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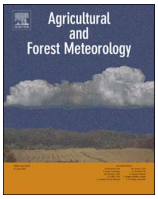

# Experimental evaluation of flux footprint models

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## ABSTRACT

In this study we experimentally evaluate analytical flux footprint models, as well as models based on Lagrangian stochastic particle dispersion. For this purpose, we conducted tracer experiments at a grassland site in southern Germany. An artificial tracer was released continuously over a number of flux-averaging intervals from a surface source. The flux contributions from the tracer source were measured by eddy covariance and compared to those predicted by footprint models. Furthermore, an additional eddy covariance measurement tower was used to evaluate the along-wind distribution of footprint models, as well as to analyze to what extent a forest edge upwind of the measurement tower affects model performance. Additionally, we quantify footprint model uncertainty resulting from the random error of input parameters.

Our measurements show that all evaluated models match observations roughly, but tend to underestimate the value of the footprint maximum, and overestimate its distance. The analysis of stability dependence of model performances indicates that one model, based on simulation outputs of a Lagrangian stochastic model, clearly underestimates observations for near neutral to stable conditions, while no clear stability dependence could be identified for the performance of the other models.

As expected, model performance is sensitive to an abrupt change in surface roughness and sensible heat flux at a forest edge in the near upwind fetch of the measurement tower. Using the local apparent roughness length (derived from measured wind speed and friction velocity) only slightly or negligibly improved model performance compared to the use of a constant local roughness length (determined from local surface characteristics). Thus we confirm experimentally that footprint estimates and related data quality assessments should be handled with care at sites with inhomogeneities in surface roughness.

## 1. Introduction

The widespread use of footprint estimates in conjunction with eddy covariance measurements illustrates that flux footprint modelling is an important, and therefore commonly used, data quality assessment tool in micrometeorology. Over homogeneous surfaces where fluxes from all parts of the surface are assumed to be equal the location of the footprint is not an issue. However, in practical flux measurement conditions ideal conditions are hardly met and complex, heterogeneous sites with naturally varying land cover changes are the rule (Schmid, 2002). Over inhomogeneous areas, the distribution of individual sources/sinks varies within the source area, depending on footprint size and location. In this case, footprint estimates provide valuable information about the spatial representativeness of a flux measurement.

Currently, various models are used to estimate the source area of a flux measurement (see Leclerc and Foken, 2014, for a recent review). In general, researchers are following three different approaches in footprint modelling: first, simple and computationally less intensive analytical models and (semi-) empirical parameterizations (e.g., Hsieh et al., 2000; Kljun et al., 2015; Kormann and Meixner, 2001; Neftel et al., 2008; Schmid, 1994), second, Lagrangian particle models (forward and backward) that are able to account for three-dimensional turbulent diffusion and non-Gaussian inhomogeneous turbulence (e.g., Baldocchi, 1997; Flesch et al., 1995; Kljun et al., 2002; Rotach et al., 1996), and third, the development towards complex "full flow" large eddy simulations (LES) which attempt to address spatial heterogeneity and non-ideal topography explicitly (e.g., Leclerc et al., 1997; Steinfeld et al., 2008). Analytical models and parameterizations assume horizontally homogeneous turbulence, which implies an omnidirectional uniform surface with regard to topography, aerodynamic roughness, and thermal stratification (Rannik et al., 2012). Although this assumption is not usually fulfilled in practical flux measurement conditions, such computationally inexpensive models are often applied at non-ideal, heterogeneous sites, because they are more practical for real

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time data evaluation and long-term observations. Consequently, such source area estimates contain increased uncertainties and can be used just as a first approximation for real observation conditions (Rannik et al., 2012). This difficulty raises the question of how reliable footprint model results are at real-world flux sites. Therefore, footprint model evaluation experiments under non-ideal surface and atmospheric conditions are required (Foken and Leclerc, 2004).

Up to now, there are just a few studies that evaluate flux footprint models. They follow mainly four different approaches: first, the use of artificial tracers (Finn et al., 1996; Leclerc et al., 2003a,b; Mölder et al., 2004); second, the use of natural tracers where known differences in source strength (e.g., of two adjacent fields) are exploited (Goeckede et al., 2005; Marcolla and Cescatti, 2005; Nicolini et al., 2015; Reth et al., 2005; van de Boer et al., 2013); third, the use of wind-tunnel tracer experiments (Kljun et al., 2004); and fourth, the inter-comparison of footprint models (Kljun et al., 2015, 2003; Markkanen et al., 2009). Additionally, footprint models can also be tested implicitly by applying them over areas with small-scale inhomogeneity and analyzing the variability of measured fluxes as a function of flux footprint size and orientation (Schmid, 1997; Schmid et al., 1991).

While the first group of studies used line sources of an artificial tracer to evaluate the 1-dimensional, crosswind integrated footprint, in the present work we evaluate the 2-dimensional, crosswind distributed footprint, using a single, small finite surface source. To our knowledge, no previous study has directly evaluated the 2-dimensional flux footprint distribution.

The specific aim of the present study is to assess the applicability and utility of our proposed 2-dimensional flux footprint evaluation method at the hand of the analytical footprint models by Schmid (1994) and Kormann and Meixner (2001), as well as the footprint parameterizations of Hsieh et al. (2000) and Kljun et al. (2015), in real field conditions. For this purpose, validation experiments with a small ($\sim 1\ m^2$) surface source of an artificially released tracer gas (methane) were conducted at a grassland site in southern Germany. Methane was chosen as tracer gas for two reasons: first, because of its measurability with a fast response sensor, and second, because of its negligible natural flux at the chosen experimental site. The tracer flux was measured by the eddy covariance technique. By comparing measured flux contributions from the tracer source to those predicted by the footprint models, the accuracy of the modelled 2-dimensional flux footprint can be assessed. With different experimental setups, we are able to examine contributions to the measured flux from sources at various upwind and crosswind distances. Furthermore, we analyze the extent to which footprint model performance is affected, if upwind turbulence is disturbed by abrupt changes in surface roughness and sensible heat flux.

## 2. Materials and methods

### 2.1. Model evaluation approach

The flux footprint is a probability function that describes the relation between the spatial distribution of surface sources/sinks and a measured flux. It can be expressed in an integral equation over domain R, following Schmid (1994):

$$F(r)=\int_R \tilde{Q}\left(r'\right)\cdot f\left(r-r'\right)dr' \tag{1}$$

where F is the measured flux at location r, $\tilde{Q}$ is the spatial distribution of stationary surface sources/sinks and f is the footprint or source weight function.

In case of a 2-dimensional footprint function, i.e., when it includes not only the crosswind integrated distribution in along-wind direction, but also the crosswind dispersion, a source-weight density or footprint value for every location relative to the flux measurement can be determined, following e.g. Schmid (1997) as a linear combination of the crosswind integrated footprint $\overline{f}^y$ and the crosswind distribution $D_y$:

$$f(x, y, z_m) = \overline{f}^y(x, z_m)\cdot D_y(x, y) \tag{2}$$

where x is the upwind distance, y is the crosswind distance, and $z_m$ is the measurement height. The approach to determine f, $\overline{f}^y$ and $D_y$ differs among footprint models.

If this footprint function is integrated over a finite elemental surface area, the resulting factor reflects the probability of the elemental surface source to contribute to the measured flux. Considering an elemental surface source with a constant emission rate Q, the spatial distribution of stationary surface sources/sinks $\tilde{Q}$ can be expressed as

$$\tilde{Q}(r') = Q\cdot\delta(r') \tag{3}$$

where δ denotes the Dirac-delta distribution function. For this special case, equivalent to Eq. (4) in Schmid (1994), (1) simplifies to

$$F(r) = Q\cdot f(r-r') \tag{4}$$

Therefore, the measured flux at location r results from the source strength Q multiplied with the footprint weighting factor at the source's location. After transforming (4) the footprint weighting factor can be inferred from the measured flux, divided by the source strength:

$$f\left(r-r'\right) = \frac{F(r)}{Q} \tag{5}$$

In this study, we evaluate the analytical flux footprint models of Kormann and Meixner (2001) (hereinafter referred to as KM) and Schmid (1994) (FSAM), as well as the empirical footprint parameterizations based on Lagrangian simulation results of Kljun et al. (2015) (FFP) and Hsieh et al. (2000) (HS). While the first three models provide 2-dimensional footprints HS is only 1-dimensional by neglecting crosswind dispersion. Since our evaluation strategy with the given experiment setup (Section 2.3) requires a 2-dimensional source weight function, we expanded the crosswind integrated footprint of Hsieh et al. (2000) with the crosswind component of the KM model. This was also done by van de Boer et al. (2013), who applied the crosswind component of KM, as well as the one proposed by Detto et al. (2006), to the originally 1-dimensional model of Hsieh et al. (2000) and found no difference between these two, based on their natural tracer experiment.

Corresponding formulae of the footprint functions used in this study can be found in the original publications. However, the crosswind integrated distribution of FSAM (Schmid, 1994) given as

$$\overline{f}^y\left(x, z_m\right) = -\int_{z_0}^{z_m} \overline{u}(z)\cdot\frac{\partial}{\partial x}\overline{C}^y\left(x, z\right)dz \tag{6}$$

where $\overline{f}^y$ is the crosswind integrated flux footprint distribution, $\overline{C}^y$ is the crosswind integrated concentration distribution and $\overline{u}(z)$ the mean wind speed profile, was determined following the parameterization of Horst and Weil (1994)

$$\overline{f}^y \approx -\frac{d\overline{z}}{dx}\frac{\partial}{\partial\overline{z}}\left(\frac{z_m}{\overline{z}}\right)\left(\frac{\overline{u}(z_m)}{U(\overline{z})}A\exp\left(-\left(\frac{z_m}{b\overline{z}}\right)^r\right)\right) \tag{7}$$

with the mean plume height $\overline{z}$, the measurement height $z_m$, the mean wind speed $\overline{u}$ at $z_m$, the plume advection velocity U and additional parameters A, b and r (for definitions, see Gryning et al., 1987; and Horst and Weil, 1994).

As the parameterization in (7) is only an approximate solution of (6), its integration with respect to x (upwind distance) does not equal unity exactly. To force the computed integral footprint to unity, discrete footprint function increments are sorted according to their value and then summed to where the footprint function decreases to 1% of its maximum. The footprint function is then scaled by this sum. At this point, we should mention that versions of FSAM distributed after December 1996 contained an error that affected the shape of the