Evaluating a Flux Footprint Model Using Tracer Release Experiments and Tall Tower Eddy Covariance Measurements

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Motivation

- Footprint estimation is crucial for determining the spatial origin of fluxes measured by eddy covariance (EC) and for quantifying the contributions from different areas within the source region.
- Footprint models often rely on theoretical assumptions, such as homogeneous and stationary conditions, which can differ significantly from real-world scenarios.
- We measure gas fluxes from a 300-meter-tall mast equipped with three EC levels and five profile levels at Hove, a rural heterogeneous landscape east of Copenhagen, Denmark (Fig. 1).
- To evaluate the reliability of the Flux Footprint Prediction (FFP) (Kljun et al., 2015) under real-world conditions, we estimate the footprint in the tall tower EC using an empirical method - the tracer release experiment (TRE). In such experiment, a gas is emitted at a known rate at a known location.

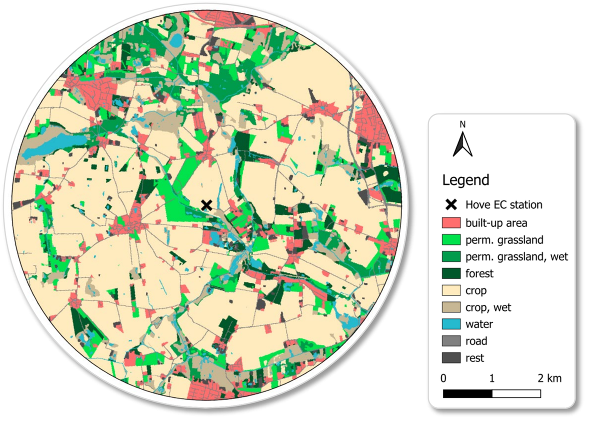

Figure 1. Landscape, 4km around the Hove mast.

Methodology

- Three experiments (Table 1) were conducted around the Hove mast (55.7169°N, 12.4918°E). The site primarily consisted of grassland and farmland, with wheat being the main crop, which had been harvested before the experiments.
- Acetylene (C_2H_2) was released as an artificial tracer due to its zero background concentration at the site. It was emitted from point sources aligned with the mast roughly along the wind directions (Fig. 2, Fig. 5).
- Two gas analysers (CH_4/C_2H_2 and N_2O/C_2H_2, Picarro) measured C_2H_2 concentrations from both the EC and profile systems simultaneously at a frequency of 1 Hz.

Table 1. Information about the three TRE campaigns.

Exp. No.	Date	Start time	Duration	Release rate	Release distance[1]	Measurement height[2]
1	2024-08-16	10:24	04 h 05 m	1.5 kg/h	874 m	90 m, 115 m
2	2024-09-19	13:20	02 h 53 m	1.0 kg/h	434 m, 448 m	115 m
3	2024-11-16	09:28	03 h 32 m	1.5 kg/h	876 m	70 m

[1]Release distance: distance between the release point and the EC tower. The release point was relocated at 15:13 during Exp2.
[2]The measurement height was switching between 90 m and 115 m in Exp1.

Theory

- Under ideal conditions, the measured flux can be defined in Eq. 1. Since C_2H_2 was only emitted from one pixel in the TREs, Eq.1 can be simplified to Eq. 2.
- The measured EC fluxes of C_2H_2 (F_{EC_m}) were calculated using EddyPro software (v7.0.9, LI-COR).[3]
- The predicted footprints of the release points ($f_{(x,y)_p}$) were estimated by running the FFP (1×1m grid).
- Predicted flux (F_{EC_p}, Eq. 3) is supposed to be identical to F_{EC_m}. Similarly, measurement-based footprint ($f_{(x,y)_m}$, Eq. 4) should be identical to $f_{(x,y)_p}$.

$$F_{EC}\{0,0,z_m\} = \int_0^{+\infty}\int_{-\infty}^{+\infty} Q_{(x,y)} f_{(x,y,z_m)}\, dx\, dy \quad \text{(Eq. 1)}$$

$$F_{EC} = Q_{(x,y)} f_{(x,y)} \quad \text{(Eq. 2)}$$

F_{EC}: turbulent flux
$Q_{(x,y)}$: surface flux or controlled release rate
$f_{(x,y)}$: footprint function
(x, y): relative coordinate of the release point at relative height of 0 m

(Rey-Sanchez et al., 2022; Schmid, 2002)

$$F_{EC_p} = f_{(x,y)_p} Q_{(x,y)} \quad \text{(Eq. 3)}$$

$$f_{(x,y)_m} = F_{EC_m} / Q_{(x,y)} \quad \text{(Eq. 4)}$$

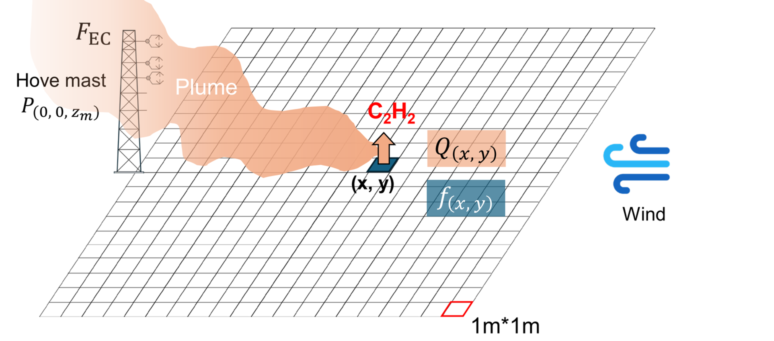

Figure 2. Schematic of tracer release experiment (after Heidbach, 2018).

[3]Both fluxes and footprints were processed using a rolling 30-minute averaging interval with a 5-minute step size.

Results & Discussion

Relationships between turbulent transport and concentration

- The measured C_2H_2 concentrations (Fig. 3) are significantly lower than those at the emission source and exhibit strong fluctuations due to the combined effects of molecular diffusion, turbulent mixing, and turbulent transport.
- Our time series represent a cross-section of the plume at the monitoring point $P_{(0,0,z_m)}$, alternately capturing C_2H_2-containing air parcels (Fig. 3d-f, coloured points) that are lifted along wind direction by large-scale turbulence fast enough to reach this height, and background C_2H_2-free air parcels (Fig. 3d-f, white points). Other air parcels that pass the tower either below or above $P_{(0,0,z_m)}$ will not be measured.
- Air parcels also experience cross-wind horizontal transport, and the average wind direction, which may differ from the wind direction at $P_{(0,0,z_m)}$, influences the proportion of the air parcel that reaches the sensor at $P_{(0,0,z_m)}$ (Fig.3d-f).

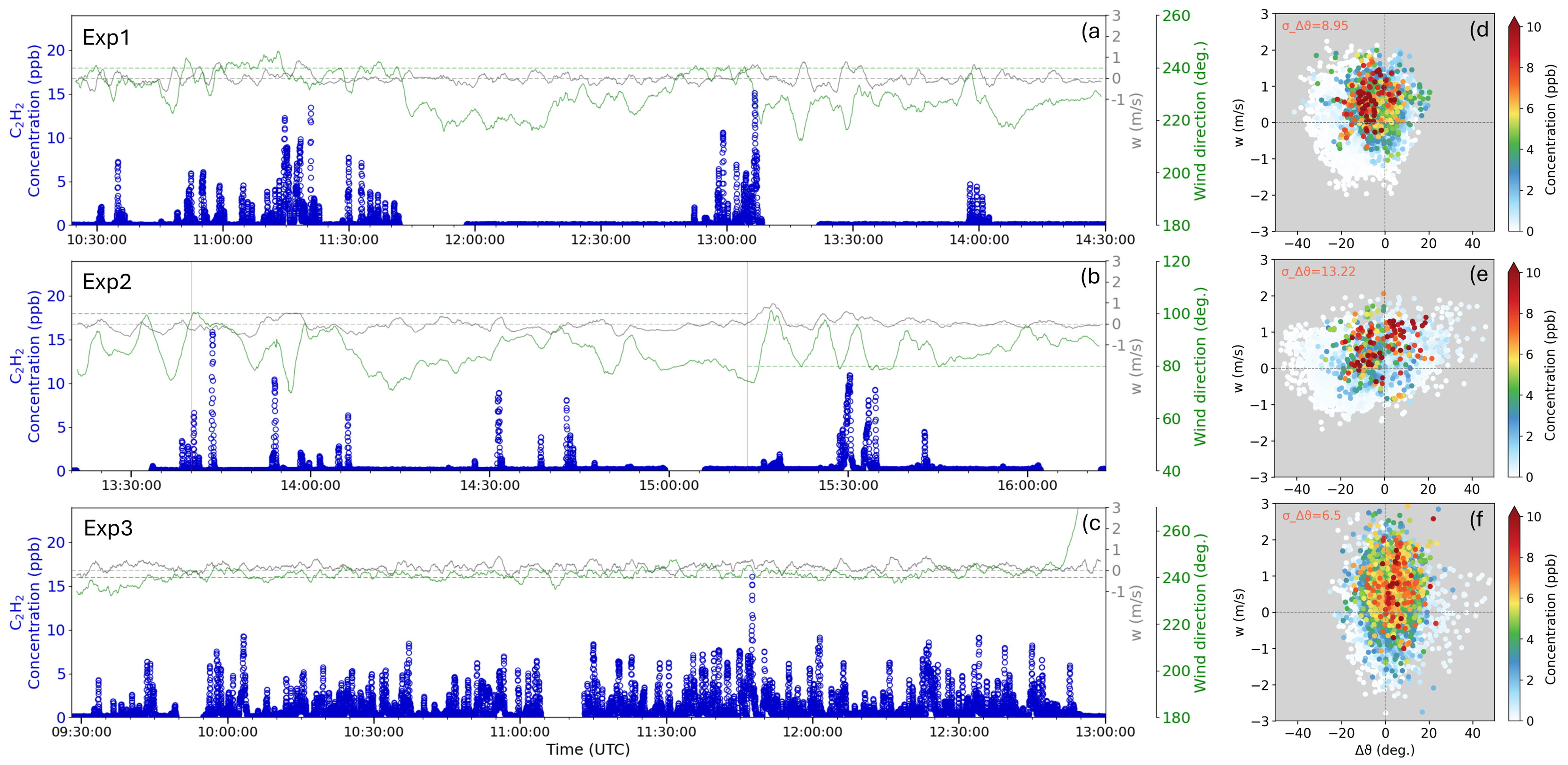

Figure 3. Time series (a-c) and quadrant analysis (d-f) of C_2H_2 concentration, vertical wind speed (w) and wind direction. $\Delta\theta$ is defined as the difference between the wind direction and the azimuth angle from the tower to the releasing point.

Comparison of predicted and measured footprints

- Footprint climatology for each TRE campaign is shown in Fig. 5.
- Two sets of footprints, $f_{(x,y)_m}$ and $f_{(x,y)_p}$, are of similar scale, but exhibit some bias (Fig. 4). Most of the time, $f_{(x,y)_p}$ is higher than $f_{(x,y)_m}$, with the bias possibly due to storage change. The bias decreases as the release time increases, particularly in Exp3 (Fig. 4c).
- An unusual case occurs in Exp2 (Fig. 4b) around 14:30, $f_{(x,y)_m}$ exceeds $f_{(x,y)_p}$, which potentially be associated with non-stationarity. The plateau detected during 11:30 and 12:00 in Exp3 (Fig. 4c) is linked to the abnormal peak observed in the raw concentration time series (Fig. 3c).

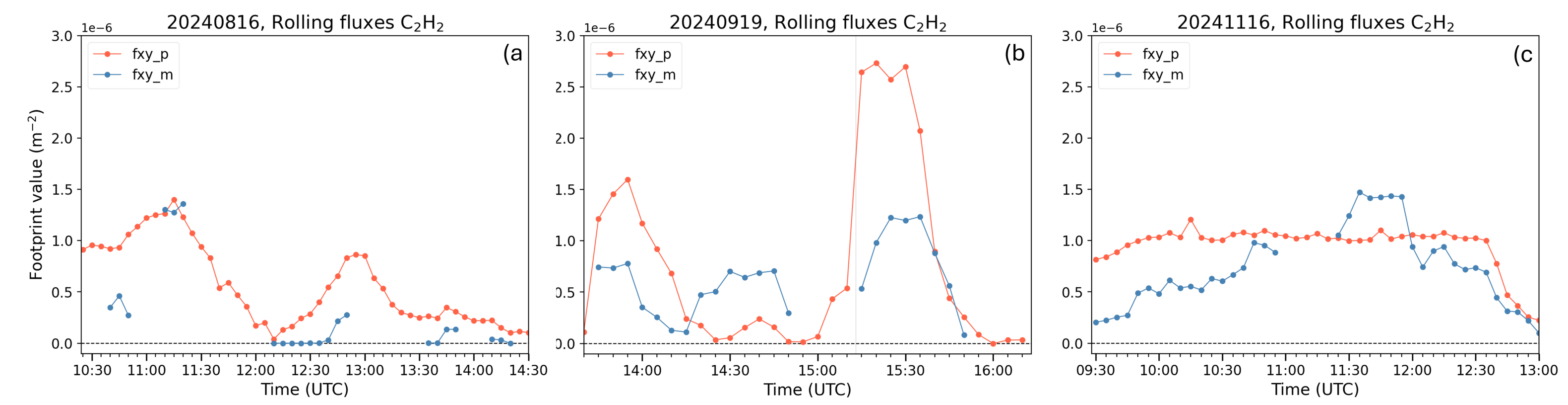

Figure 4. Comparison of the modelled footprint (fxy_p) and measured footprint (fxy_m) at release point.

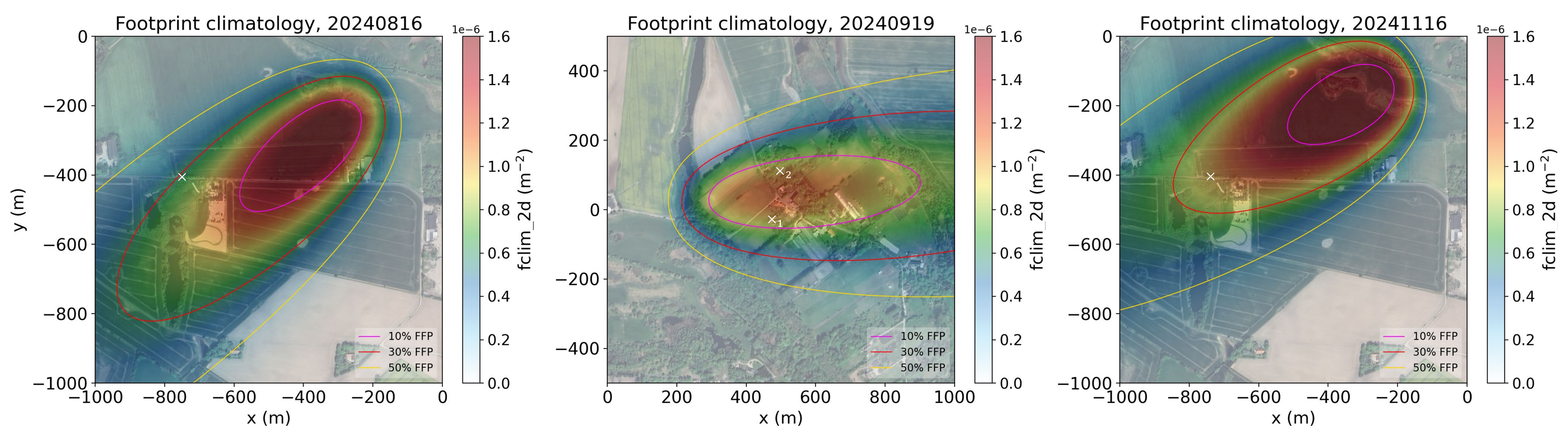

Figure 5. Footprint climatology of three TRE campaigns. White crosses (×) represent release points. The EC tower is located at (0, 0).

Profile

- In EC flux observations, the storage change represents the temporal variation of gas concentration (e.g., CO_2, CH_4, H_2O) below the measurement height.
- Accounting for storage change allows the surface flux to be more accurately quantified, as it consists of both the turbulent flux and the rate of change in gas concentration within the control volume.

$$S = \int_0^{z_m} \overline{\frac{\partial c_z}{\partial t}}\, dz \quad \text{(Eq. 5)}$$

z_m: measurement height
c_z: gas concentration at height z
t: averaging interval

$$F_{sf} = F_{EC_m} + S \quad \text{(Eq. 6)}$$

(Finnigan, 2006)

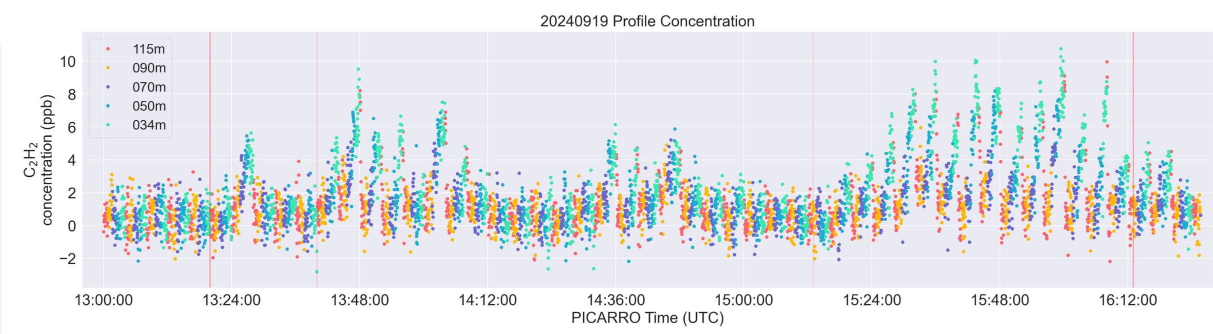

Figure 6. Profile concentrations of C_2H_2 from five levels in Exp2.

- C_2H_2 profile concentrations were measured at various heights (115 m, 90 m, 70 m, 50 m, and 34 m) of the tower in our TREs (e.g., Fig. 6).
- Vertically integrated storage changes (S) were quantified using Eq. 5 and added to F_{EC_m} (Eq. 6).
- The resulted surface fluxes are closer to the model-predicted fluxes but also reveal unexpected negative fluxes (e.g., Fig. 7).
- Single-point vertical profiles observations may not accurately represent the concentration changes across the entire observation area, leading to underestimation or overestimation of the storage term.

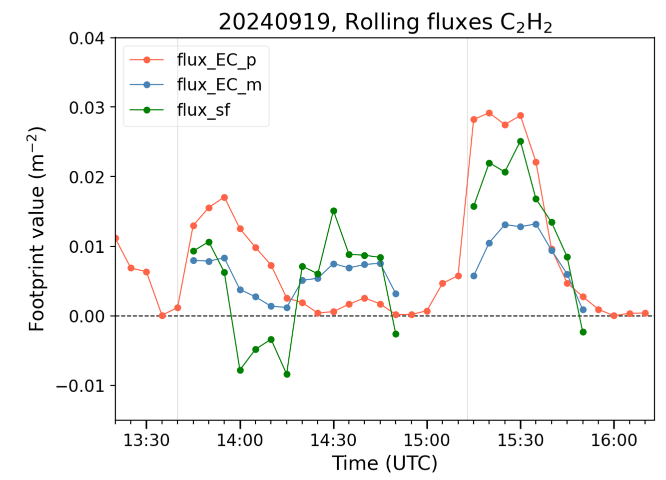

Figure 7. Comparison of model-predicted footprint (flux_EC_p), measured flux (flux_EC_m) and estimated surface flux (flux_sf) in Exp2.

Key Takeaways

- Tracer release experiments can provide independent information and offer empirical examination of the causal relationships between the surface flux at a point in the upstream surface and the flux at measurement level $P_{(0,0,z_m)}$.
- Considering the comparison between the FFP-predicted flux footprint and the EC measurement-based flux footprint, which have similar orders of magnitude, the model's performance is deemed acceptable, acknowledging possible bias of the two approaches.
- The bias may arise from the model's inability to capture complex turbulent transport processes. Alternatively, the bias could result from limitations in the measured data, such as instrument accuracy, property of flow influenced by non-stationarity, roughness or precipitation, and other factors not accounted for in the model.
- The storage change is typically calculated under the assumption that gas concentrations are uniformly distributed below the measurement height. However, under heterogeneous conditions (e.g., TRE), this assumption does not hold, leading to potential errors in storage change estimation and surface flux calculation, which need to be reconsidered.

References

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Acknowledgements

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