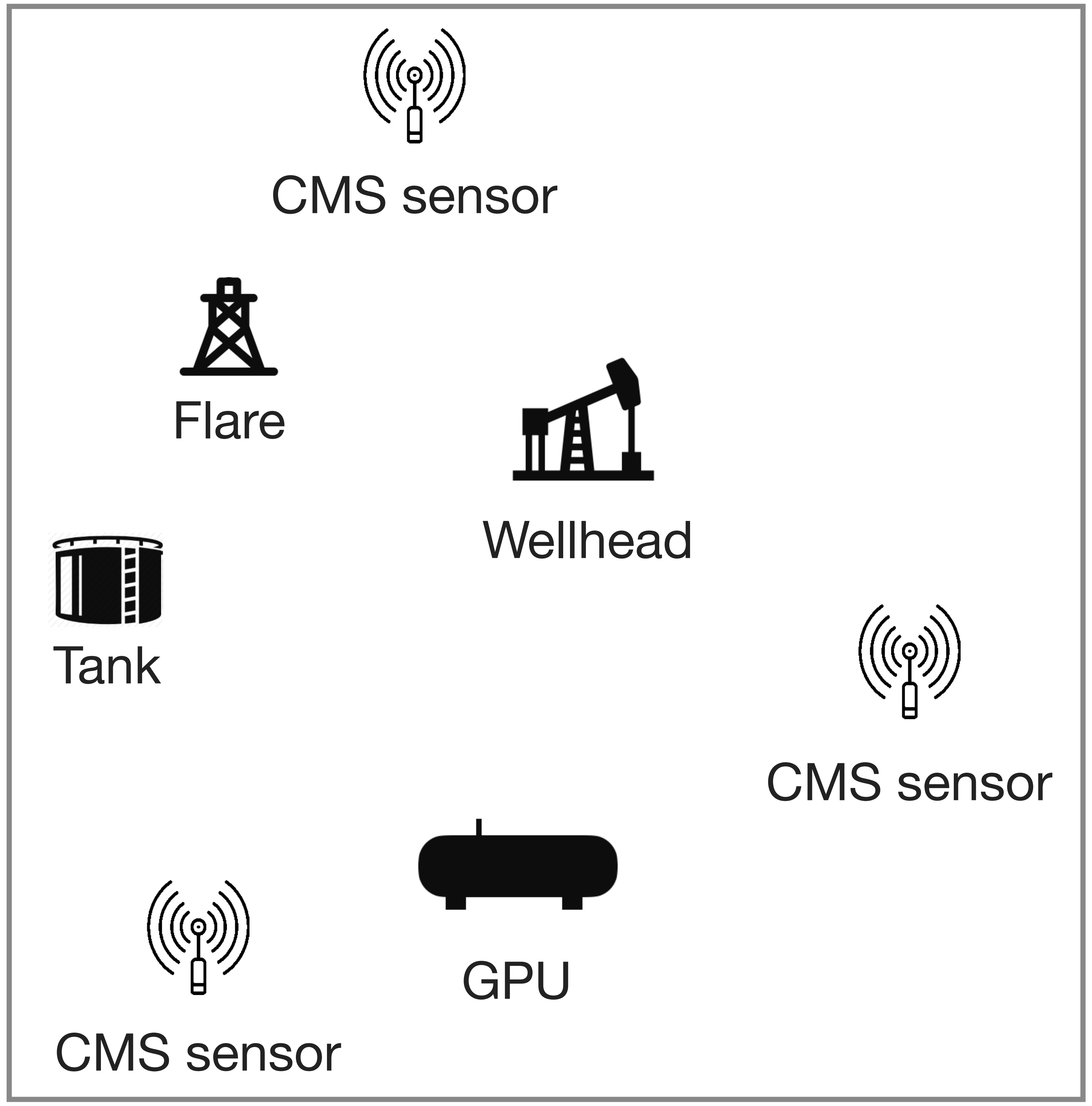

# Bottom-up top-down reconciliation case study




13 snapshot measurements over 4 days

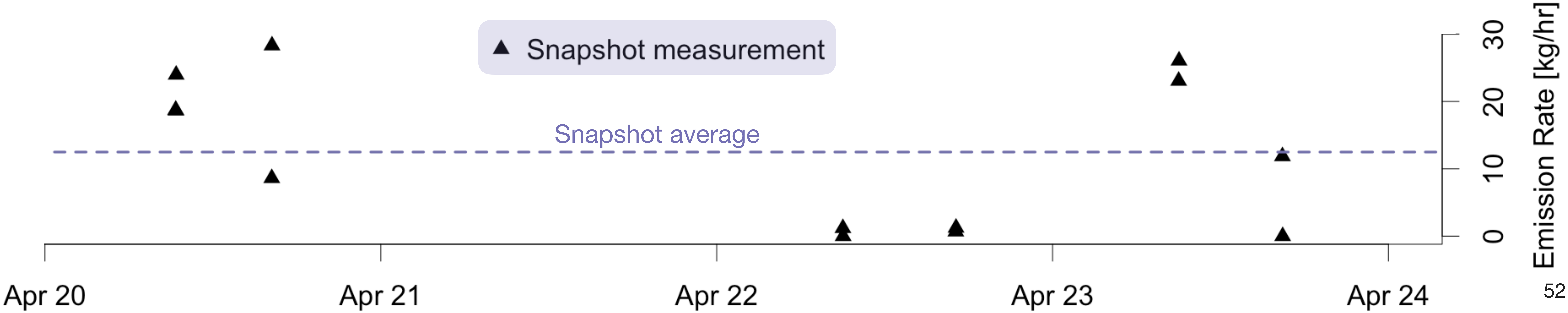
average = 12.5 kg/hr






13 snapshot measurements over 4 days → average = 12.5 kg/hr

Bottom-up inventory during snapshot measurements → 0.8 kg/hr

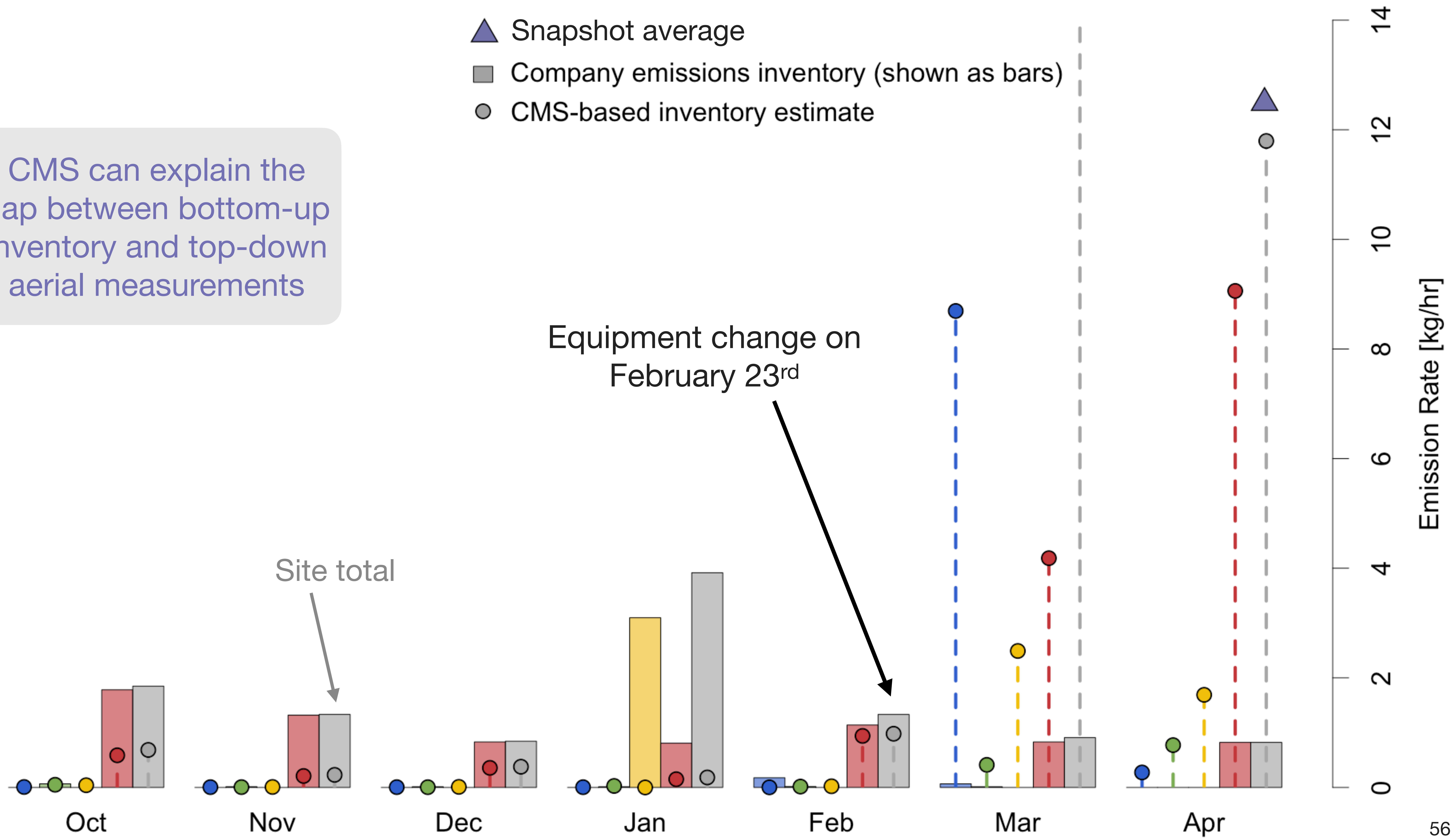



CMS sensor
Flare
Wellhead
Tank
CMS sensor
GPU
CMS sensor
Snapshot average
Company emissions inventory (shown as bars)
Average snapshot measurement
Site total
Emission Rate [kg/hr]
0
2
4
6
8
10
12
14
Oct
Nov
Dec
Jan
Feb
Mar
Apr

CMS sensor
Flare
Wellhead
Tank
CMS sensor
GPU
CMS sensor
Snapshot 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
14
Emission Rate [kg/hr]

CMS sensor
Flare
Wellhead
Tank
CMS sensor
GPU
CMS sensor
Snapshot 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
14
Emission Rate [kg/hr]

CMS can explain the gap between bottom-up inventory and top-down aerial measurements



# Chapter 2:

## Reconciling aerial measurements and bottom-up inventories

Concluding thoughts:

- Multi-scale measurements are complementary.
- Measurements at high temporal resolution are valuable, especially for site-level analysis.

Towards multiscale measurement-informed methane inventories: reconciling bottom-up site-level inventories with top-down measurements using continuous monitoring systems.

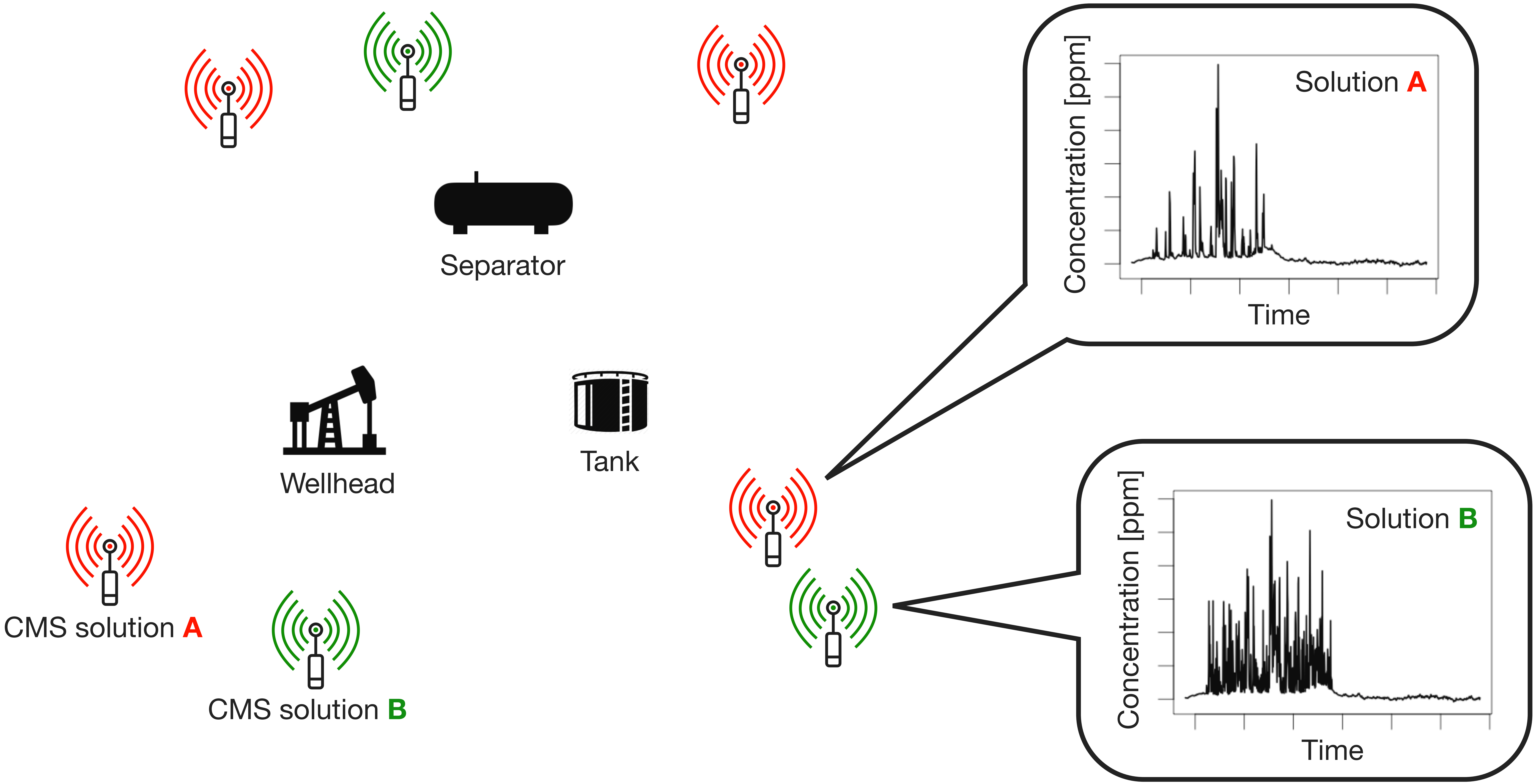
**William Daniels**, Jiayang (Lyra) Wang, Arvind Ravikumar, Matthew Harrison, Selina Roman-White, Fiji George, Dorit Hammerling. *Environmental Science and Technology,* 57(32), 11823-11833, (2023).

Multi-scale methane measurements at oil and gas facilities reveal necessary framework for improved emissions accounting.

Jiayang (Lyra) Wang, **William Daniels**, Dorit Hammerling, Matthew Harrison, Kaylyn Burmaster, Fiji George, Arvind Ravikumar. *Environmental Science and Technology,* 56(20), 14743-14752, (2022).

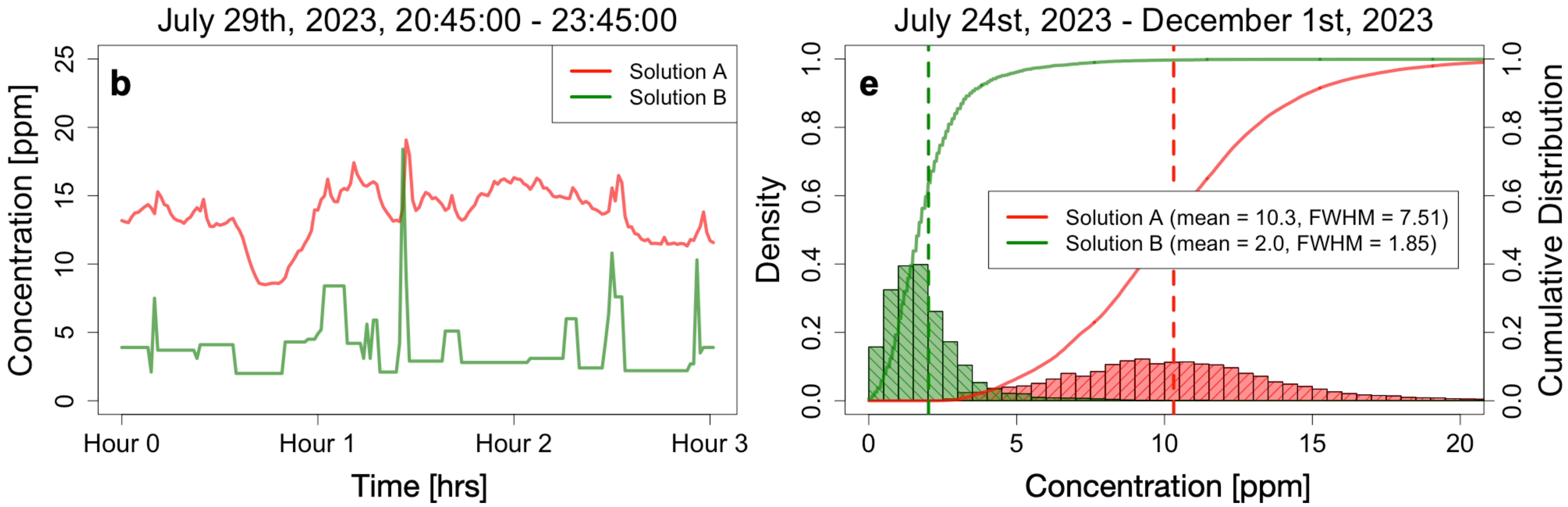
# Chapter 3:

## Intercomparison of CMS solutions

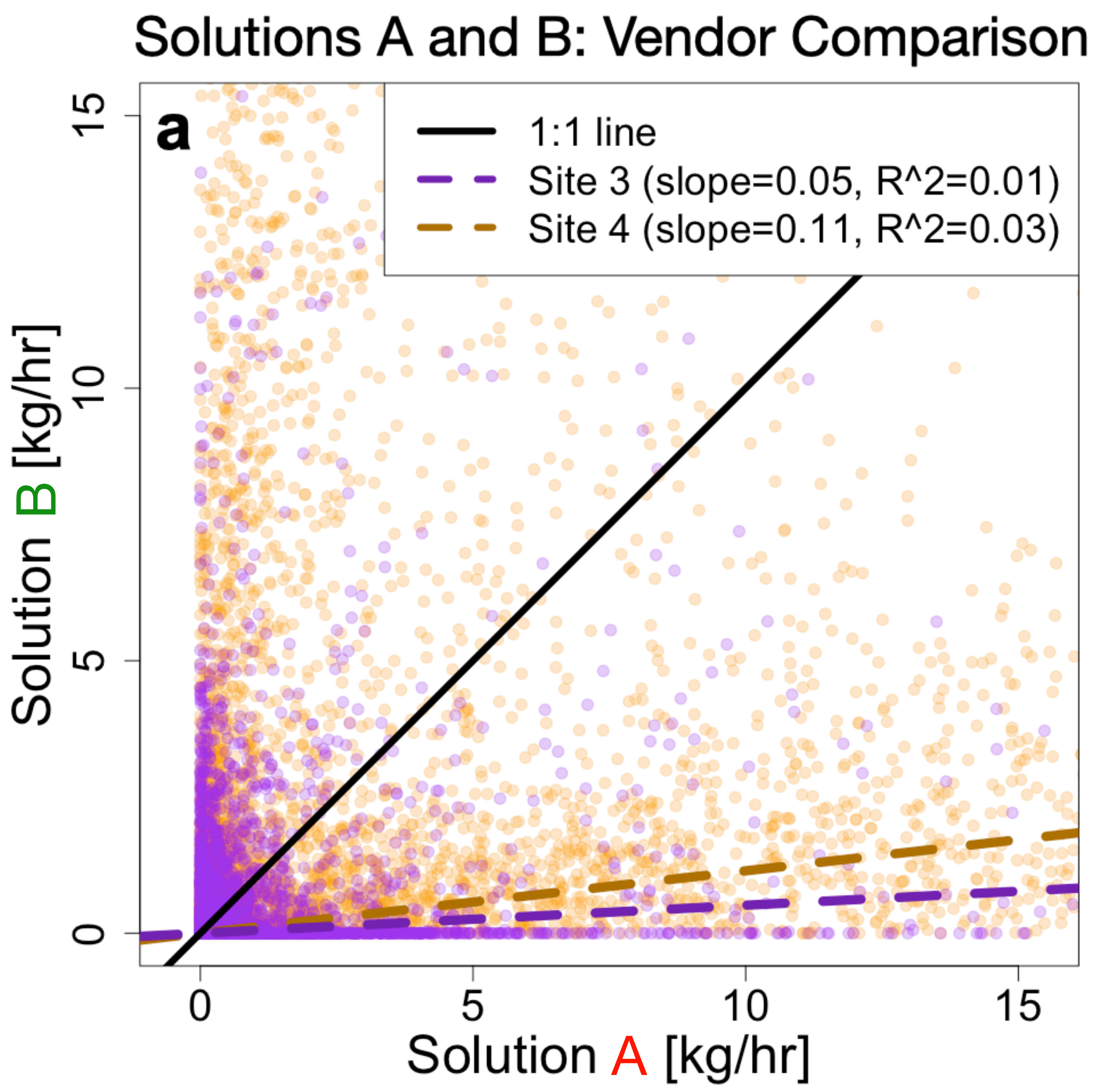



# Sensor intercomparison setup

# Finding #1: Raw concentration data different between co-located sensors

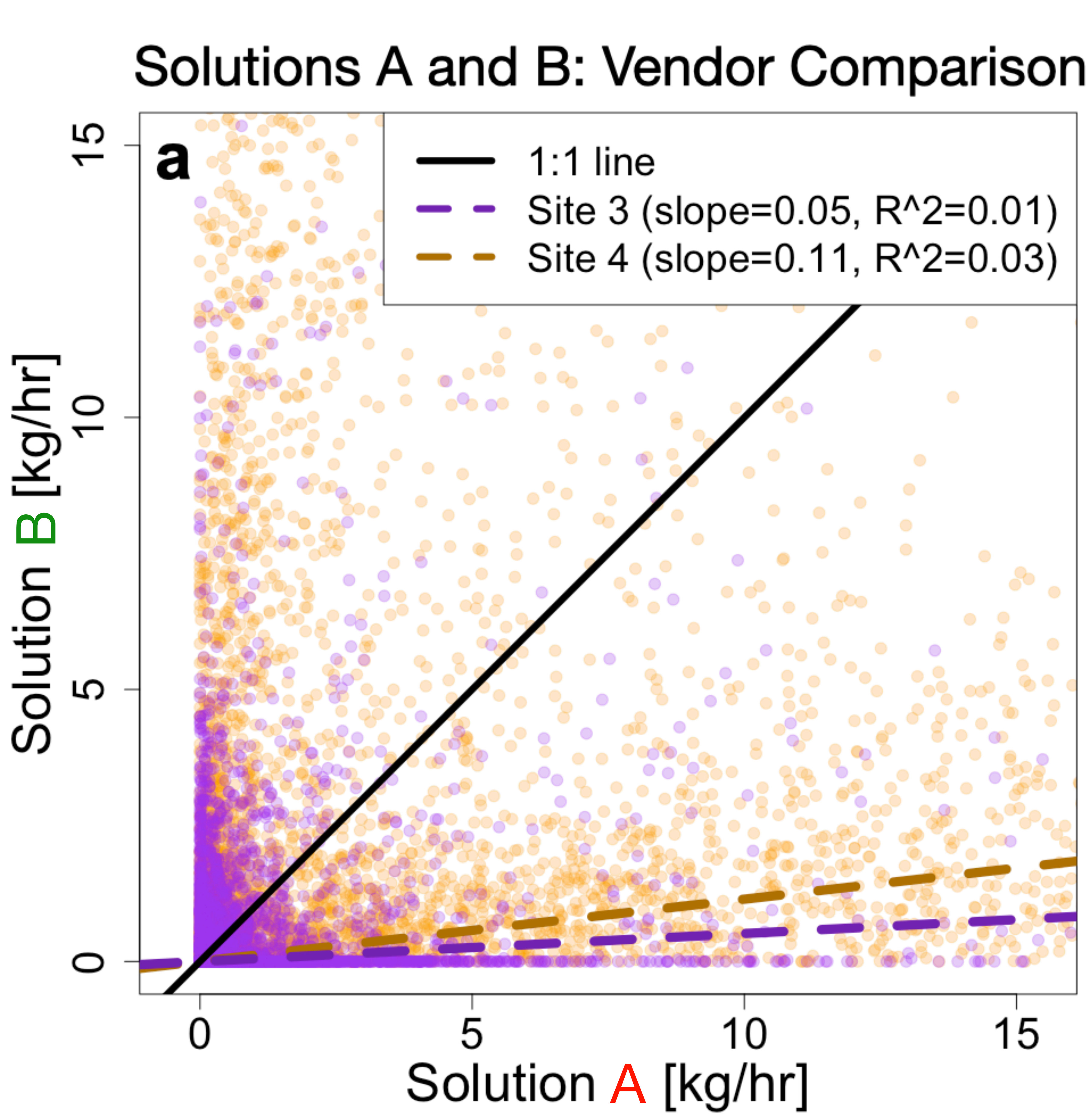


# Finding #2: Quantification estimates vary dramatically at the 30-minute scale

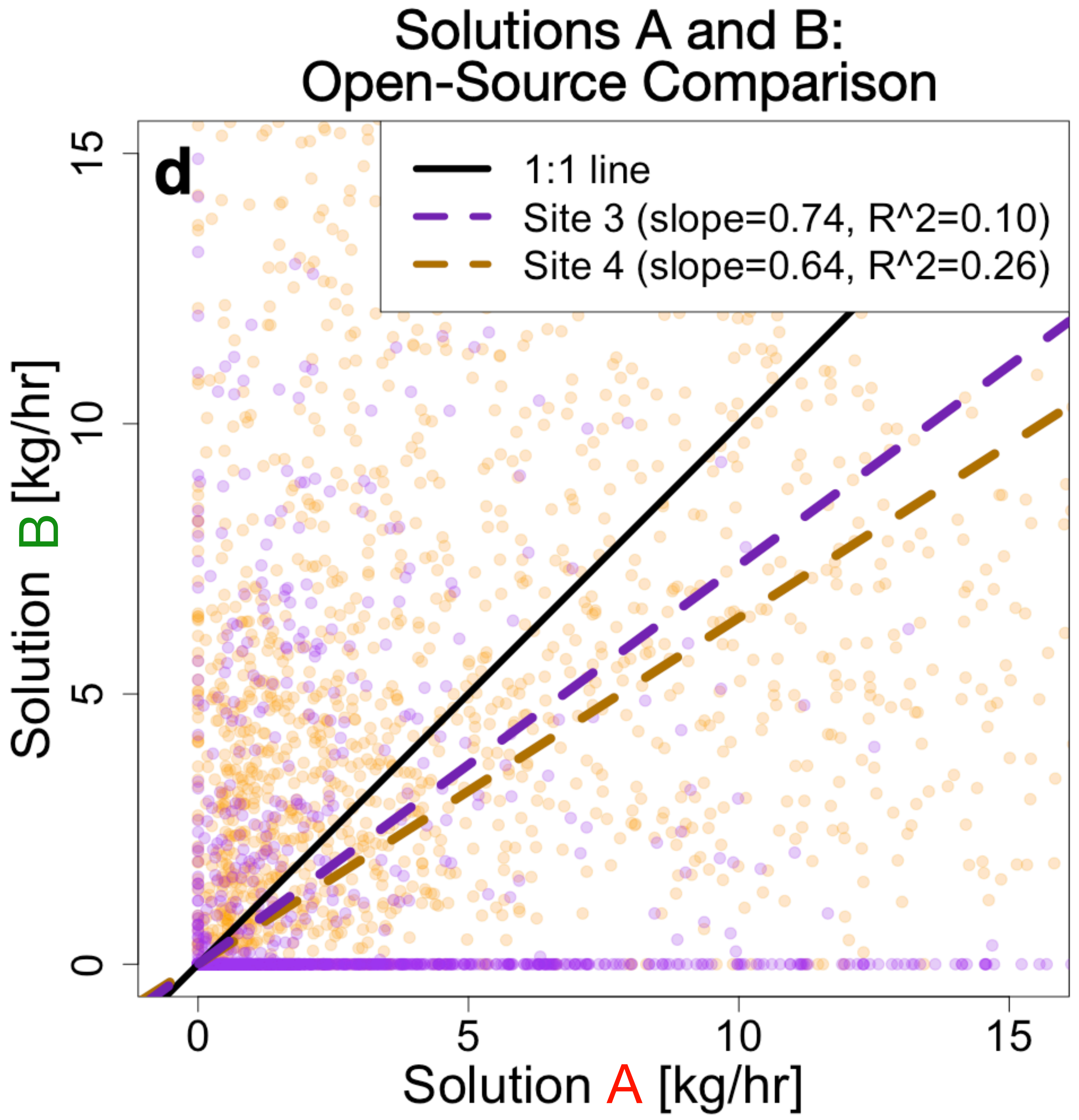



Emission rate estimates
from the **CMS vendors**

# Finding #2: Quantification estimates vary dramatically at the 30-minute scale

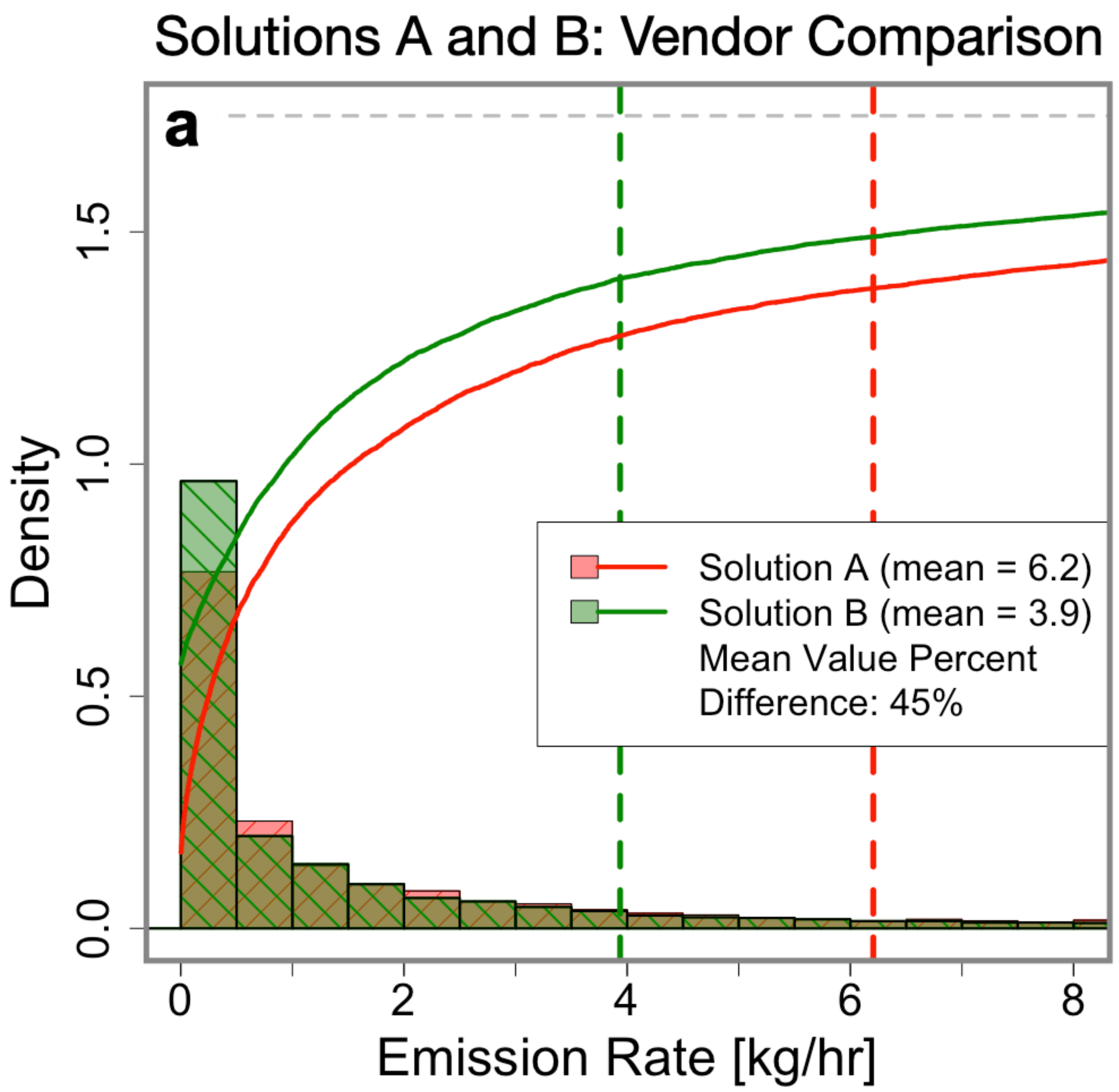



Emission rate estimates
from the **CMS vendors**



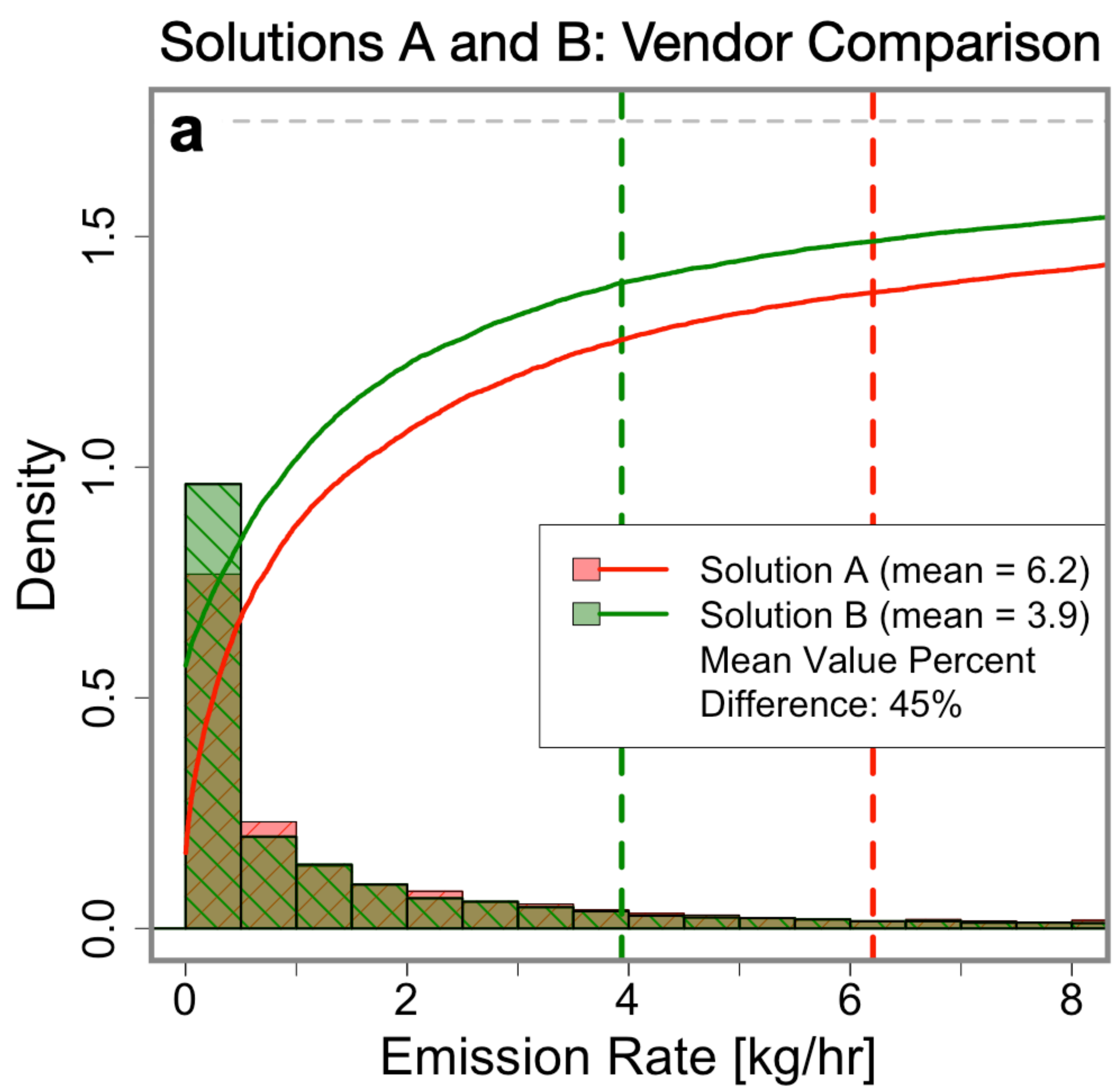

Emission rate estimates
from the **DLQ algorithm**

# Finding #3: Quantification estimates begin to align at the month-scale

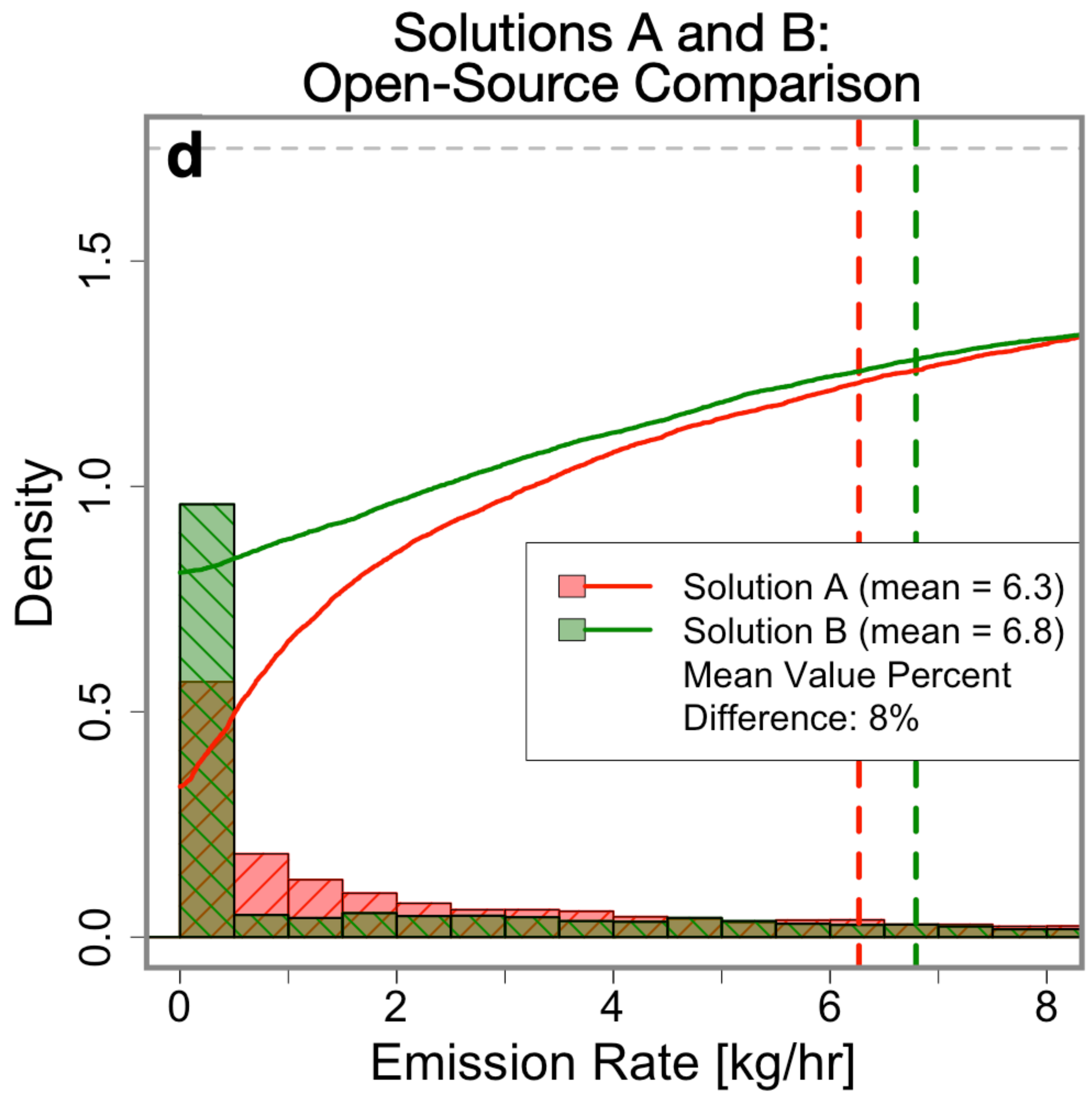



Emission rate estimates
from the **CMS vendors**

# Finding #3: Quantification estimates begin to align at the month-scale

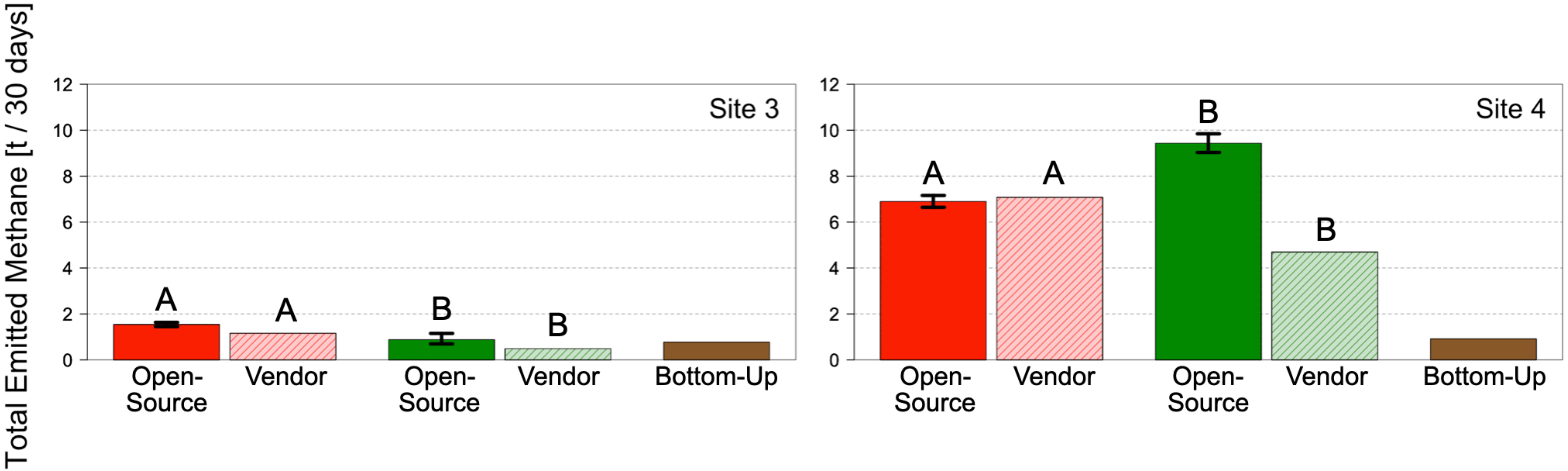



Emission rate estimates
from the **CMS vendors**




Emission rate estimates
from the **DLQ algorithm**

# Finding #4: Similar sites do not necessarily have similar emissions



# Chapter 3:

## Intercomparison of CMS solutions

Concluding thoughts:

- Important to assess CMA performance in the field in addition to controlled releases.
- Current CMS solutions may be more useful when data is aggregated at hourly or monthly scales.

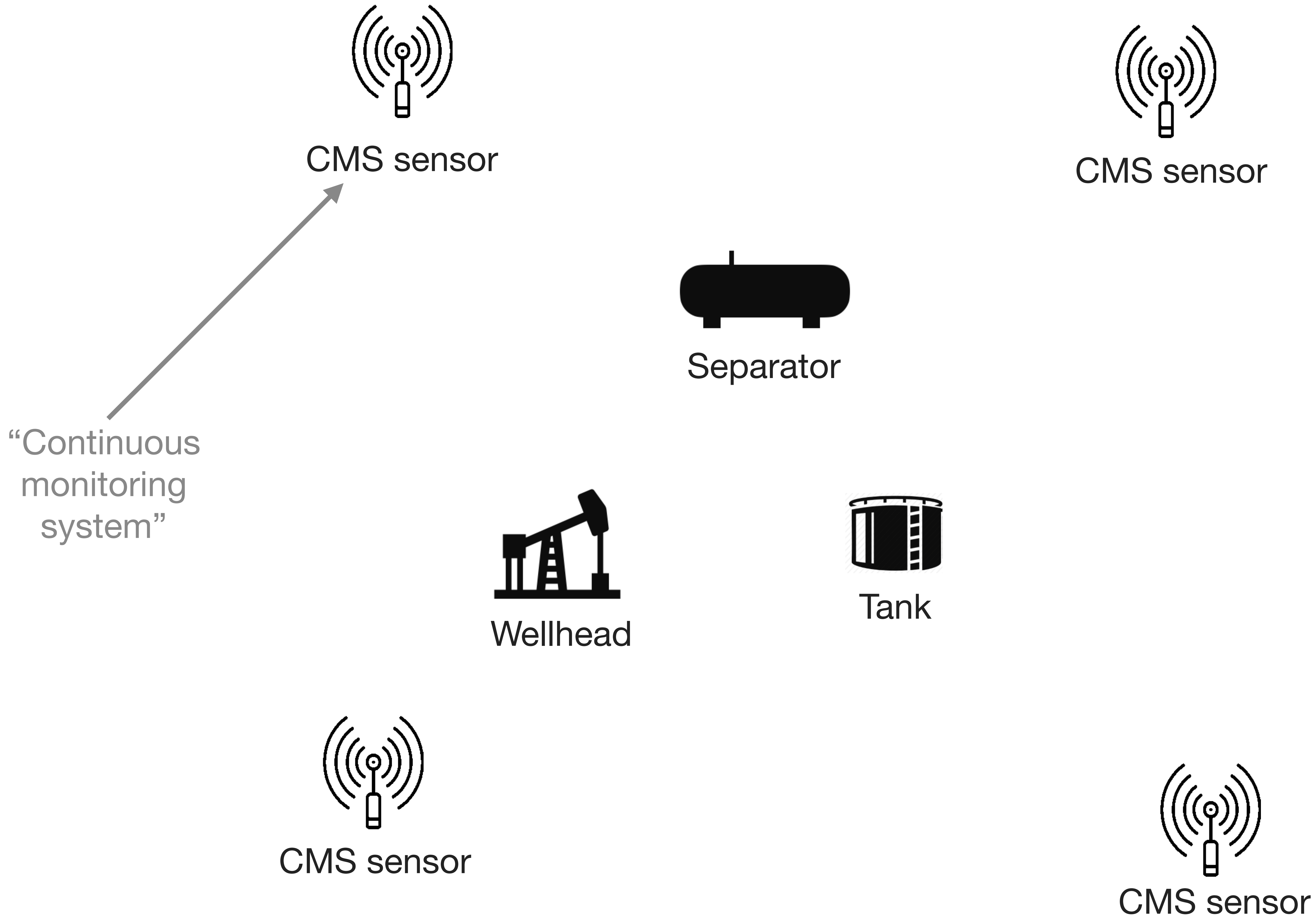
Intercomparison of three continuous monitoring systems on operating oil and gas sites.

**William Daniels***, Spencer Kidd*, Lydia (Shuting) Yang, Shannon Stokes, Arvind Ravikumar, Dorit Hammerling.

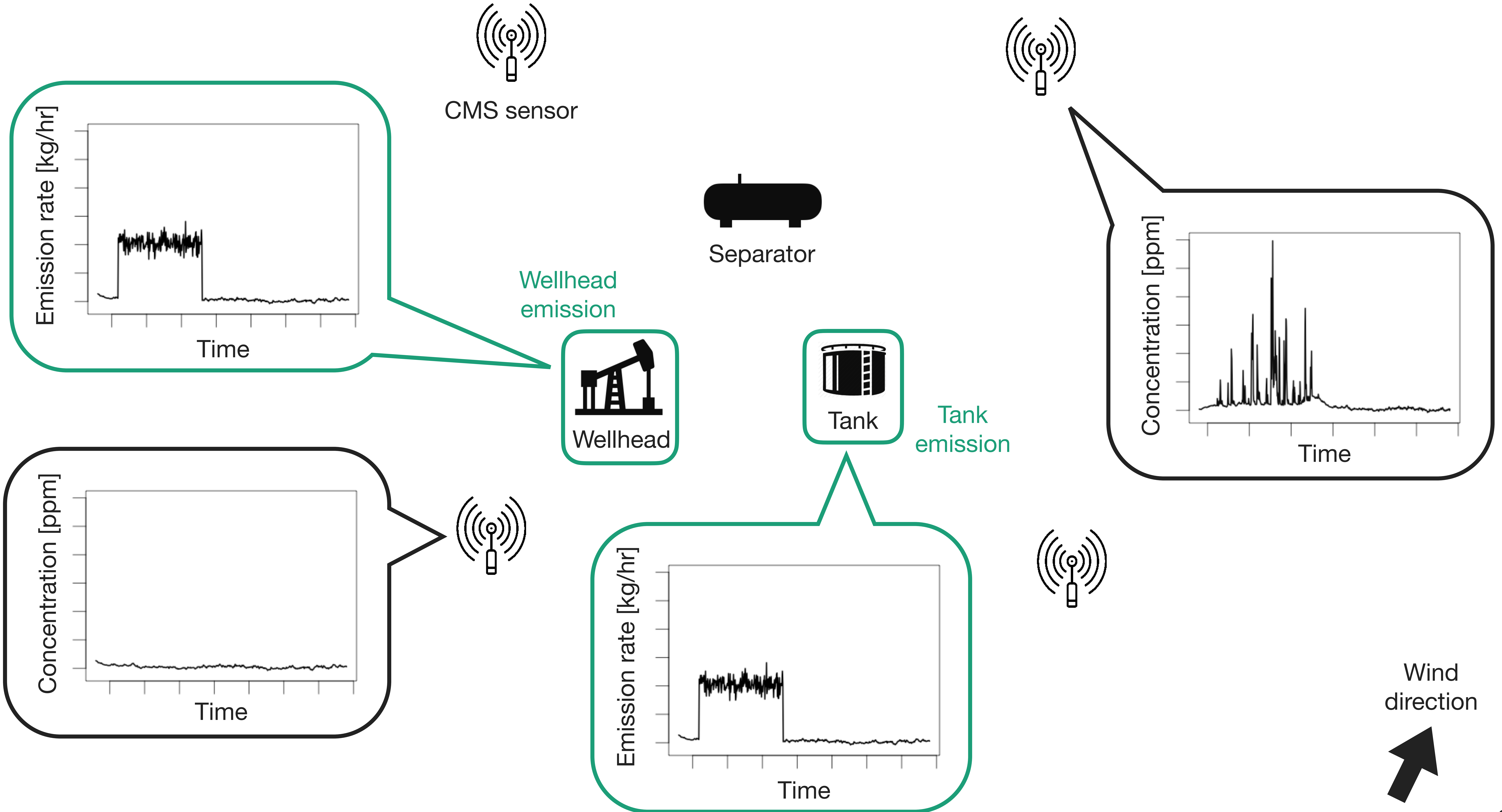
*ACS ES&T Air, in press,* (2024).

# Chapter 4:

## Multi-source emission detection, localization, and quantification




# The multi-source continuous monitoring inverse problem



CMS sensor
Emission rate [kg/hr]
Time
Separator
Wellhead emission
Wellhead
Tank
Tank emission
Concentration [ppm]
Time
Concentration [ppm]
Time
Emission rate [kg/hr]
Time
Wind direction

# Model hierarchy

n = number of observations
p = number of potential sources

Assume a multiple linear regression model at the data level

$$y = X\beta + \epsilon$$

$$y \equiv \{y_1, \ldots, y_n\}, \beta \equiv \{\beta_1, \ldots, \beta_p\}, X \in \mathbb{R}^{n \times p}$$

Concentration observations from CMS sensors

Emission rates for each source

Simulated concentrations from forward model, with each column assuming a different source

# Model hierarchy

n = number of observations
p = number of potential sources

Assume a multiple linear regression model at the data level

$$y = X\beta + \epsilon$$

$$y \equiv \{y_1, \ldots, y_n\}, \beta \equiv \{\beta_1, \ldots, \beta_p\}, X \in \mathbb{R}^{n \times p}$$

Assume that the errors $\epsilon \equiv \{\epsilon_1, \ldots, \epsilon_n\}$ are are identically distributed, Gaussian, and autocorrelated such that

$$\epsilon \sim N(0, \sigma^2 R)$$

# Model hierarchy

n = number of observations
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Assume a multiple linear regression model at the data level

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Assume that the errors $\epsilon \equiv \{\epsilon_1, \ldots, \epsilon_n\}$ are are identically distributed, Gaussian, and autocorrelated such that

$$\epsilon \sim N(0, \sigma^2 R)$$

Let the errors follow an AR(1) process such that

$$\epsilon_i = r\epsilon_{i-1} + w$$

Autocorrelation coefficient

Gaussian white noise

# Model hierarchy

n = number of observations
p = number of potential sources

Assume a multiple linear regression model at the data level

$$y = X\beta + \epsilon$$

$$y \equiv \{y_1, \ldots, y_n\}, \beta \equiv \{\beta_1, \ldots, \beta_p\}, X \in \mathbb{R}^{n \times p}$$

Assume that the errors $\epsilon \equiv \{\epsilon_1, \ldots, \epsilon_n\}$ are are identically distributed, Gaussian, and autocorrelated such that

$$\epsilon \sim N(0, \sigma^2 R)$$

Let the errors follow an AR(1) process such that

$$\epsilon_i = r\epsilon_{i-1} + w$$

This gives us: $y \sim N(X\beta, \sigma^2 R)$

# Model hierarchy

n = number of observations
p = number of potential sources

Given an AR(1) process for $\epsilon$, the correlation matrix is

$$R = \begin{bmatrix} 1 & r & r^2 & \dots & r^{n-1} \\ r & 1 & r & \dots & \vdots \\ r^2 & r & 1 & \dots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ r^{n-1} & \dots & \dots & \dots & 1 \end{bmatrix}$$

# Model hierarchy

n = number of observations
p = number of potential sources

Given an AR(1) process for $\epsilon$, the correlation matrix is

$$R = \begin{bmatrix} 1 & r & r^2 & \dots & r^{n-1} \\ r & 1 & r & \dots & \vdots \\ r^2 & r & 1 & \dots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ r^{n-1} & \dots & \dots & \dots & 1 \end{bmatrix}$$

which has closed form expressions for the inverse and determinant:

$$R^{-1} = \frac{1}{(1 - r^2)} \begin{bmatrix} 1 & -r & 0 & \dots & 0 \\ -r & 1 + r^2 & -r & \dots & \vdots \\ 0 & -r & 1 + r^2 & \dots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & \dots & \dots & 1 \end{bmatrix}$$

and

$$|R| = (1 - r^2)^{n-1}$$

# Model hierarchy

n = number of observations
p = number of potential sources

Data-level: $y = X\beta + \epsilon$

$\epsilon \sim N(0, \sigma^2 R)$

The remainder of the hierarchy takes the following form

Spike-and-slab prior allows samples to be identically zero

$$\beta_i \sim \begin{cases} 0, & z_i = 0 \\ \text{Exp}(\tau_i^2 \sigma^2), & z_i = 1 \end{cases}$$

"Slab" component is non-negative

Proportion of samples where $z_i = 1$ gives posterior probability that source $i$ is emitting

$$z_i \sim \text{Bernoulli}(\theta_i)$$

$$\theta_i \sim \text{Beta}(a_i, b_i)$$

$$\tau_i^2 \sim \text{Inv-Gamma}(c_i, d_i)$$

$$\sigma^2 \sim \text{Inv-Gamma}(\nu/2,\ \nu/2)$$

$$\nu \sim \text{Inv-Gamma}(\alpha_1, \alpha_2)$$

$$r \sim \text{Uniform}(0, 1)$$

$a_i$, $b_i$, $c_i$, $d_i$ can contain operator insight

# Model hierarchy

$$\beta_i \sim \begin{cases} 0, & z_i = 0 \\ \mathrm{Exp}(\tau_i^2 \sigma^2), & z_i = 1 \end{cases}$$

$$z_i \sim \mathrm{Bernoulli}(\theta_i)$$

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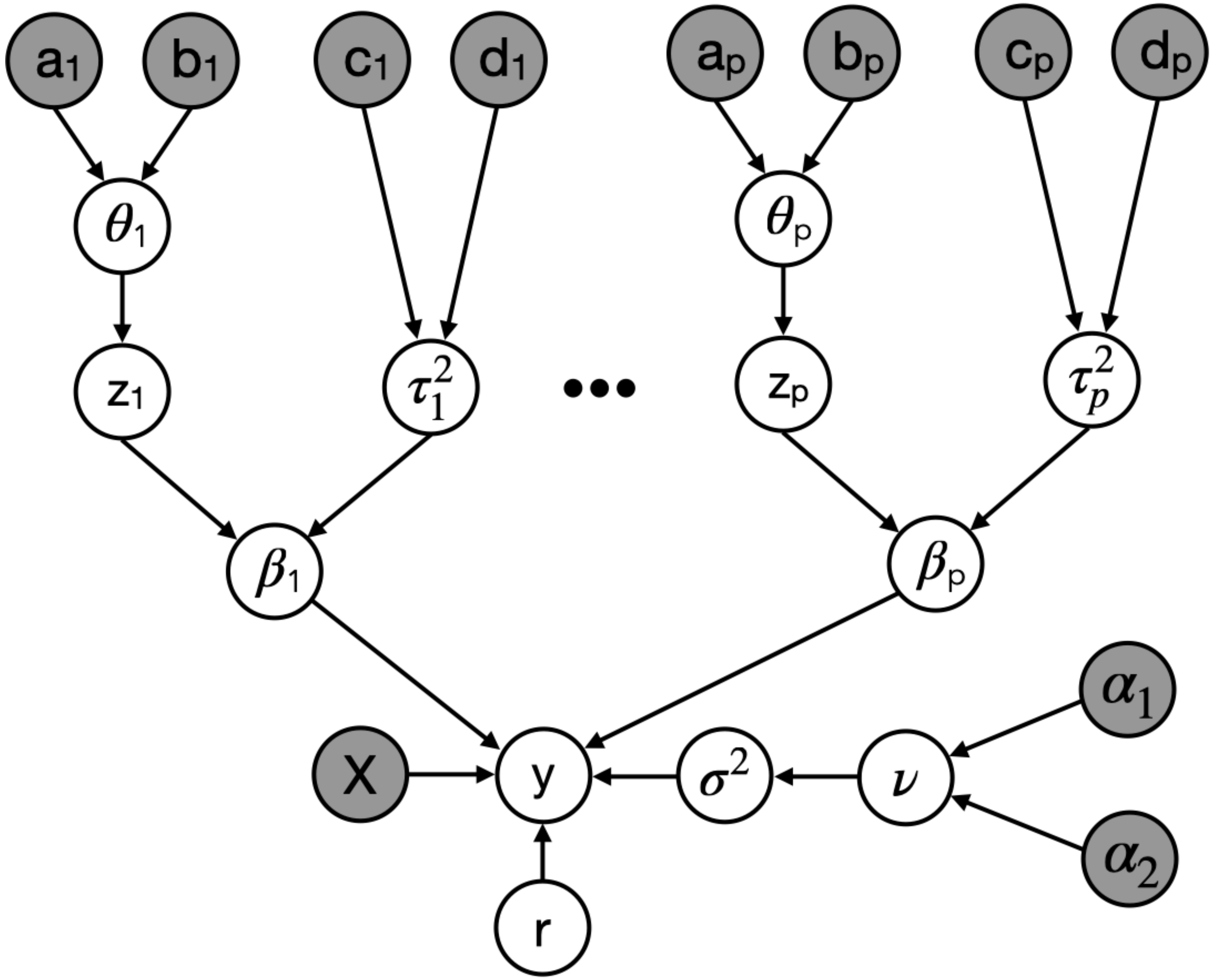


# Sampling from the posterior

We can derive Gibbs updates for all parameters except $\nu$.

$$\theta_i|\xi \sim \text{Beta}(z_i + a_i, 1 - z_i + b_i)$$

$$\sigma^2|\xi \sim \text{Inv-Gamma}\left(\frac{\nu}{2} + \frac{n}{2}, \frac{\nu}{2} + \frac{1}{2}(y - X\beta)^T R^{-1}(y - X\beta)\right)$$

$$r|\xi \sim \begin{cases} \mathcal{N}(X\beta, \sigma^2 R) & 0 < r < 1 \\ 0 & \text{otherwise} \end{cases}$$

$$\tau_i^2|\xi \sim \text{Inv-Gamma}\left(z_i + c_i, \frac{\beta_i}{\sigma^2} + d_i\right)$$

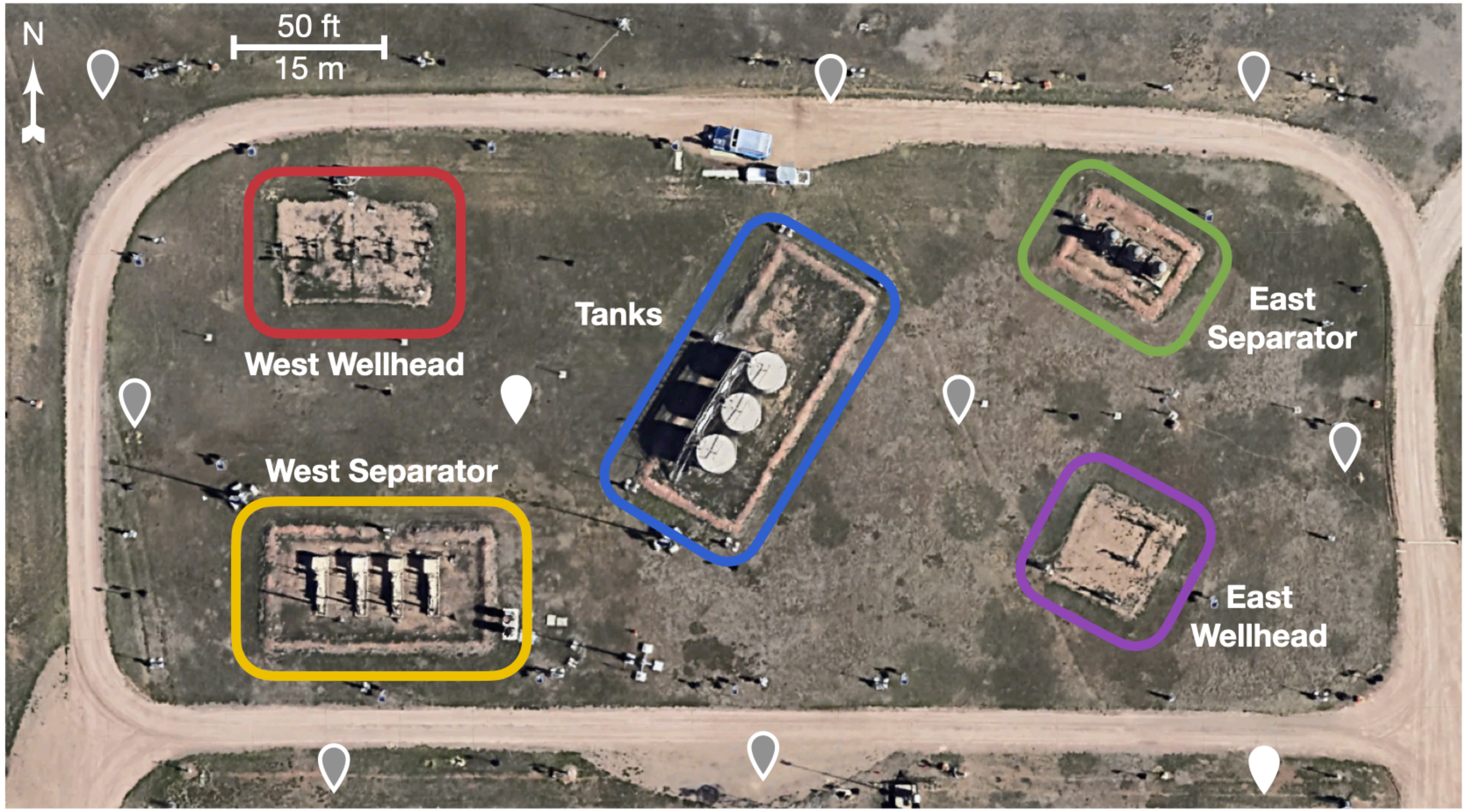
$$\beta_i|\xi \sim \begin{cases} 0 & z_i = 0 \\ \mathcal{N}\left(\left(\frac{X^T R^{-1} X}{\sigma^2}\right)^{-1}\left(\frac{X^T R^{-1} y}{\sigma^2} - \frac{e_i}{\tau_i^2 \sigma^2}\right), \left(\frac{X^T R^{-1} X}{\sigma^2}\right)^{-1}\right) & z_i = 1 \end{cases}$$

$$z_i|\xi \sim \text{Bernoulli}\left(1 - \frac{1 - \theta_i}{(1 - \theta_i) + \theta_i\left(\frac{1}{\tau_i^2 \sigma^2}\right)\exp\left(\frac{\left(\sum_{j=1}^n (w_j X_{j,i}^* + w_j^* X_{j,i}) - \frac{2}{\tau_i^2}\right)^2}{4\sigma^2 \sum_{j=1}^n X_{j,i} X_{j,i}^*}\right)\left(\frac{2\sigma^2 \pi}{\sum_{j=1}^n X_{j,i} X_{j,i}^*}\right)^{1/2}\left(\frac{1}{2}\right)}\right)$$

$$\nu|\xi \sim \text{?} \quad \text{(Use a Metropolis–Hastings step)}$$

Iterative samples from each full conditional gives you samples from the joint posterior!

# Model evaluation on multi-source controlled release data



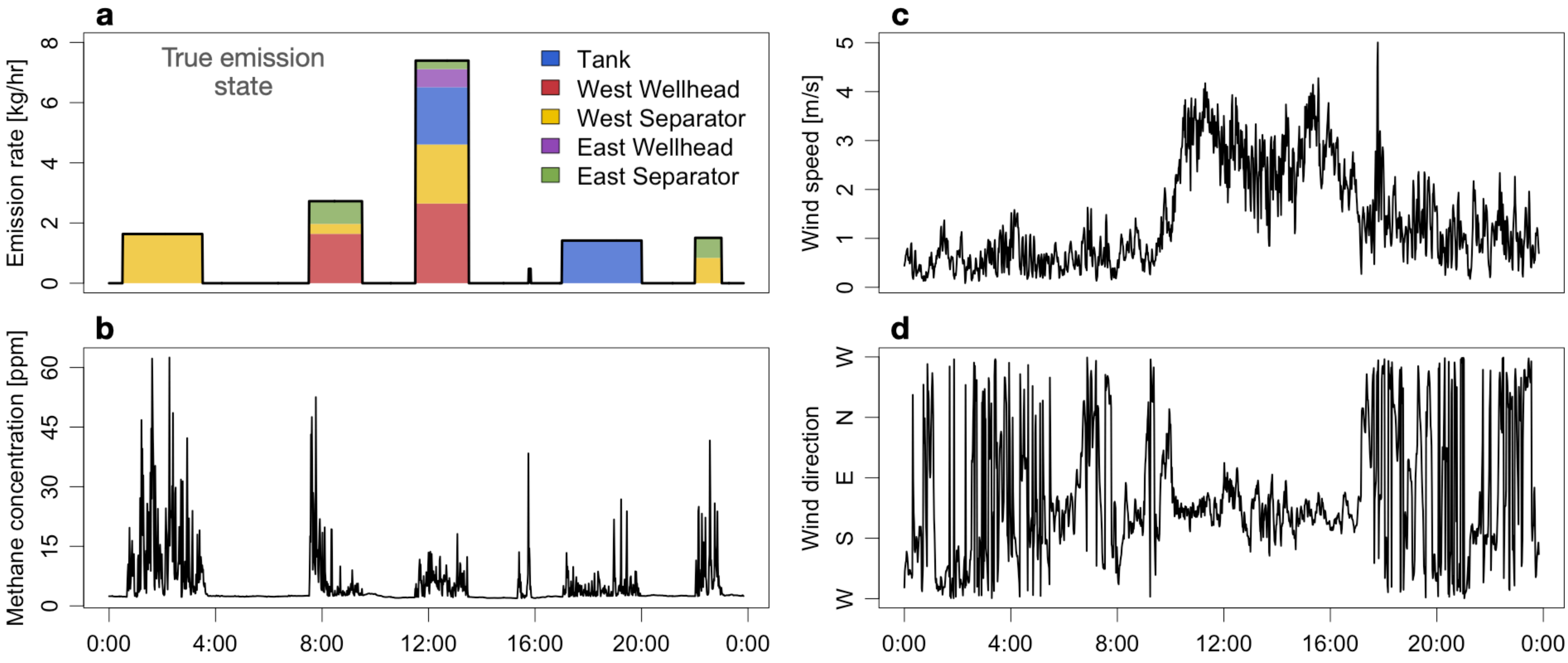

Methane Emissions Technology Evaluation Center (METEC)

337 controlled releases:
- **99** (29%) single-source
- **238** (71%) multi-source

Emission rates range from **0.08** to **7.2** kg/hr

Emission durations range from **0.5** to **8** hours

# Model evaluation on multi-source controlled release data



# Simulation study

## Vary the degree of autocorrelation

For each controlled release, replace actual concentration observations with

$$\tilde{y} = X\beta_T + \tilde{\epsilon}$$

where $\beta_T$ are the true emission rates and are errors that follow an AR(1) process.

# Simulation study

## Vary the degree of autocorrelation

For each controlled release, replace actual concentration observations with

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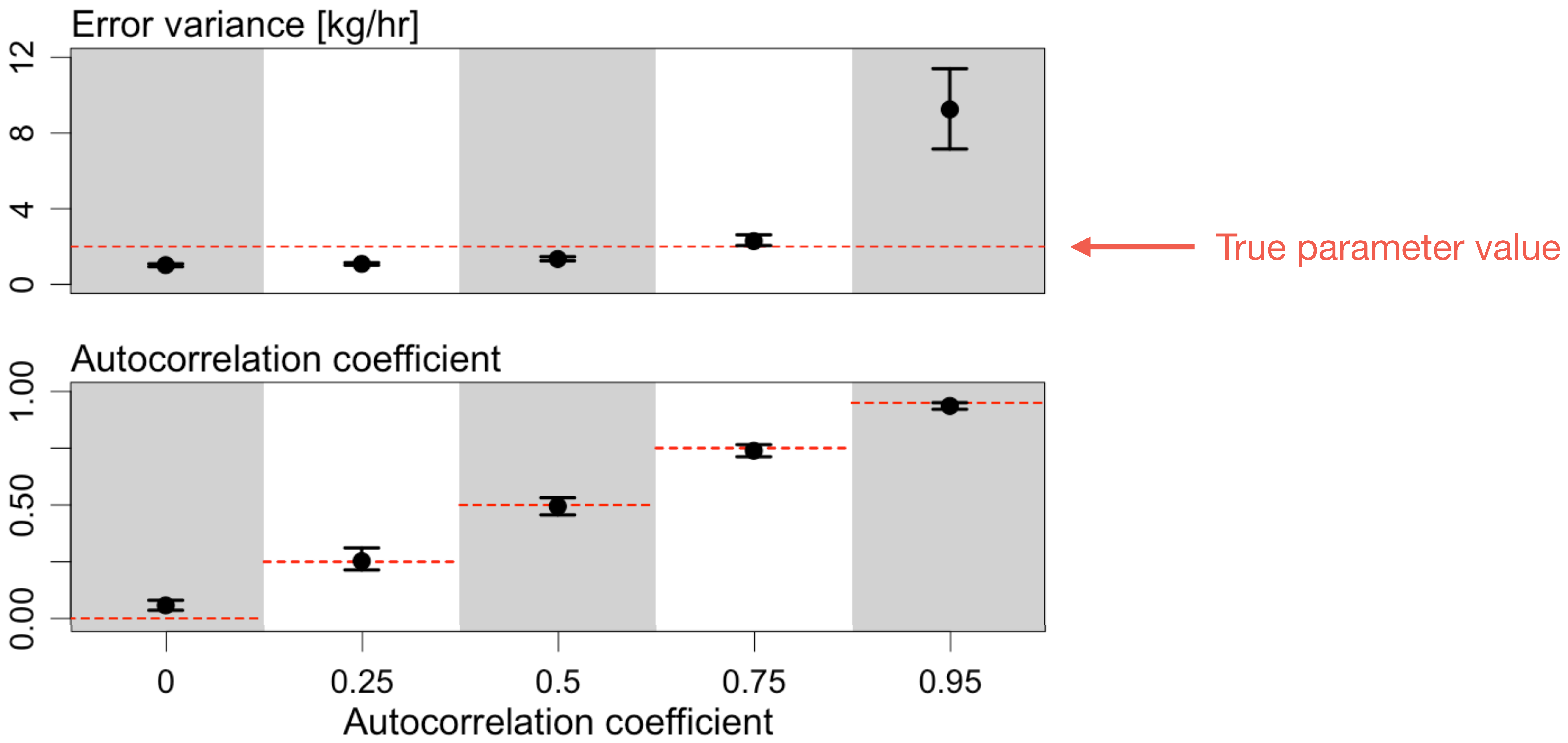

# Simulation study

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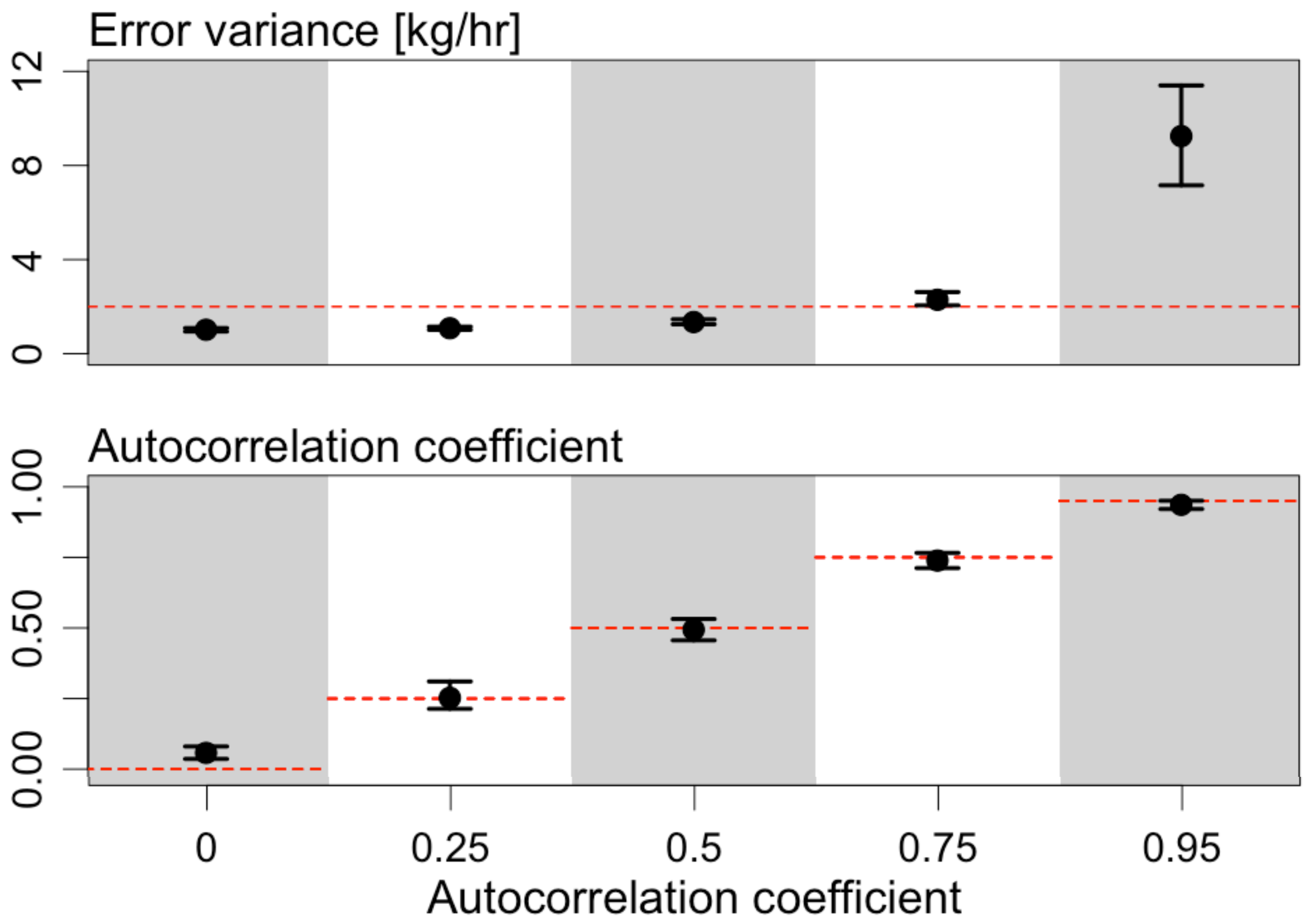
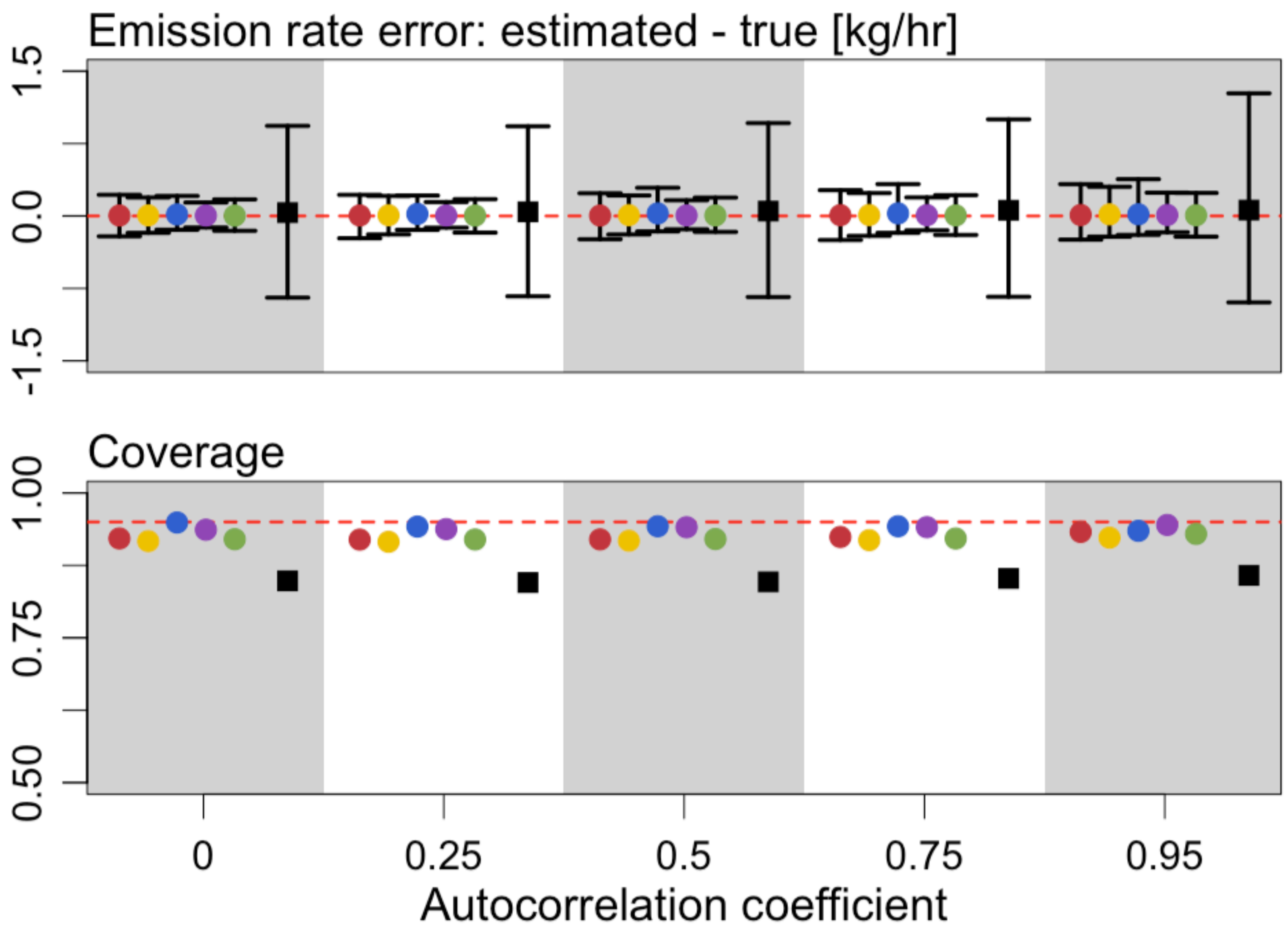
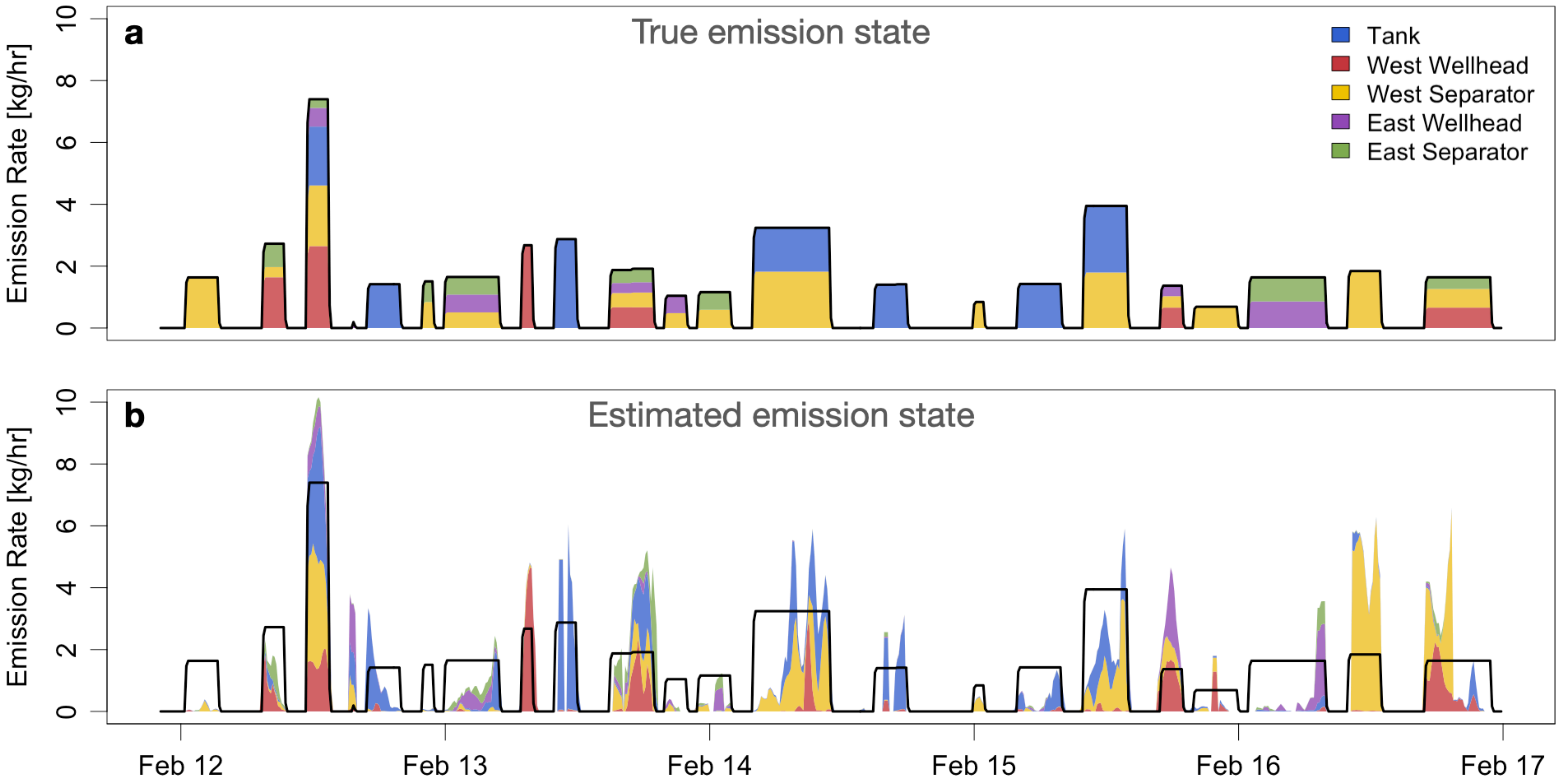
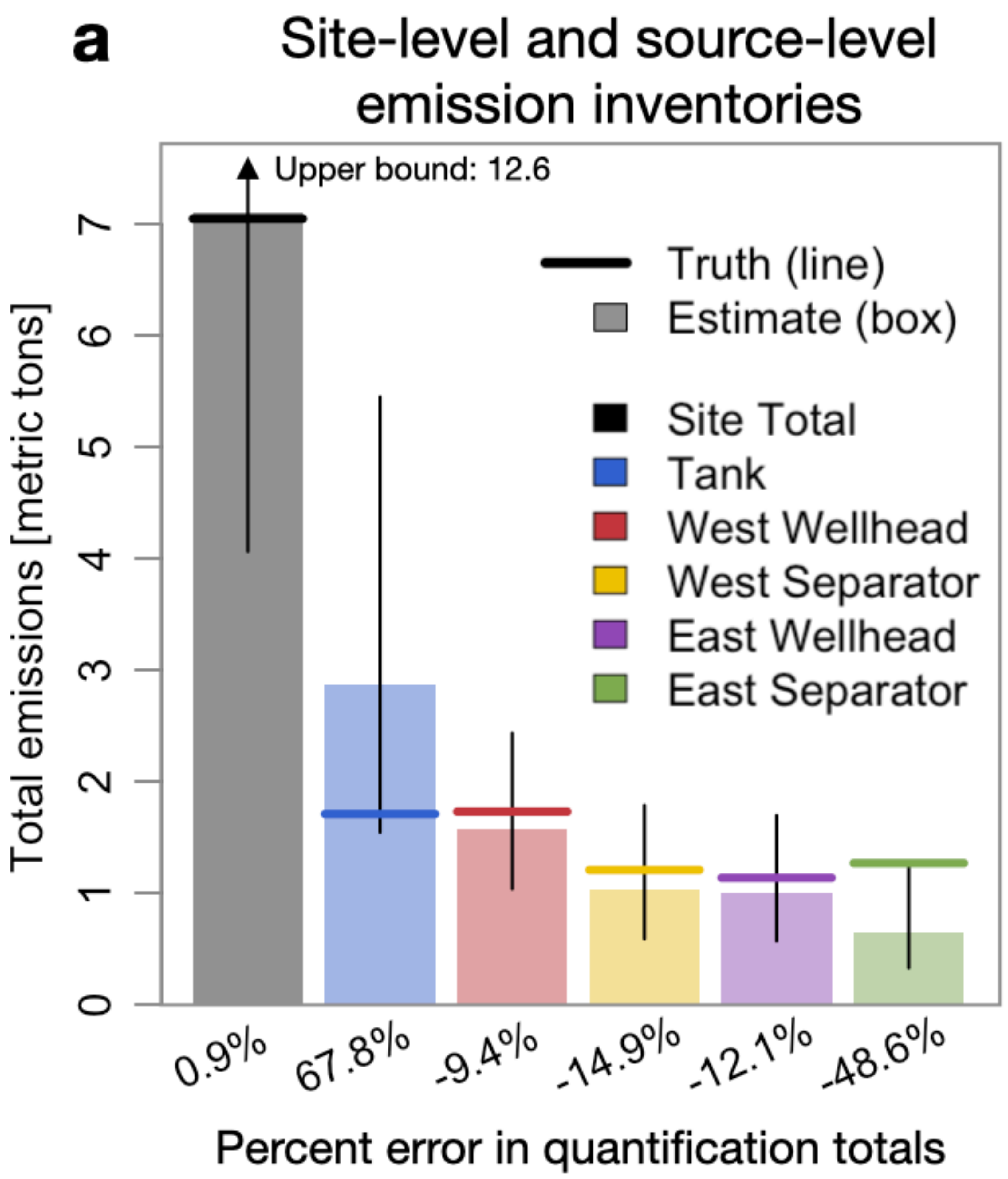


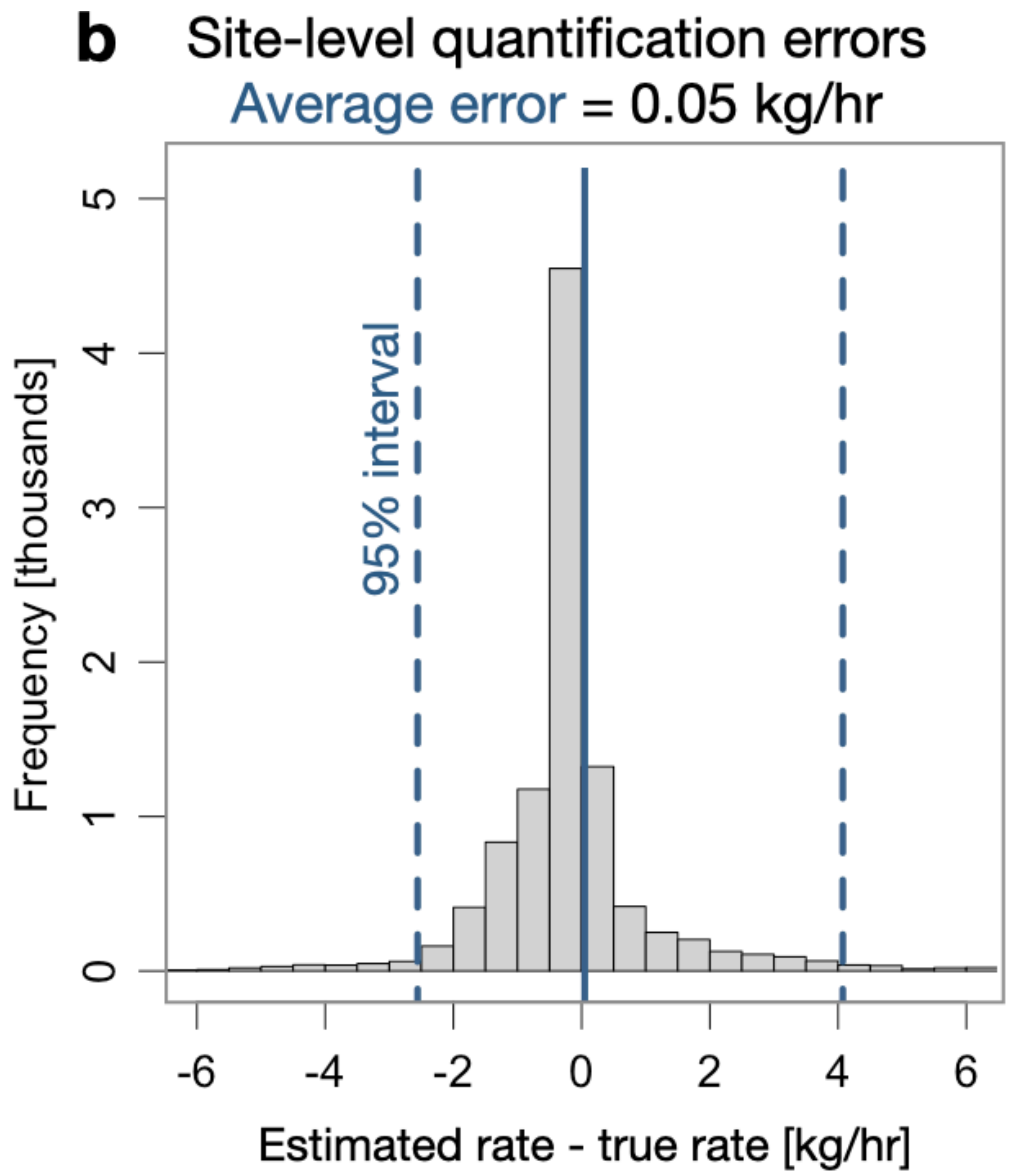



# Model evaluation on multi-source controlled release data



# Model evaluation on multi-source controlled release data



# Model evaluation on multi-source controlled release data

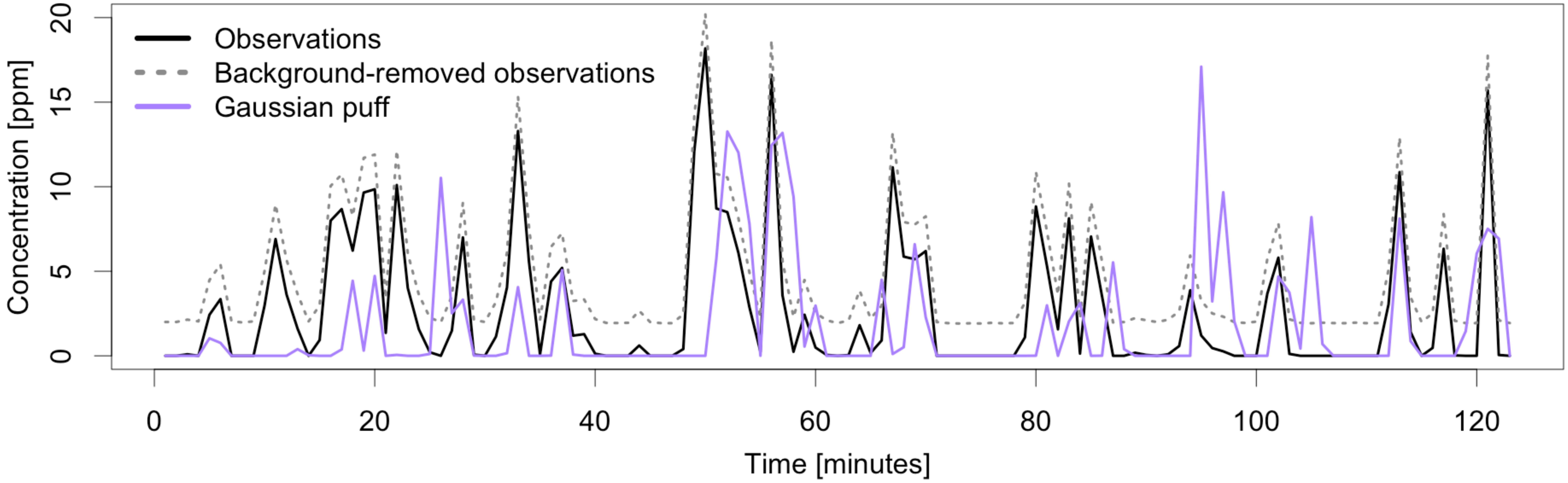
# Simulation study

## Vary the degree of spike misalignment

For each controlled release, replace actual concentration observations with

$$\tilde{y} = X\beta_T + \tilde{\epsilon}$$

but move a given percent of the spikes in the fake observations to a different time during the release.



# Simulation study

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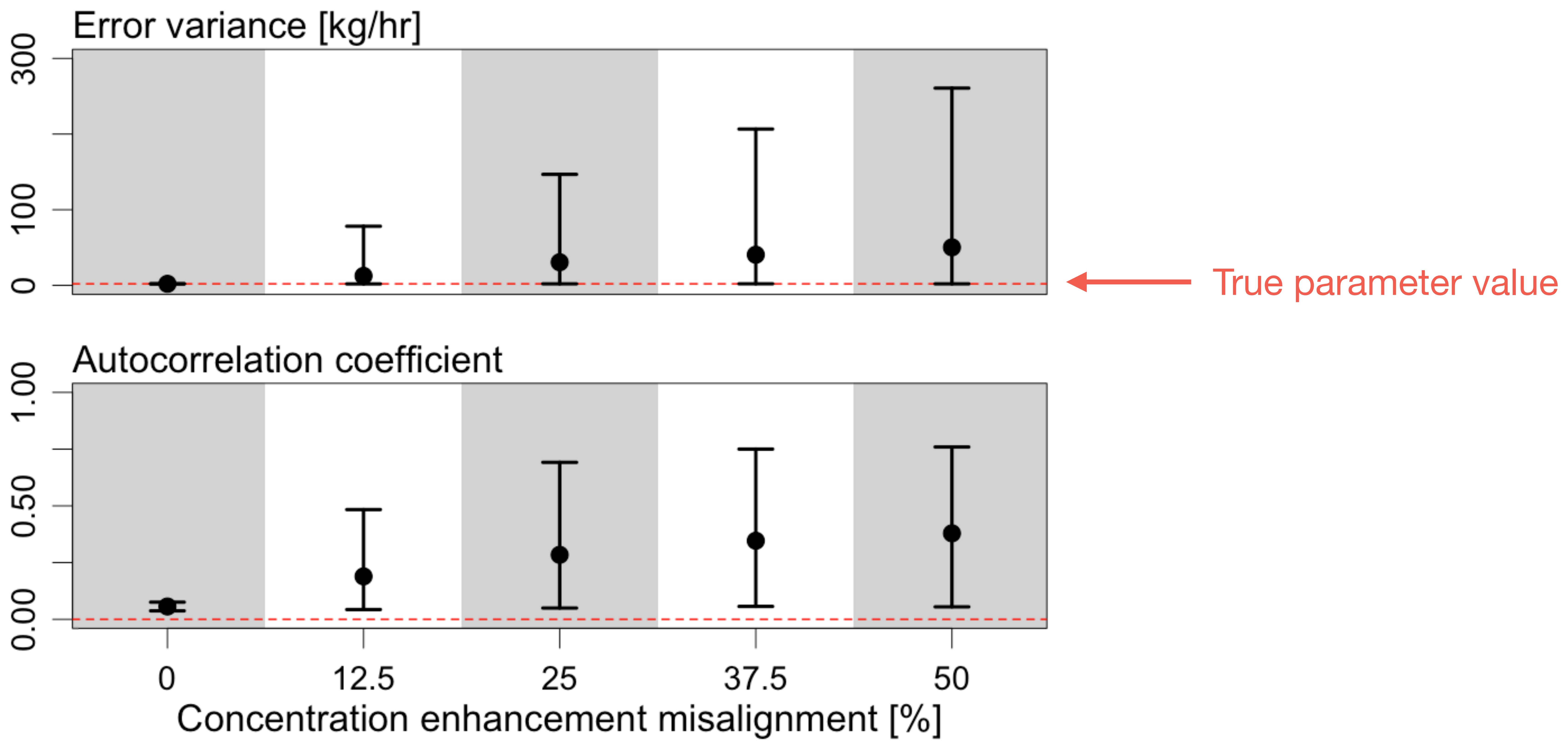

# Simulation study

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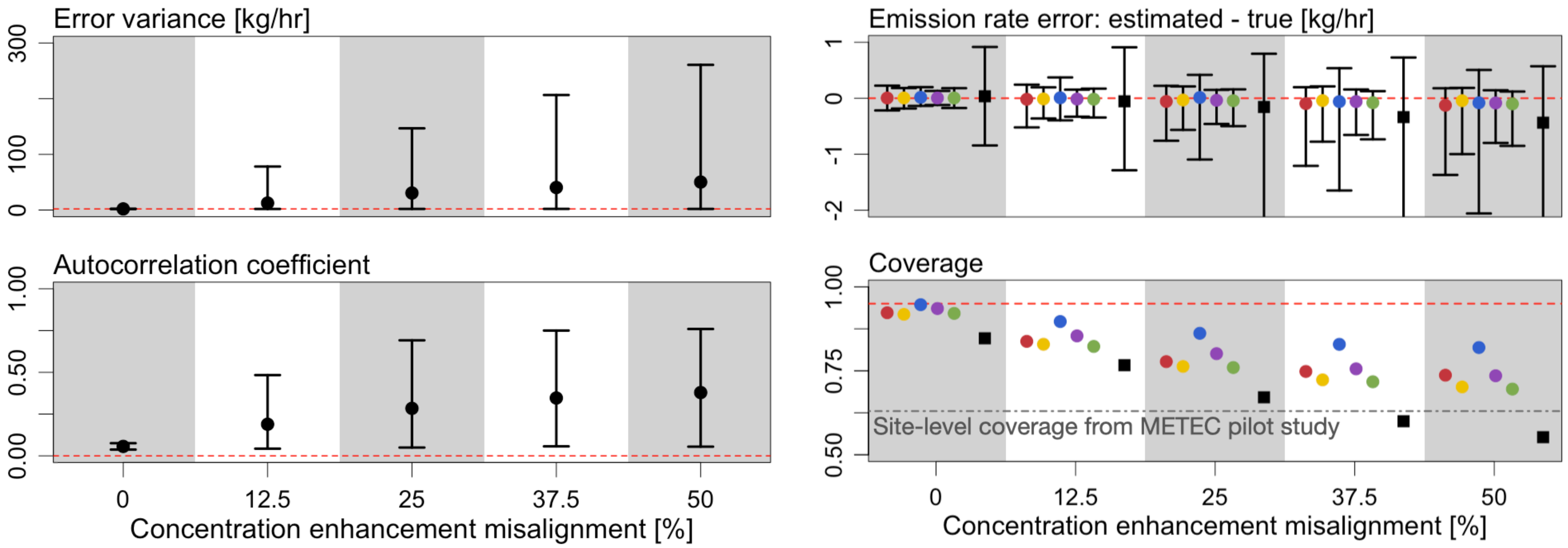


# Chapter 4:
## Multi-source emission detection, localization, and quantification

To do before submission:

- Finish comparison to the other methods

A Bayesian hierarchical model for methane emission source apportionment.

**William Daniels**, Douglas Nychka, Dorit Hammerling.
*Journal of the American Statistical Association,* in preparation, (2024).

# Chapter 5:

## Robust duration estimates

# A policy driven research project

AUTHENTICATED U.S. GOVERNMENT INFORMATION GPO

50282 **Federal Register** / Vol. 88, No. 146 / Tuesday, August 1, 2023 / Proposed Rules

**ENVIRONMENTAL PROTECTION AGENCY**

**40 CFR Part 98**

**[EPA–HQ–OAR–2023–0234; FRL–10246–01–OAR]**

**RIN 2060–AV83**

**Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems**

**AGENCY:** Environmental Protection Agency (EPA).

**ACTION:** Proposed rule.

**SUMMARY:** The Environmental Protection Agency (EPA) is proposing to amend requirements that apply to the petroleum and natural gas systems source category of the Greenhouse Gas Reporting Rule to ensure that reporting is based on empirical data, accurately reflects total methane emissions and waste emissions from applicable facilities, and allows owners and operators of applicable facilities to submit empirical emissions data that appropriately demonstrate the extent to which a charge is owed. The EPA is also proposing changes to requirements that

*Federal eRulemaking Portal. www.regulations.gov* (our preferred method). Follow the online instructions for submitting comments.

*Mail:* U.S. Environmental Protection Agency, EPA Docket Center, Air and Radiation Docket, Mail Code 28221T, 1200 Pennsylvania Avenue NW, Washington, DC 20460.

*Hand Delivery or Courier (by scheduled appointment only):* EPA Docket Center, WJC West Building, Room 3334, 1301 Constitution Avenue NW, Washington, DC 20004. The Docket Center's hours of operations are 8:30 a.m.–4:30 p.m., Monday-Friday (except Federal holidays).

*Instructions:* All submissions received must include the Docket Id. No. for this proposed rulemaking. Comments received may be posted without change to *www.regulations.gov/*, including any personal information provided. For detailed instructions on sending comments and additional information on the rulemaking process, see the "Public Participation" heading of the **SUPPLEMENTARY INFORMATION** section of this document.

The virtual hearing, if requested, will be held using an online meeting platform, and the EPA will provide information on its website

EPA may publish any comment received to its public docket. Do not submit to the EPA's docket at *www.regulations.gov* any information you consider to be confidential business information (CBI), proprietary business information (PBI), or other information whose disclosure is restricted by statute. Multimedia submissions (audio, video, etc.) must be accompanied by a written comment. The written comment is considered the official comment and should include discussion of all points you wish to make. The EPA will generally not consider comments or comment contents located outside of the primary submission (*i.e.,* on the web, cloud, or other file sharing system). Commenters who would like the EPA to further consider in this rulemaking any relevant comments that they provided on the 2022 Proposed Rule regarding proposed revisions at issue in this proposal must resubmit those comments to the EPA during this proposal's comment period. Please visit *www.epa.gov/dockets/commenting-epa-dockets* for additional submission methods; the full EPA public comment policy; information about CBI, PBI, or multimedia submissions, and general guidance on making effective comments.

# A policy driven research project

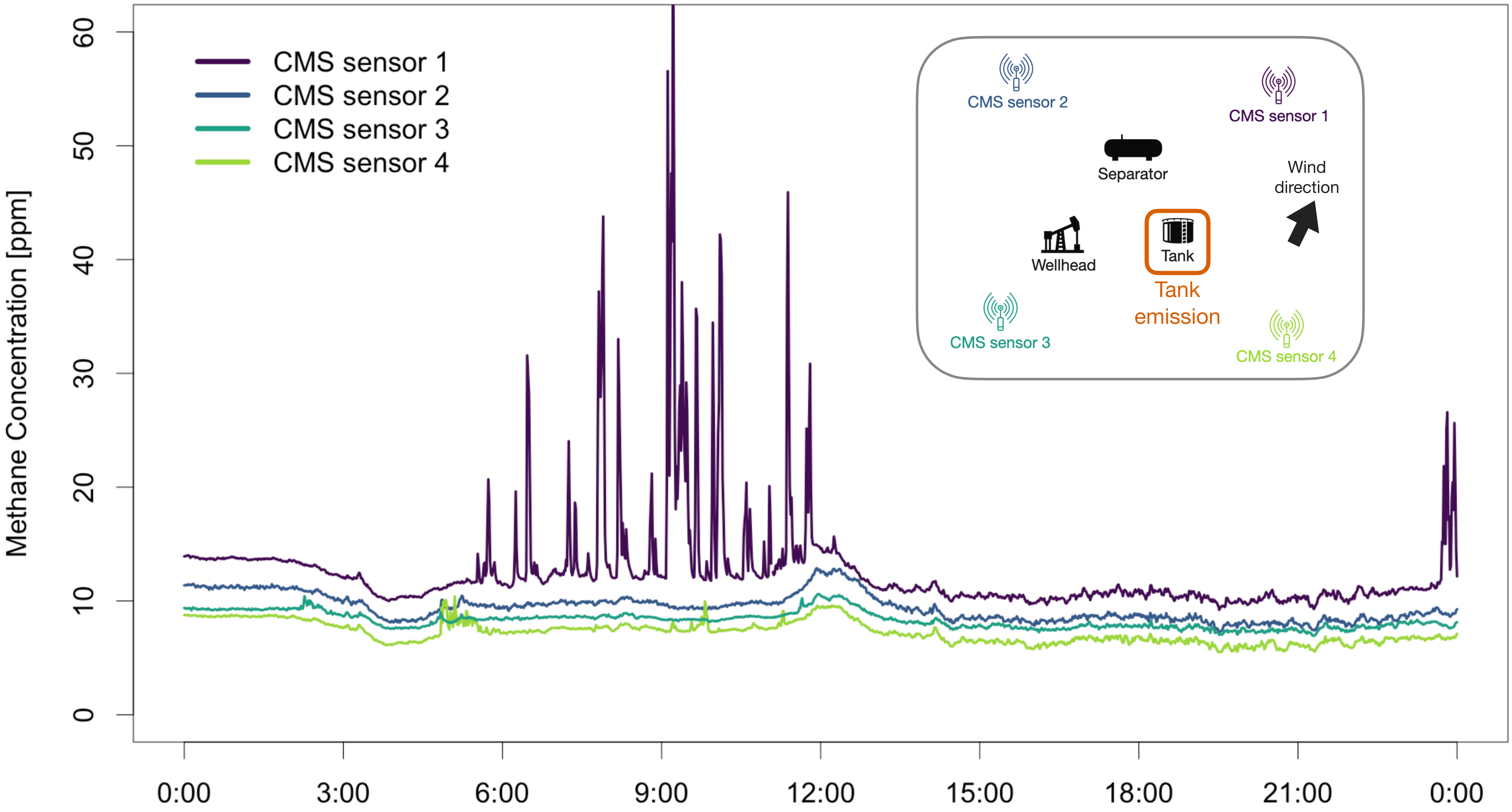
**40 CFR Part 98:**
**Proposed updates to the EPA's Greenhouse Gas Reporting Program (GHGRP) to take effect January 2025**

… also proposing a **100 kg/hr $CH_4$ emission threshold** to align with the super-emitter response program proposed in the NSPS OOOOb. These emissions are generally intermittent, with widely varying durations …

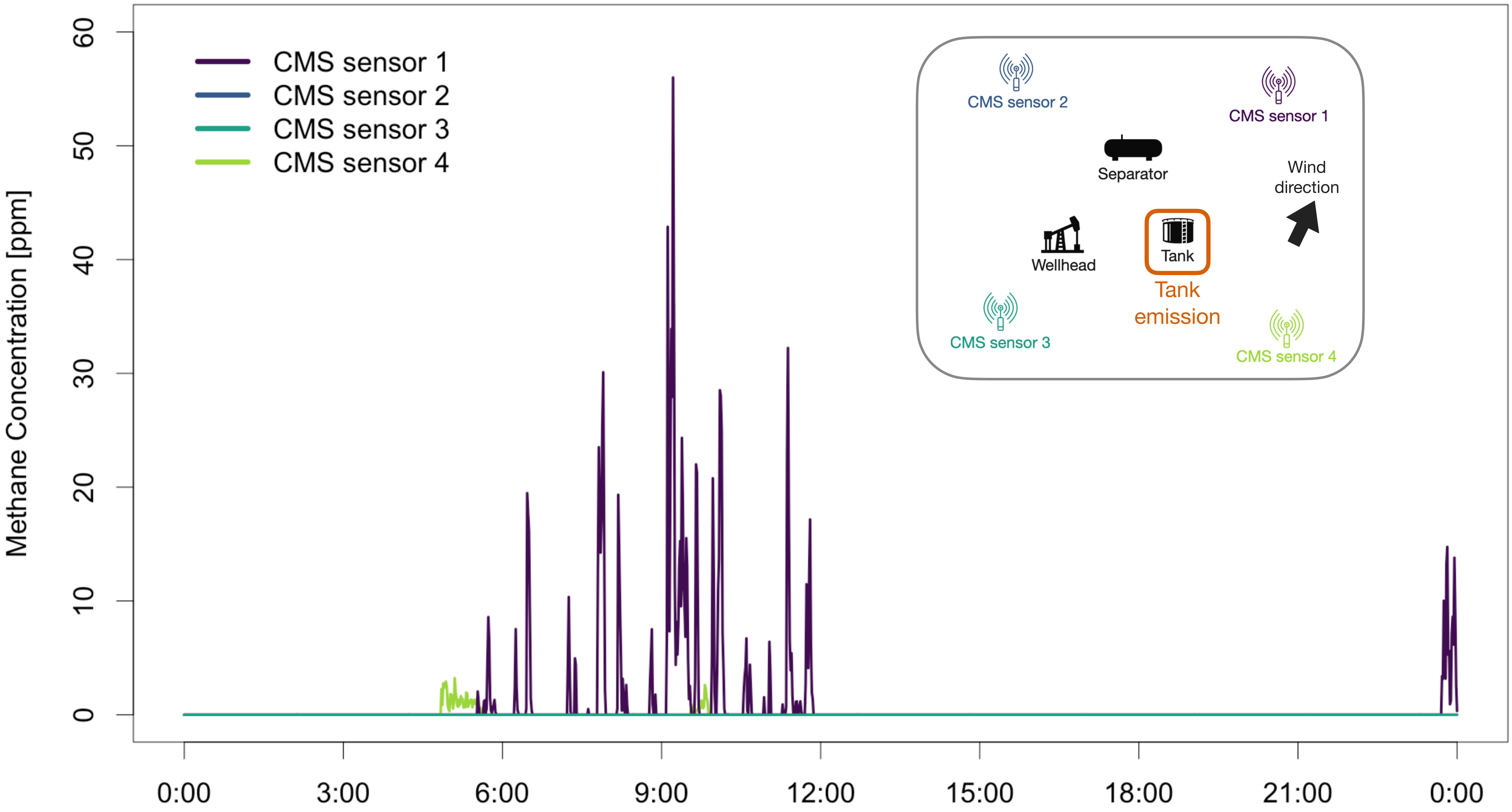
… also proposing that reporters would provide the start date and time of the release, **duration of the release**, and the method used to determine the start date and time …

Oil and gas operators required to report all methane emissions > 100 kg/hr

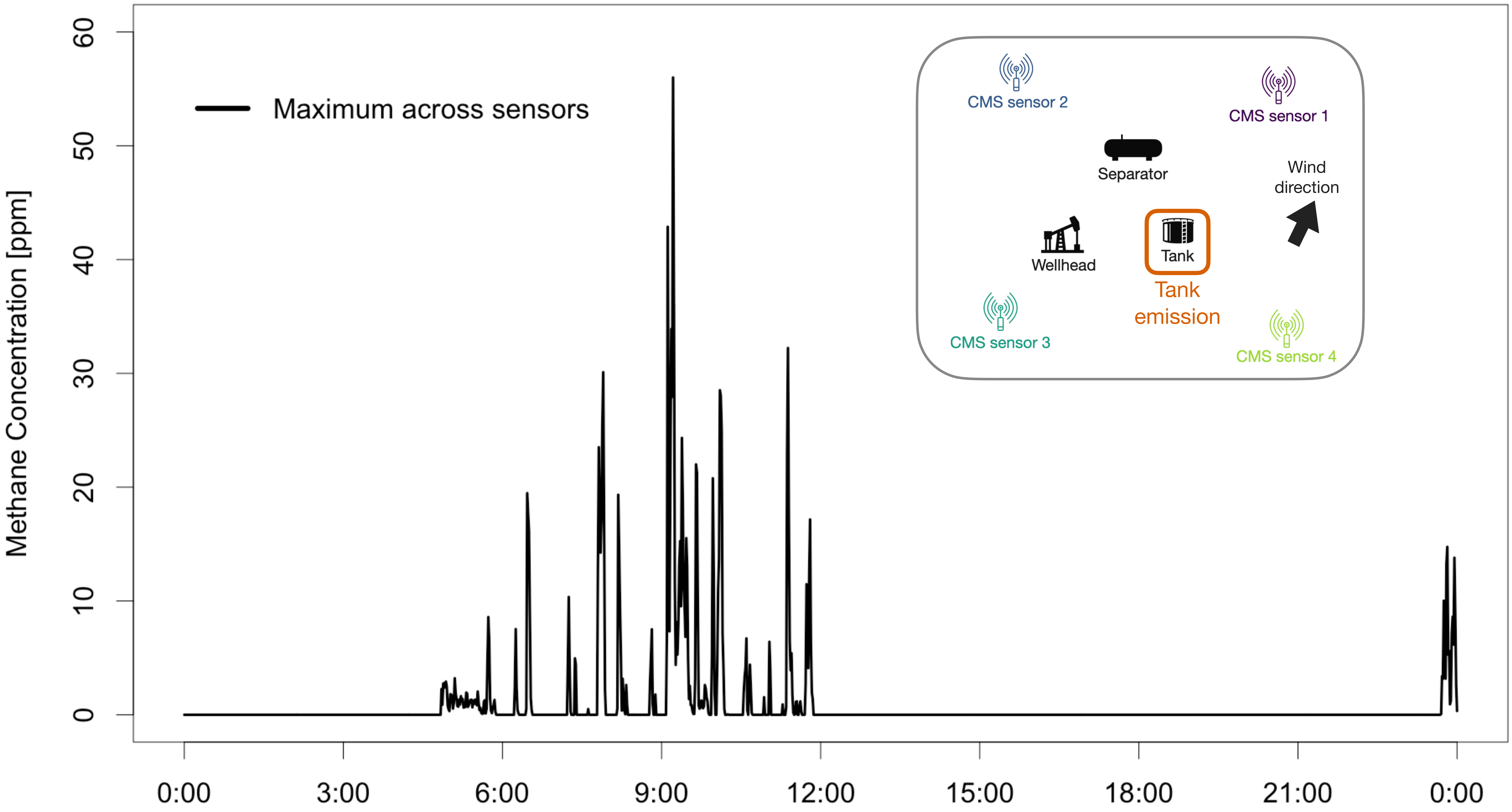
For each of these emissions, the operator must estimate an emission duration



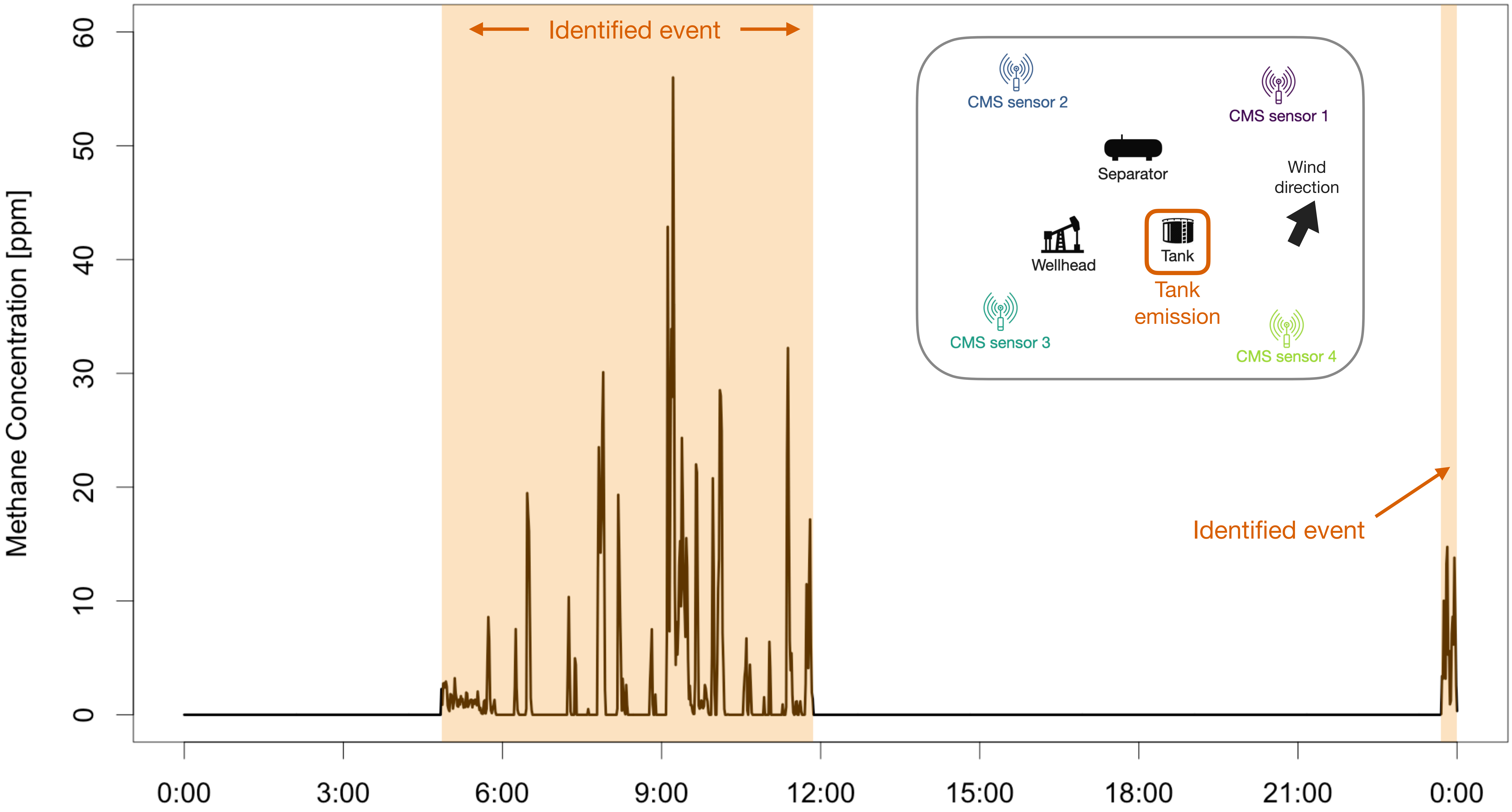
Methane Concentration [ppm]
0
10
20
30
40
50
60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
CMS sensor 1
CMS sensor 2
CMS sensor 3
CMS sensor 4
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
Tank emission
CMS sensor 3
CMS sensor 4



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 1
CMS sensor 2
CMS sensor 3
CMS sensor 4
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
Tank emission
CMS sensor 3
CMS sensor 4

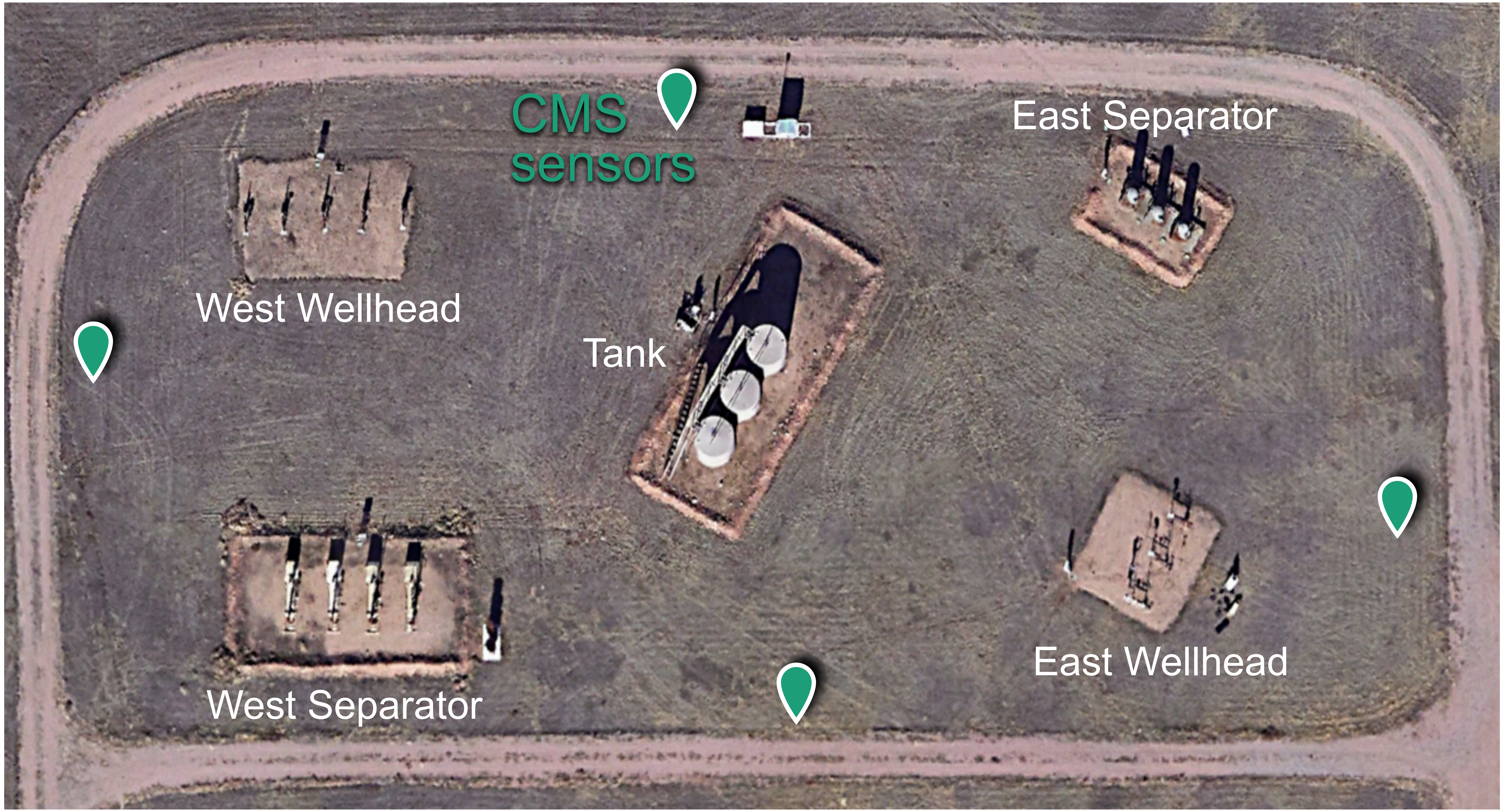


Methane Concentration [ppm]
0
10
20
30
40
50
60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00
Maximum across sensors
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
Tank emission
CMS sensor 3
CMS sensor 4



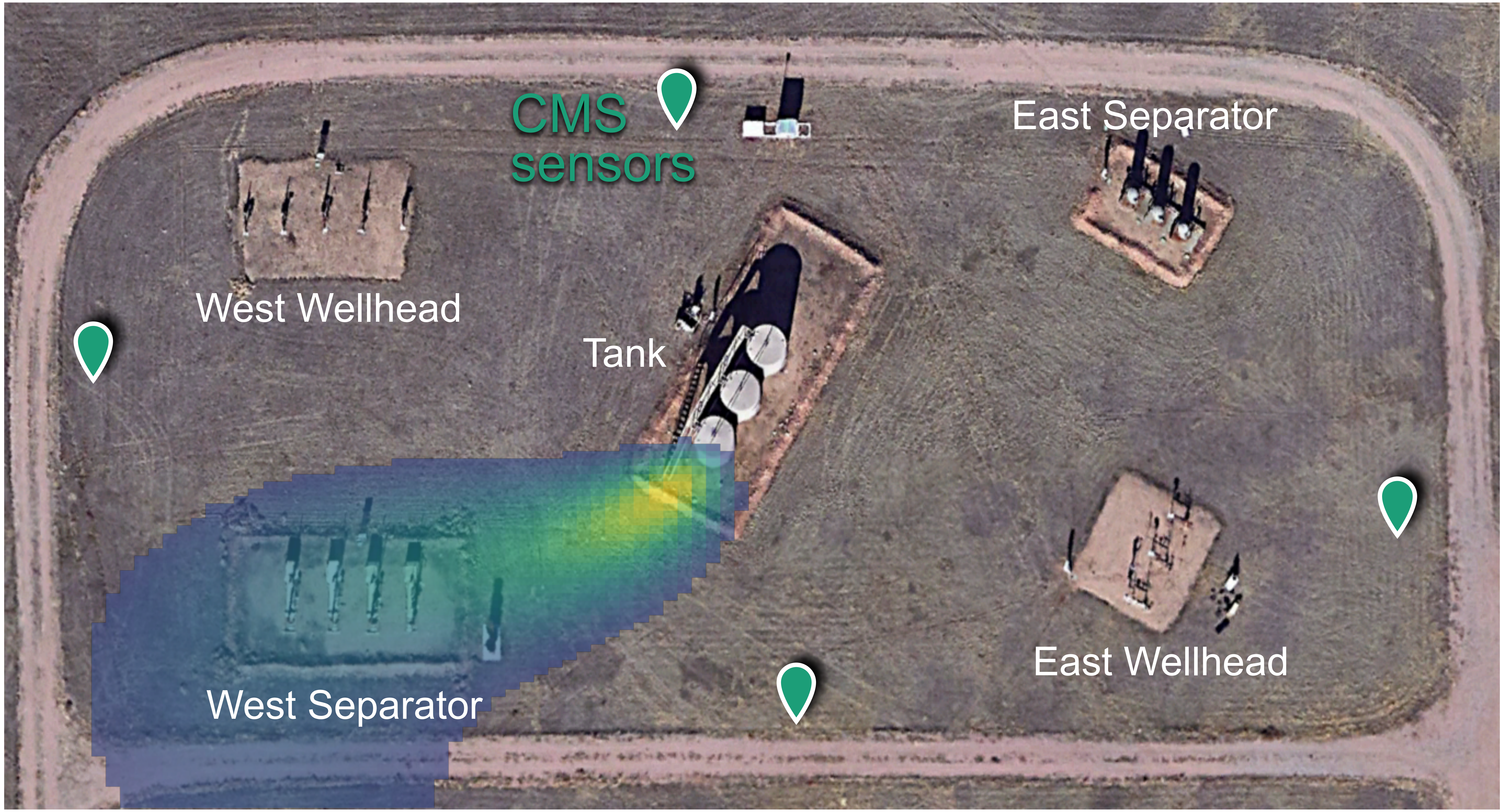
Identified event
CMS sensor 2
CMS sensor 1
Separator
Wind direction
Wellhead
Tank
Tank emission
CMS sensor 3
CMS sensor 4
Identified event
Methane Concentration [ppm]
0
10
20
30
40
50
60
0:00
3:00
6:00
9:00
12:00
15:00
18:00
21:00
0:00

# One problem… incomplete sensor coverage



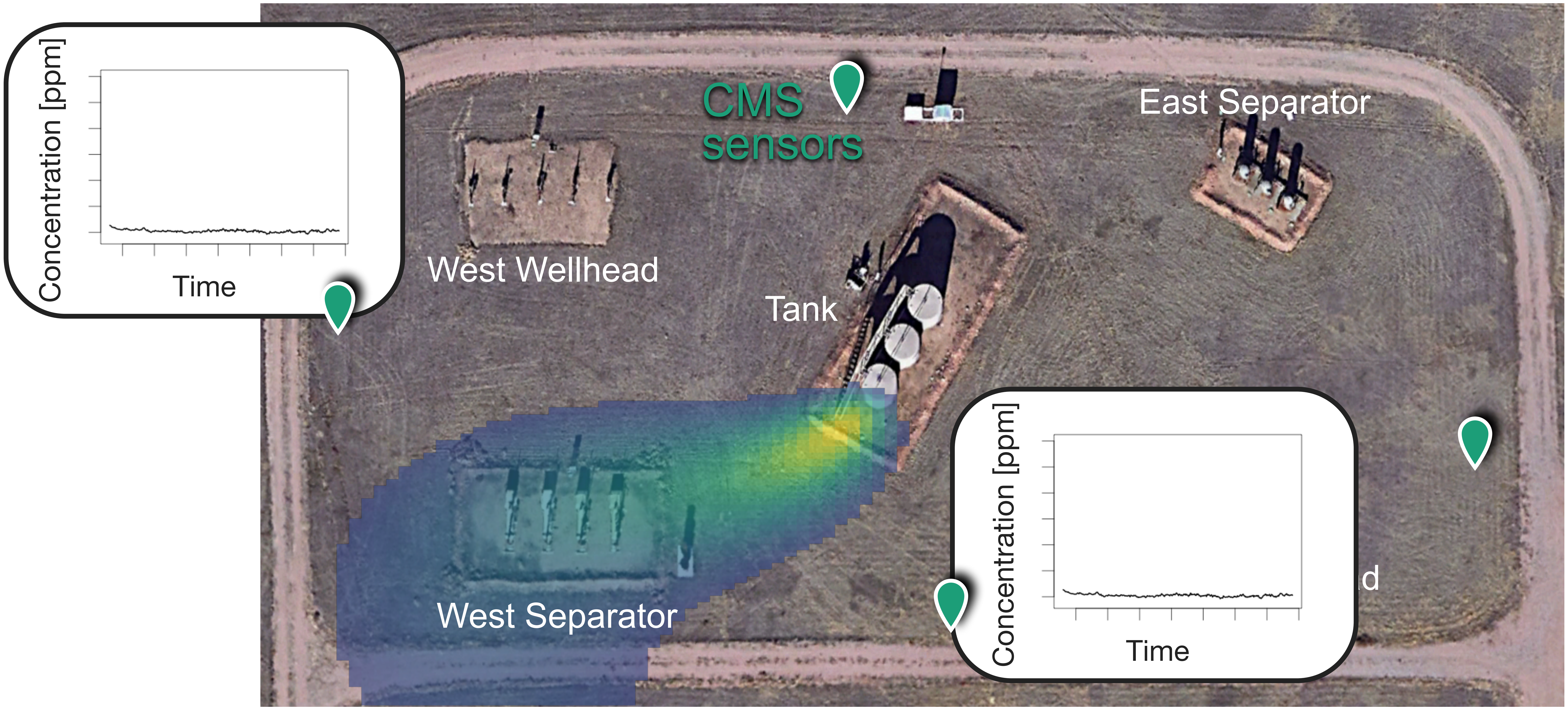
# One problem… incomplete sensor coverage

Wind direction



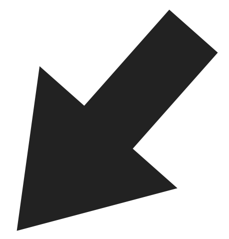
# One problem… incomplete sensor coverage

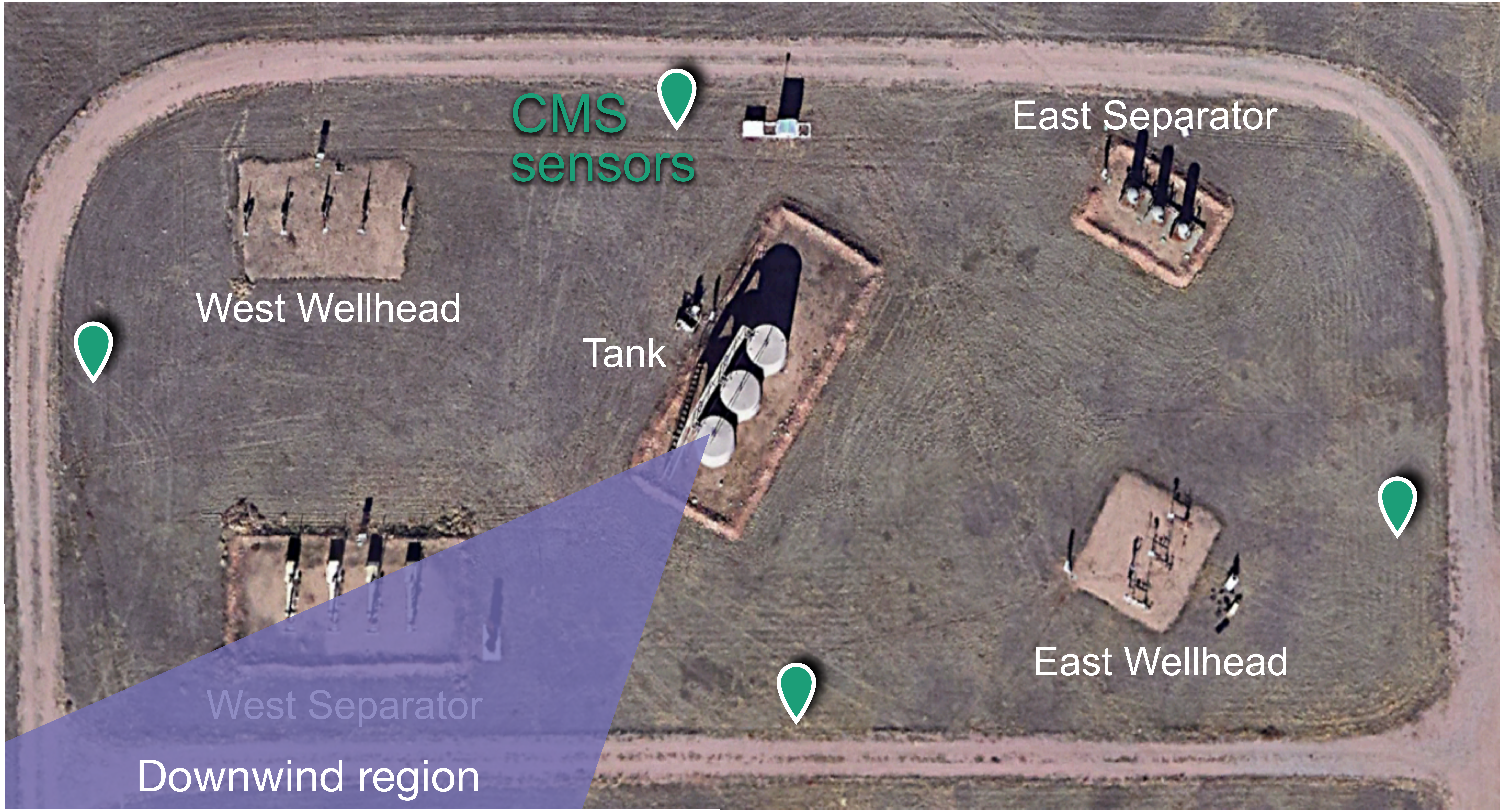
Wind direction




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

# However, we can estimate when this happens!

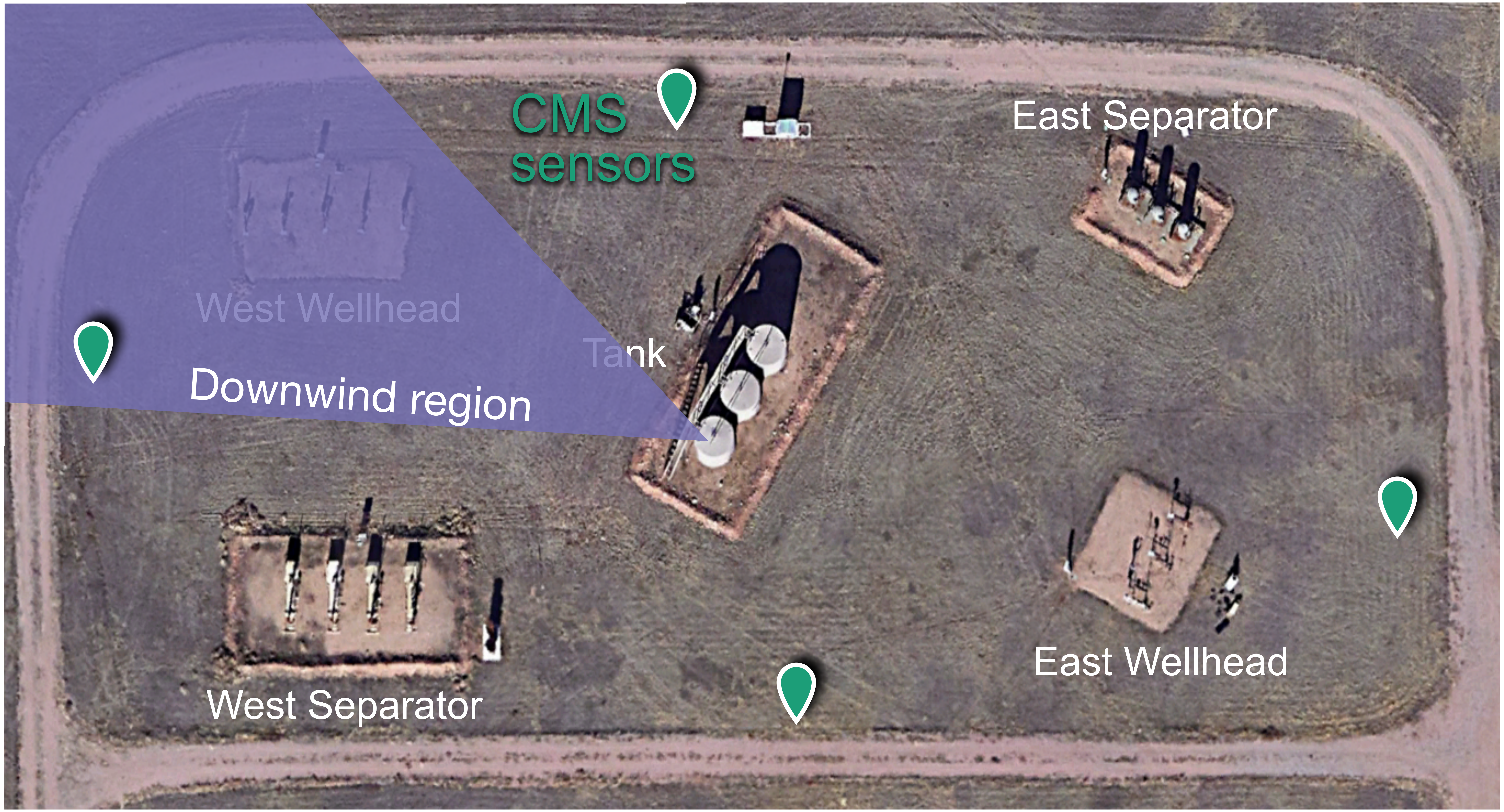



Downwind region **does not** overlap with CMS sensors = period of “**no information**”

# However, we can estimate when this happens!

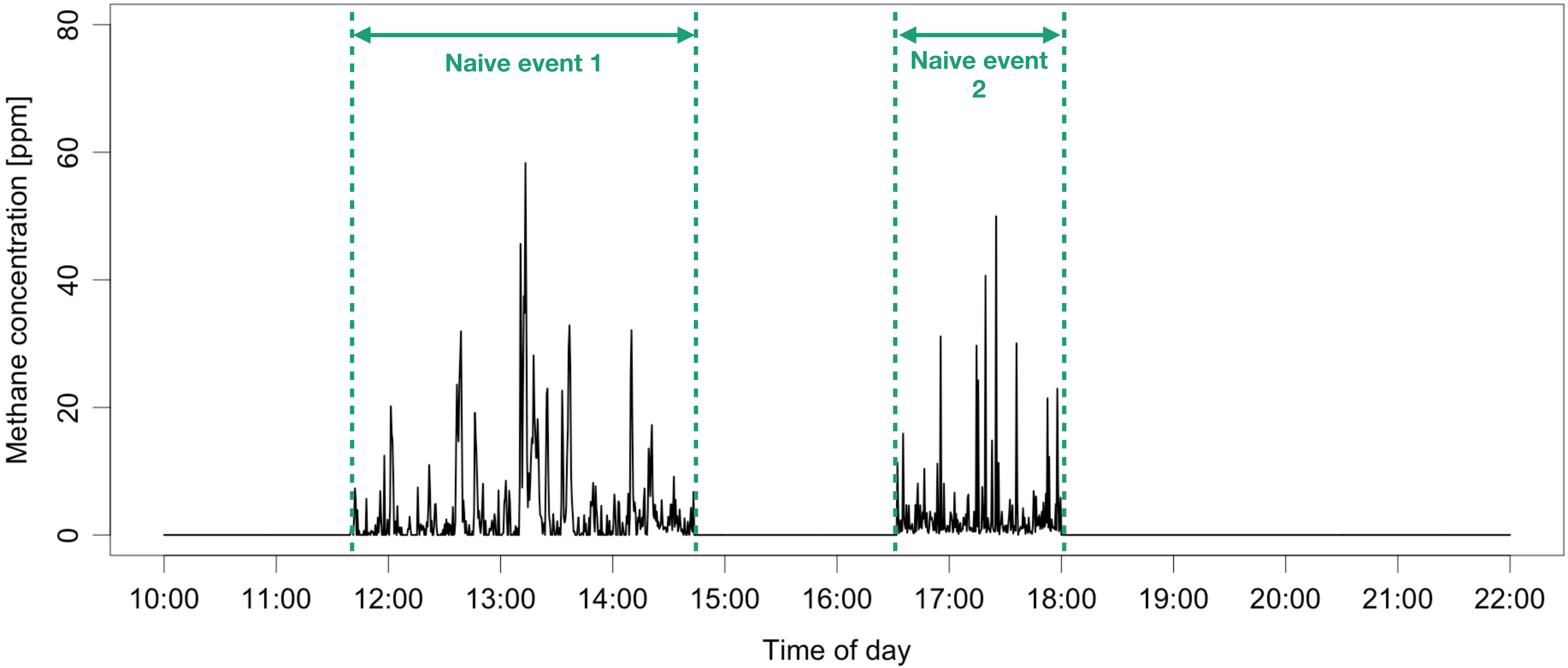
Wind direction




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

# Probabilistic Duration Model

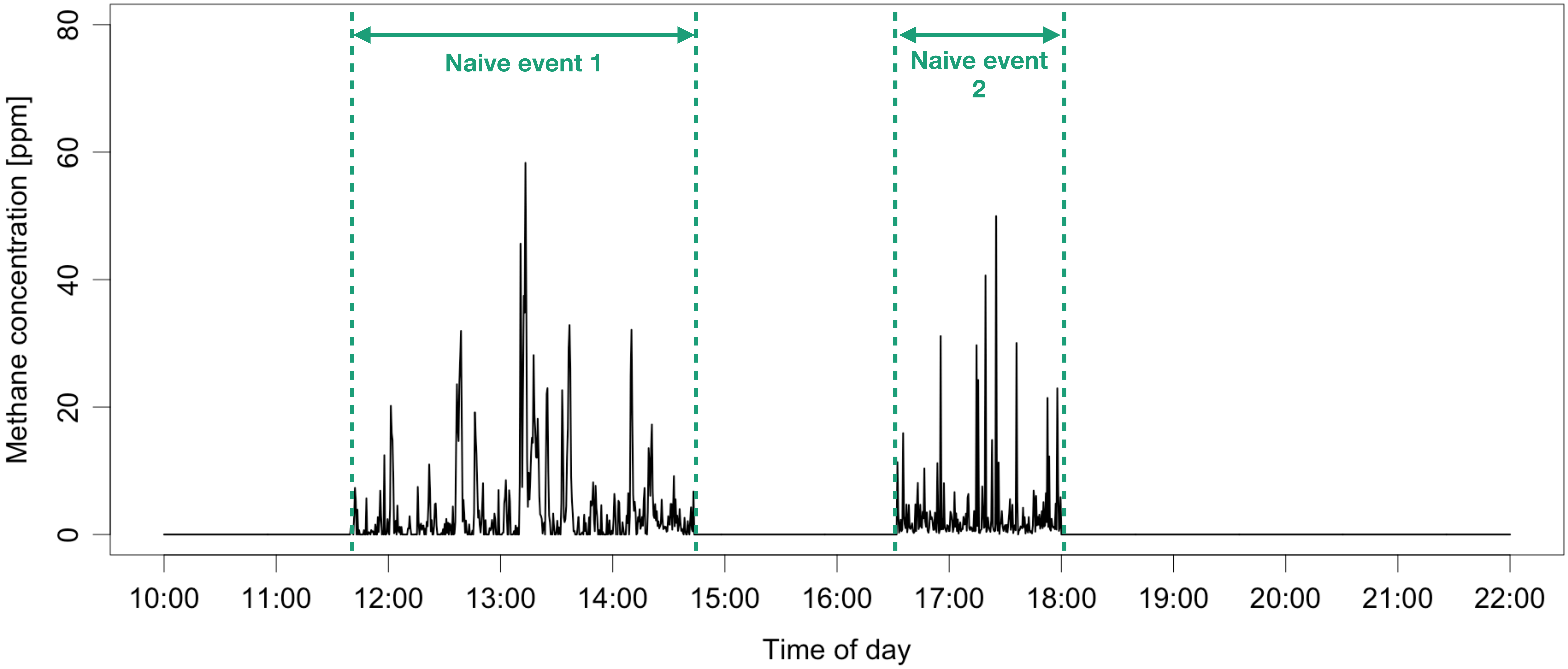
## Step 1: Identify naive events



**Probabilistic Duration Model**

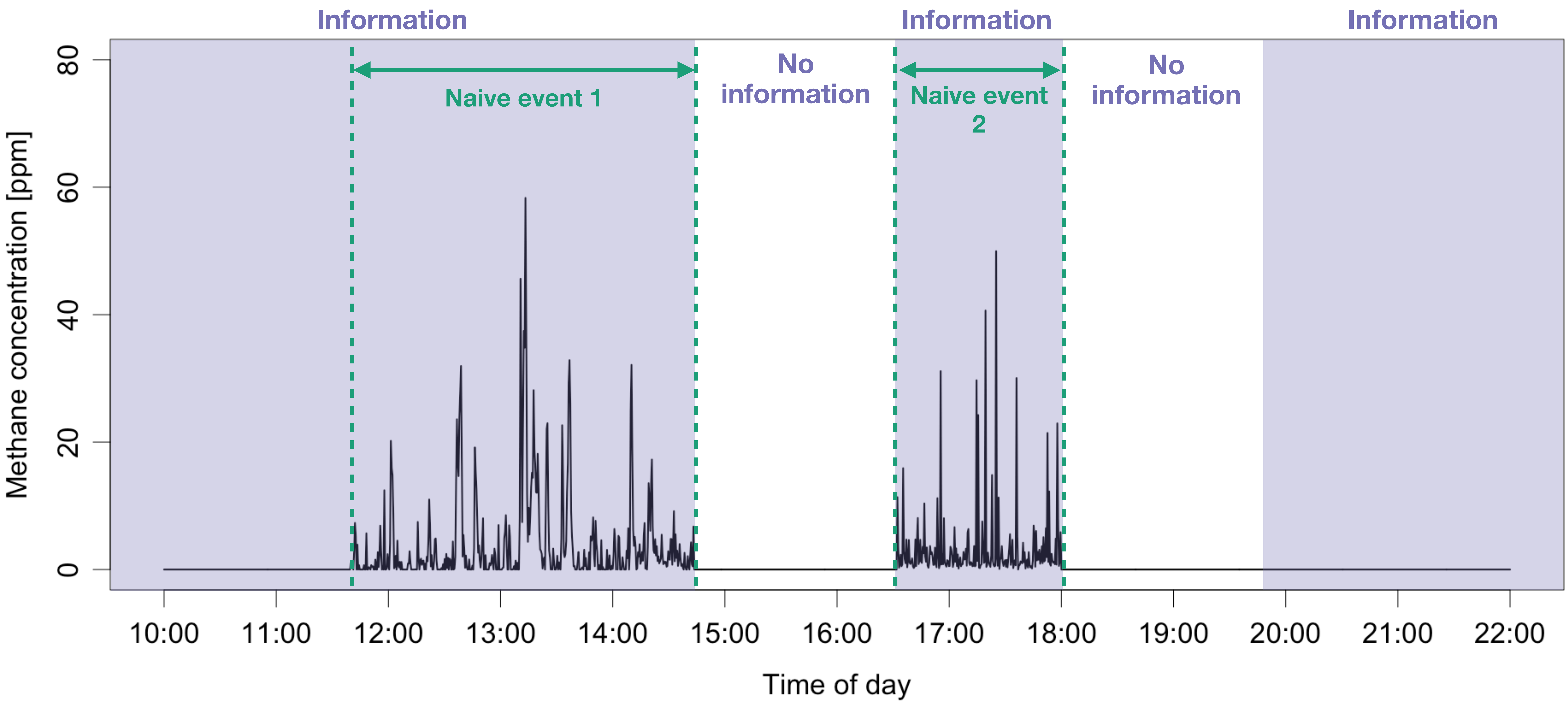
Step 1: Identify naive events

Example: we want a duration estimate for naive event 1



# Probabilistic Duration Model

## Step 2: Identify periods of information

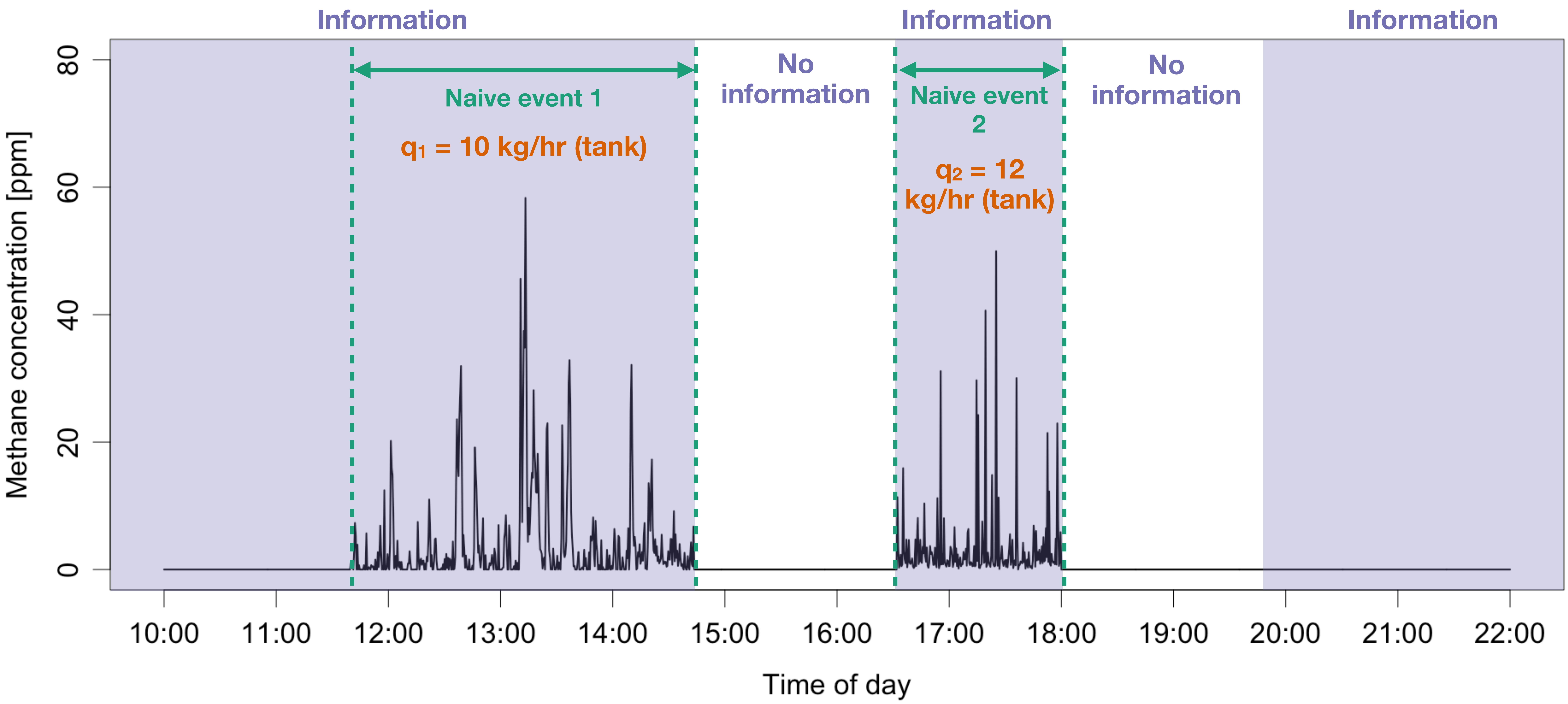


# Probabilistic Duration Model

## Step 3: Compute probability of combining events

$$\mathbb{P}_{i,j} = 1 - \frac{|q_i - q_j|}{P_{95}(\boldsymbol{q}) - P_5(\boldsymbol{q})}$$

$$\mathbb{P}_{1,2} = 0.85$$

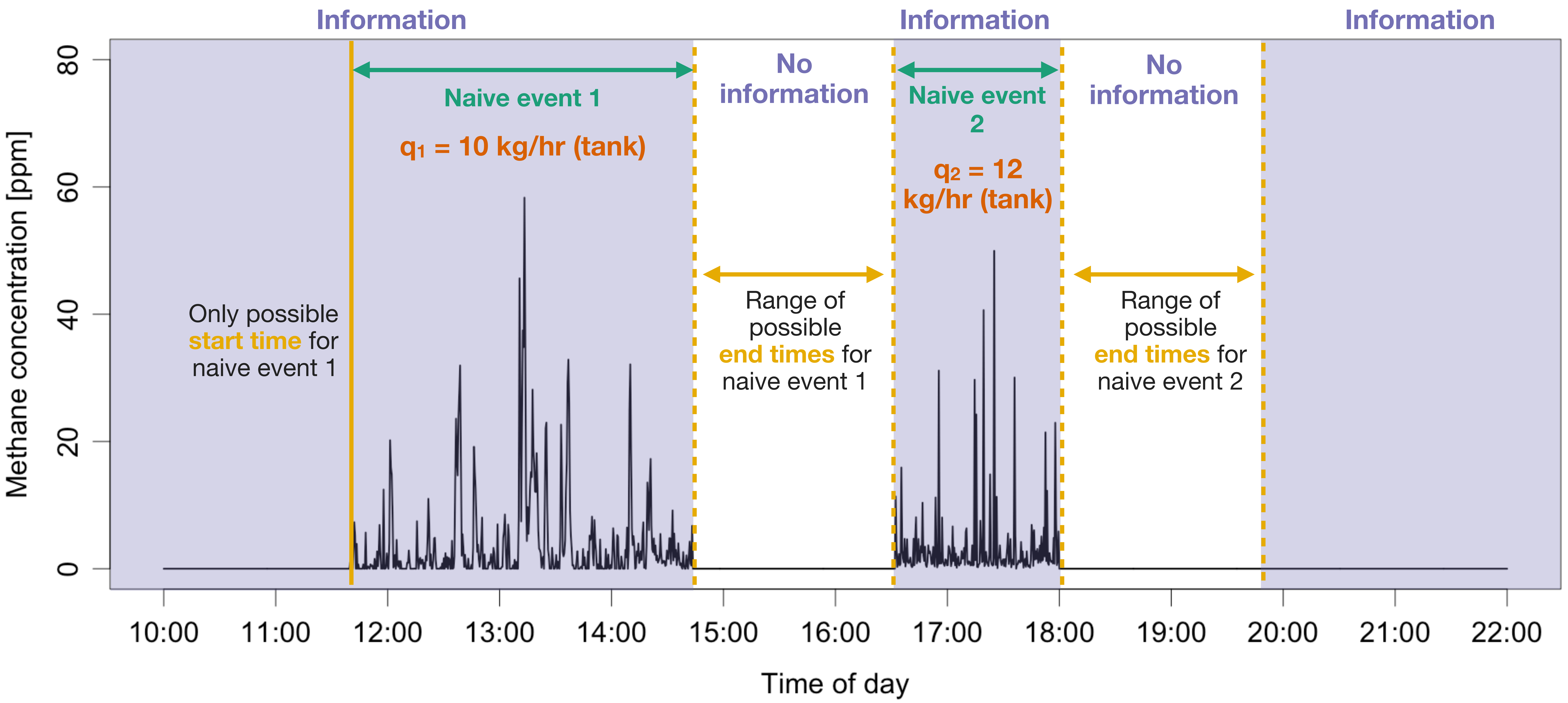


# Probabilistic Duration Model

## Step 4: Sample start and end times

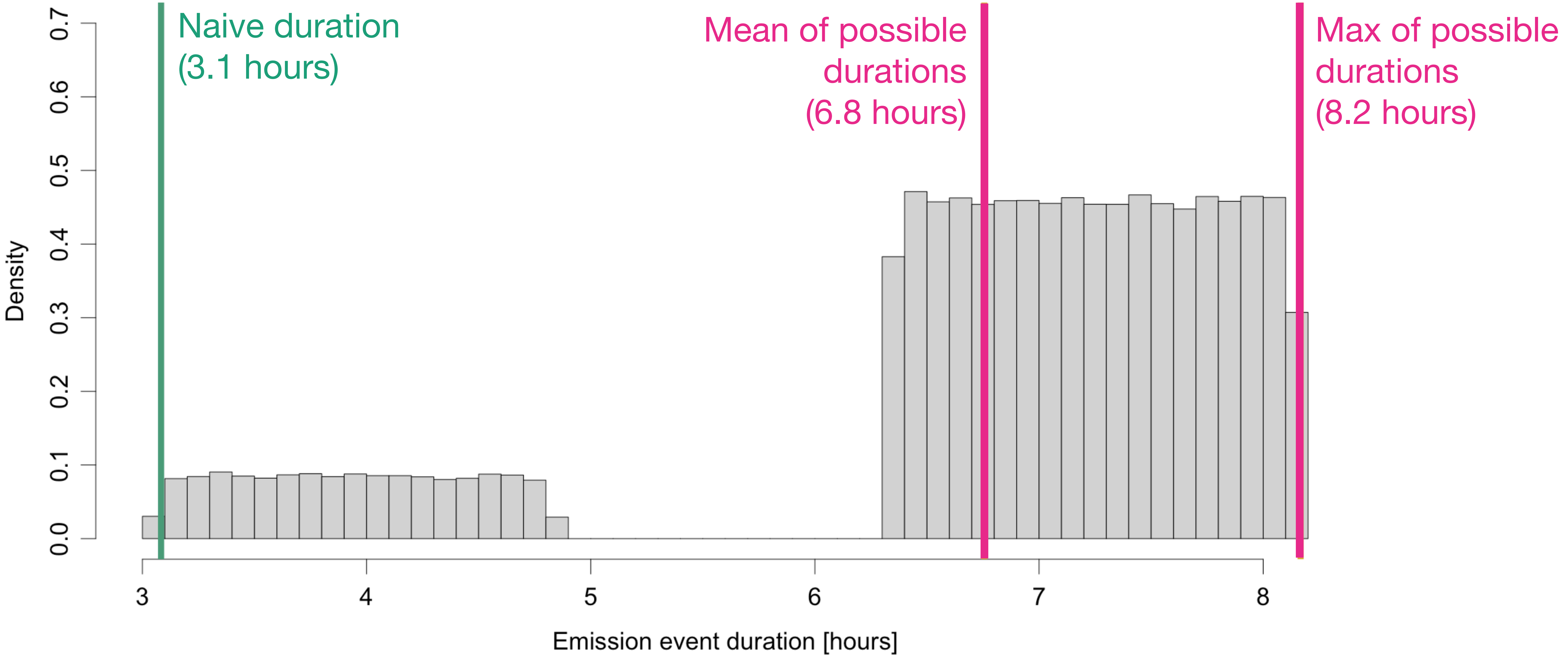
$$\mathbb{P}_{i,j} = 1 - \frac{|q_i - q_j|}{P_{95}(\boldsymbol{q}) - P_5(\boldsymbol{q})}$$

$$\mathbb{P}_{1,2} = 0.85$$



# Probabilistic Duration Model

## Step 5: Compute distribution of durations



# Probabilistic Duration Model

## Mixture model of uniform distributions

We want the distribution of durations for naive event $k$.

# Probabilistic Duration Model

## Mixture model of uniform distributions

We want the distribution of durations for naive event $k$.

First, consider the simplest case where there is zero probability of combining with neighboring events.

$$S_k \sim \text{Unif}(\cdot, \cdot) \quad \text{and} \quad E_k \sim \text{Unif}(\cdot, \cdot)$$

Here the durations are simply: $D_k = E_k - S_k \sim \text{Trap}(\cdot, \cdot, \cdot, \cdot)$.

# Probabilistic Duration Model

## Mixture model of uniform distributions

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Here the durations are simply: $D_k = E_k - S_k \sim \text{Trap}(\cdot,\cdot,\cdot,\cdot)$.

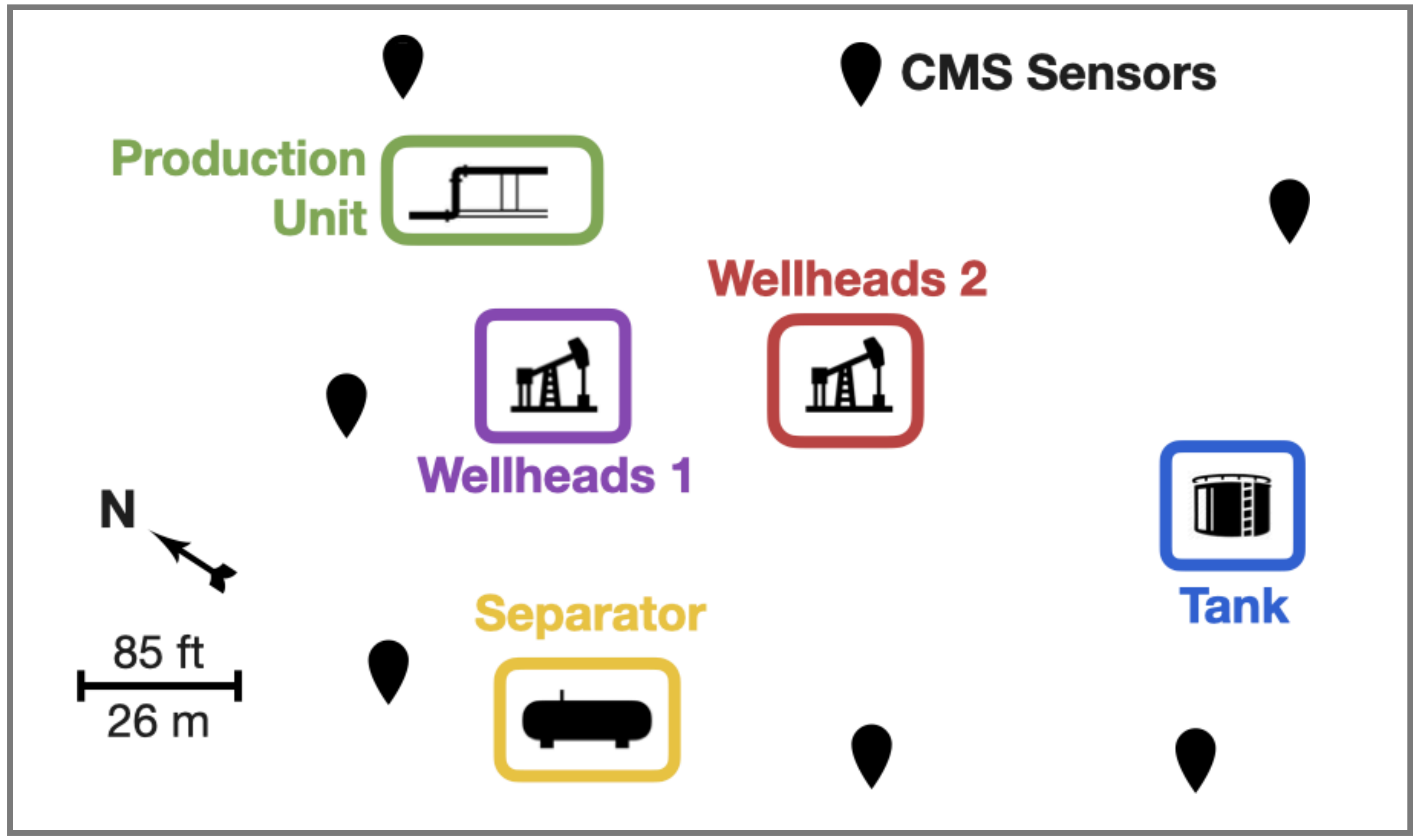
Next, consider the situation with $n$ preceding events and $m$ subsequent events:

$$S_k \sim \sum_{i=1}^{n} \mathbb{P}_{k,i} S_i \quad \text{and} \quad E_k \sim \sum_{j=1}^{m} \mathbb{P}_{k,j} E_j$$

Again the durations are: $D_k = E_k - S_k \sim \, ?$

# Case study:

## Bounding the duration of an aerial measurement




Aerial technology detects separator emission of 9.6 kg/hr

| Detected emission rate | | Potential duration estimates | | Total emitted methane |
|---|---|---|---|---|
| 9.6 kg/hr | X | naive duration: 1.78 hours | = | 17.1 kg |
| | | mean of possible durations: 10.2 hours | | 97.9 kg |
| | | max of possible durations: 18.8 hours | | 180.5 kg |
| 9.6 kg/hr | X | time since previous aerial survey: 3 months | = | 21,024 kg |

# Throw back to the multi-source evaluation

# Throw back to the multi-source evaluation - information filtered

# Chapter 5:

## Robust duration estimates

Concluding thoughts:

- EPA interested in this methodology.
- Note sure if the WEC will survive, but Europe might implement something similar.

Estimating methane emission durations using continuous monitoring systems.

**William Daniels**, Meng Jia, Dorit Hammerling.

*Environmental Science and Technology Letters,* 11(11), 1187-1192, (2024).

# Thank you!

Questions?

COLORADO SCHOOL OF MINES

EEMDL
Energy Emissions Modeling and Data Lab

U.S. DEPARTMENT OF ENERGY