

## 1. Motivation

In most footprint studies **computationally inexpensive models** are applied

BUT:

Assumption of horizontally **homogeneous turbulence** can usually not be fulfilled in reality

Increased **uncertainties**

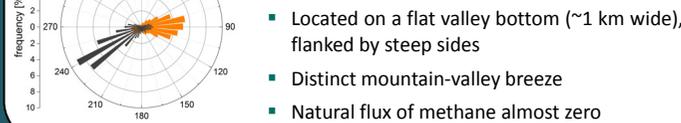
Evaluation at real-world flux sites

Up to now, there are no experiments that evaluate the **2D flux footprint directly**

## 2. TERENO-Research Site „Graswang“, Bavaria



Fig. 1: a) Grassland site in Graswang, southern Germany (47.57° N, 11.03° E; 870 m a.s.l.) with b) the CH<sub>4</sub> flux measurement system and c) the tracer gas diffuser of ~1 m<sup>2</sup> size, c) frequency distribution of wind direction, July-Oct 2013.



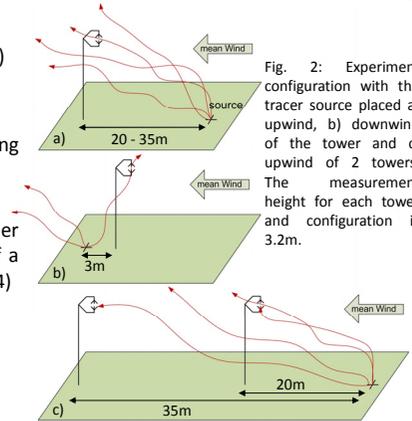
- Located on a flat valley bottom (~1 km wide), flanked by steep sides
- Distinct mountain-valley breeze
- Natural flux of methane almost zero

## 3. Methods

- Eddy covariance measurements (CSAT3, LI7700, LI7500)
- Surface source of ~1 m<sup>2</sup> size (Fig. 1c)
- Tracer gas: CH<sub>4</sub>
- Release rate: 6-8 l min<sup>-1</sup> continuously over one averaging period (10 minutes)
- 3 different experiment configurations (Fig. 2)
- Evaluation of 3 footprint models: Kormann and Meixner (2001), Hsieh et al. (2000) and a parameterization of a backward Lagrangian footprint model (Kljun et al., 2004)
- Flux estimated by the model is determined with

$$\eta = Q_{\eta} f$$

flux estimated by footprint model      footprint weighting factor  
tracer release rate



## 4. Results – Experiments with upwind source

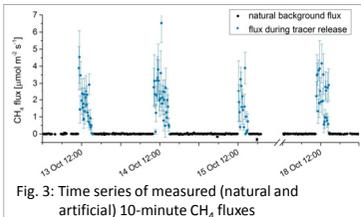


Fig. 3: Time series of measured (natural and artificial) 10-minute CH<sub>4</sub> fluxes

- Artificial flux in most cases ~100 times larger than the natural flux (Fig. 3)  
→ Surface source of just 1 m<sup>2</sup> is a good possibility to precisely validate the 2D footprint
- Daytime-experiments  
→ Mostly unstable conditions
- Hsieh et al. (2000) matches observations best (mode of frequency distribution closest to 1, Fig. 4 left)
- All models underestimate the maximum of the footprint (Fig. 4 right)

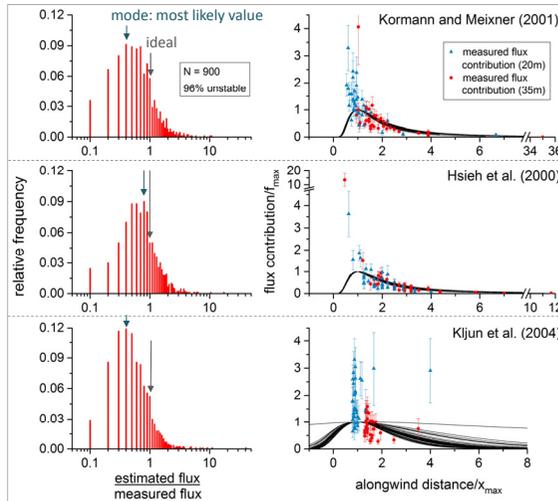


Fig. 4: Left: Frequency distribution of the ratio estimated flux / measured flux, data of experiment configurations a+c are included. Right: Measured and estimated flux contributions standardized with distance of footprint maximum as a function of along-wind distance; only data of experiment configuration c are shown. Vertical bars denote the turbulence sampling error estimated following Finkelstein and Sims (2001).

## 5. Results – Experiments with downwind source

- Flux contribution from downwind source is measurable only occasionally (Fig. 5).
- Downwind contribution depends on streamwise turbulence intensity  $\sigma_w/u$  (Fig. 6+7a).
- Kormann and Meixner (2001) and Hsieh et al. (2000) do not consider downwind contribution.
- Kljun et al. (2004) estimates a downwind contribution for any time period, even when along-wind turbulence intensity is low (Fig. 7b+c).

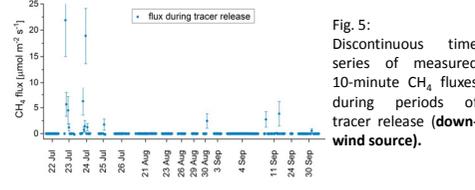


Fig. 5: Discontinuous time series of measured 10-minute CH<sub>4</sub> fluxes during periods of tracer release (downwind source).

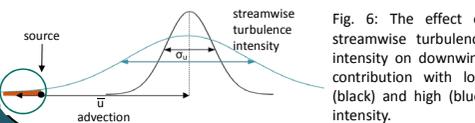


Fig. 6: The effect of streamwise turbulence intensity on downwind contribution with low (black) and high (blue) intensity.

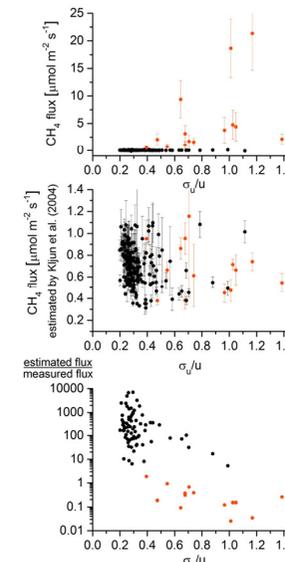


Fig. 7: a) measured 10-minute CH<sub>4</sub> fluxes, b) CH<sub>4</sub> fluxes estimated by Kljun et al. (2004) and c) model performance of Kljun et al. (2004) as a function of  $\sigma_w/u$ .

## 6. Summary

- Tracer experiments aimed at assessing the applicability and utility of commonly used footprint models at real observation conditions.
- Overall, the three evaluated models match observations roughly, but all underestimate the flux.
- We found a measurable contribution to the flux from the downwind source, depending on streamwise turbulence intensity.
- Downwind contribution occurs only intermittently and not continuously.
- The downwind footprint estimate of the Kljun et al. (2004) model needs to be optimized.

### References:

Finkelstein, P. L., and Sims, P. F., 2001. Sampling error in eddy correlation flux measurements. *Journal of Geophysical Research-Atmospheres*, 106, p. 3503-3509.  
Hsieh, C. I., Katul, G., and Chi, T., 2000. An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. *Advances in Water Resources*, 23, p.765-772.  
Kljun, N., P. Calanca, M. W. Rotach and H. P. Schmid, 2004. A simple parameterisation for flux footprint predictions, *Boundary-Layer Meteorology*, 112(3), 503-523.  
Kormann, R. and F. X. Meixner, 2001. An analytical footprint model for non-neutral stratification, *Boundary-Layer Meteorology*, 99(2), 207-224.

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