Methods and limitations in validation of footprint models

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Abstract

This paper assesses the progress made over the last decade in validating footprint models, and highlights shortcomings which need addressing. This paper also presents alternative methods of validating footprint models. The vigorous expansion of footprint models was spurred by the development and subsequent widespread application of primarily analytical solutions to the advection–diffusion equation and Lagrangian simulations. In this paper, we draw attention to the range of experimental conditions supporting both a judicious use and application of these methods. We discuss present limitations restricting footprint model applicability, mostly for sites which depart from ideal conditions and model conditions which deviate from their original assumptions. Intercomparisons of footprint models reveal differences amongst the different footprint models, prompting subsequent recent validations of footprint models. Despite the few existing studies, the issue of validation remains an outstanding problem in micrometeorology. In this paper, three concepts are discussed and compared: (1) the use of artificial tracer gases; (2) the use of natural sources of scalars; (3) the presence of obstacles in the flowfield and their influence on the footprints. Finally, the conditions of applicability of each method are discussed.

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1. Introduction

Prompted by the proliferation of eddy–covariance flux systems measuring the turbulent exchange of gases between the surface and the atmosphere for a myriad of ecosystems (Baldocchi, 1988), the last decade has seen an explosion in the field of footprint research. Following the initial papers on the subject dating back to 1990 (Leclerc and Thurtell, 1990; Schuepp et al., 1990), the interest has extended to the changes in footprint area with the physical characteristics of the sites and with atmospheric conditions. The individual sources and sinks within the footprint area all contribute to the measurements made at a point above the surface, and therefore their variation in time and space is of great importance (Leclerc et al., 2003b). Because landscapes containing natural surfaces are intrinsically inhomogeneous in their bio-geochemical source properties on all
scales, the determination of the appropriate footprint becomes ever more complicated.

When we add the vegetation-specific response to environmental variables such as water stress, local cloud formation and sun angle to the fact that gaseous exchange is species-dependent, the problem of accurately assigning a fraction of the flux contributed by a given patch poses a formidable challenge. The footprint climatology further compounds the problem: surface properties upwind, often wind-direction dependent (Amiro, 1998) often lead to considerable within-footprint spatial variability. Finally, despite the care taken by experimentalists to select a site approaching ideal conditions, non-local surface forcings from regions well beyond the footprint can unexpectedly and surreptitiously arise to introduce large errors into flux measurements (Leclerc et al., 2003b). These errors are of particular concern since non-local advection, i.e. the advection outside the footprint region/fetch region, cannot be separated from the within-footprint surface-atmosphere turbulent exchange data, unless specific methods such as tracer methods are used to precisely apportion the respective contribution of each source area (Leclerc et al., 2003b). This may call for a re-examination of the footprint concept, in which the very nature of the definition assumes that 100% of the measured flux is contained within the footprint envelope. It is thus important to realize that flux data does not necessarily constitute a ‘de facto’ measure of the surface-atmosphere exchange from the region delineated by the footprint.

Footprints using analytical solutions to the advection–diffusion equation with the forward approach, abound (Haenel and Grünhage, 1999; Horst, 2001; Horst and Weil, 1994; Kaharabata et al., 1997, 1999; Kormann and Meixner, 2001; Schmid, 1997, Schuepp et al., 1990; Soegaard et al., 2003) and the backward approach (Kljun et al., 2002; Wilson and Swaters, 1991). An extensive survey of this topic was presented recently by Schmid (2002).

Footprint descriptions and applications using the Lagrangian stochastic simulation (Falk, 1998; Flesch, 1996; Kurbamuradov et al., 1999; Kurbamuradov and Sabelfeld, 2000; Leclerc et al., 1997; Leclerc and Thurtell, 1990; Lee, 2003; Luhar and Rao, 1994; Markkanen et al., 2003; Rannik et al., 2000) have recently proliferated. The work by Baldocchi (1998) identifying ground versus individual canopy layer contributions to flux footprints should be highlighted, as this is the first attempt to partition the different sources inside vegetated canopies contributing to a point flux measurement.

In addition to analytical solutions and random flight methods, a third method of examining the footprint in the convective boundary layer has been used by Leclerc et al. (1997). This is, to our knowledge, the only study which uses the Large-Eddy simulation (hereafter referred to as LES) to determine footprint fluxes. This method is particularly powerful and is ideally suited for footprint studies over patchy surfaces or over terrain of moderate complexity.

Luhar and Rao (1994) used a higher-order closure model to derive inputs for a Lagrangian stochastic model to describe the change in footprint behavior resulting from a modest contrast in surface roughness and moisture conditions, simulating the step change between an arid soil to an irrigated crop. Though the Luhar and Rao (1994) study clearly contributes to our insight into the footprint behavior over terrain of spatially varying surface roughness and scalar fluxes, this line of study needs more detailed investigation.

2. Comparison concepts

In a recent intercomparison of footprint models, Kljun et al. (2003) have shown differences amongst models using similar input parameters. Therefore, an ‘in situ’ validation of footprint models in natural, non-ideal surface and atmospheric conditions is needed. Only a handful of validation experiments are available (Cooper et al., 2003; Finn et al., 1996; Leclerc et al., 1997, 2003a, 2003b), despite the remaining need for testing models for many environmental sites and source configurations. The last four studies mentioned above focus on one-dimensional validation of flux footprints, assuming a crosswind infinite tracer line source configuration. Such tracer flux studies can use source configurations, which reflect the more complex scenarios of spatial inhomogeneities in the field. This is important since footprint models are often used in ‘relaxed’ conditions, which violate the basic tenets and assumptions inherent to these models (Foken et al., 2000; Göckede et al., 2004).
There is no general criteria guiding validation of footprint models. Validation conditions and experimental set up should respect the assumptions of the footprint model. These assumptions are often for idealized conditions departing from real site conditions, where robust footprint models are most needed. Therefore, the validation should be done also for non-ideal conditions such as heterogeneous surfaces, obstacles in the source area, and should include a wide range of possible atmospheric stabilities.

In terms of operational micrometeorological research, confidence in current footprint models is critically needed not for idealized, simplified surface, site and atmospheric conditions, but for specific natural, realistic sites departing from the idealized conditions.

2.1. The use of an LES-generated dataset

An artificial dataset produced numerically has shown that the Large-Eddy simulation compares favorably against experimental data and against other models (Leclerc et al., 1997). This simulation offers additional insight into footprint characteristics as the height of the measurements above the surface increases. It shows a weakening of the surface-atmosphere linkage with height, with a dramatic reduction in the footprint peak and a more uniform contribution with upwind distance of individual upwind sources to the fluxes. This evidence also shows that the footprint envelope outside the atmospheric surface layer includes surfaces covering several kilometers, thus demonstrating the necessity of having a detailed knowledge of these upwind surface properties, as well as the footprint for that particular measurement level, even in daytime conditions. This additional information is particularly important for aircraft flux measurements or those made on high flux towers.

2.2. The use of artificial tracers

Artificial atmospheric tracers have been used to validate footprint estimates (Finn et al., 1996; Leclerc et al., 2003a, 2003b; Mölder et al., 2004). Using an artificial tracer such as SF6 provides several advantages: firstly there are no other sources, and provided a suitable tracer, is selected there is neither any sink of the tracer. When properly chosen, other advantages include their low water solubility, and their chemical inertness to atmospheric gases and ultra-violet radiation. Tracers have to be chosen that do not adhere to surfaces or tubing walls. Other gases which are atmospheric constituents can also be used as tracers: CO2 for instance, has been used earlier as a tracer to validate a Lagrangian stochastic model inside an alfalfa canopy (Leclerc et al., 1988). Given the variation in the ambient CO2 concentration from sources and sinks, the released tracer concentration must be several orders of magnitude greater than the natural spatial gradients of concentrations observed in the field.

Finn et al. (1996) and Leclerc et al. (2003a) have successfully taken advantage of the properties of the artificial tracer SF6 to determine source-receptor relationships and apply those to validate footprint models. In these experiments, the tracer was released from a line source and sampled at different positions downwind from the tracer source. A typical example of such a validation is given in Fig. 1. This is equivalent to the tracer being released at several upwind positions and sampled at a unique location, a configuration which represents the signature from

![Fig. 1. Example of validation of footprint models with artificial tracers over an 11-year-old managed slash pine canopy (Pinus elliottii L.) at the Florida AmeriFlux site near the Austin-Cary Memorial Forest of the University of Florida, Gainesville, FL, between 22 March and 26 April, 2000. Comparison of the Lagrangian footprint simulation (- - -) and the analytical solution (—) with observed footprint flux during NNE–NE winds for mildly unstable conditions against streamwise distance x, from Leclerc et al. (2003a), z is the height, d the zero-plane displacement, \( U \) the wind velocity, \( u_* \) the friction velocity, \( \sigma_w \) the standard deviation of the vertical wind velocity and \( L \) the Obukhov length.](image-url)
each of the upwind sources to a point flux measurement. Whereas the use of multiple sources causes considerable difficulty, since the multiple tracers would have to be discriminately sampled downwind, as pointed out in Leclerc et al. (2003a). Furthermore, validating the location and amplitude of the peak in the footprint function represents an experimental challenge as the peak is often close to both the modeled and measured flux measurement point with the usual problem that the vegetated surface surrounding the flux system is partly disturbed by the experimental installation.

Studies using artificial tracers have become increasingly complex as they try to approximate natural field conditions. The first study of this kind (Finn et al., 1996) tested flux footprint models over short sagebrush canopies at positions of 5 and 10 canopy heights, far away from any sources and sinks and thus, from the Lagrangian point of view, many timescales away from the canopy. The latter point is important in the description of the diffusion (Batchelor, 1953) since diffusion is a function of the distance from the source for short diffusion times and becomes a function of the turbulence for long diffusion times (approximately three or more Lagrangian timescales). The second study (Leclerc et al., 2003a) examined flux footprints over canopies of intermediate roughness, evenly spaced, closely approximating ideal conditions. In that experiment, sensors were placed within the roughness sublayer. Both the Lagrangian and analytical models tested performed adequately, with the Lagrangian model reproducing particularly well the diffusion and flux footprint close to the tracer source (Fig. 2), something that cannot be achieved with analytical solutions. The third artificial tracer study (Leclerc et al., 2003b) explored the adequacy of analytical and stochastic models when tested in the roughness sublayer over a very rough canopy. Also a study for a test site where upstream conditions hundreds of meters upwind from the footprint region exhibited considerable contrast in surface properties, when compared with the source region predicted by footprint models. Sodar data was used to support the evidence found in the tracer flux footprint study (Leclerc et al., 2003a). The results showed again that both models performed adequately when the wind blew from the undisturbed region. However, footprint fluxes were off by as much as 300% when the wind blew from the region where there was a marked change in the surface (in this case a major clearcut). This important result sheds further insight on the behavior of flux footprints and when they are applicable. Previously it was thought that assumptions of horizontal homogeneity applied only to the surface within the footprint. However these results reveal the importance of advection i.e. the contribution to a point flux measurement from outside the predicted source region when those two areas have dissimilar properties. In the Leclerc et al. (2003b) study, the contrast in surface conditions included both a change in surface roughness and a change in energy balance (bare soil in the clearcut area). In the low wind conditions often present throughout the Florida peninsula, changes in surface energy balance have been shown to create strong, organized flow circulations, similar to those shown in earlier studies by Shen and Leclerc (1994, 1995). The strength and spatial coverage of these circulations are proportional to the size of the
disturbance and inversely proportional to the wind speed (Shen and Leclerc, 1994, 1995). Since the Leclerc et al. (2003b) study clearly demonstrated that such features are of particular concern, because advection from outside the footprint region cannot be separated from the within-footprint surface-atmosphere turbulent exchange data. Thus, uncertainty arises for three-dimensional sources of carbon dioxide or water vapor, unless specific methods such as tracer flux techniques are used precisely to partition the non-local advection contribution (Leclerc et al., 2003b). In the future, the surface seen by a flux system should be considered as a composite not only of the turbulent exchange originating from distinct sources within the fetch region, but in some cases, also of sources located well outside the footprint (the non-turbulent portion of the measured flux). Thus, we should bear in mind that the current footprint definition and models may not sufficiently determine whether or not fetch is adequate.

2.3. The use of natural tracers

Few studies using natural tracers have been reported in the literature. Cooper et al. (2003) reported a recent study, in which water vapor was used as a natural tracer to study the footprint from different moisture sources seen by a two-dimensional lidar. The Cooper et al. (2003) study showed, using a combination of three-dimensional lidar and tower data, footprints observed at different heights and compared their results against those obtained using a Lagrangian simulation to calculate footprints at similar levels. In this study, the authors found an agreement between point flux measurements of evapotranspiration, lidar-derived moisture fluxes and a footprint model.

Rannik et al. (2000) have analyzed the contribution of sources and sinks of carbon dioxide to measured fluxes and concentrations above a Douglas fir forest canopy and found qualitative agreement between fluxes and simulations. Their Lagrangian stochastic model satisfied the well-mixed condition criteria (Thomson, 1987) using models by Kurbanmuradov and Sabelfeld (2000). The Thomson model has been identified by Reynolds (Reynolds, 1998) as the ‘optimal’ model, since it fulfills a series of necessary diffusion criteria. Rannik et al. (2000) also compared the Schuepp et al. (1990) compact analytical solution and that of Horst and Weil (1994). They further compared their stochastic models inside the forest canopy against that of Baldocchi (1998).

In addition to the methods discussed above, another, altogether different method of validating footprint models over a realistic site characterized by two adjoining dissimilar surfaces can be used. A test can be done using three eddy–covariance flux systems with two of these placed at a low level over each of the two adjoining surfaces with a third instrument operating at a higher level and measuring fluxes, which are a spatial integration of over sites (Fig. 3). The fractional contribution of fluxes from each site depends on atmospheric stability. The model validation can then be done by comparing the fluxes measured on the higher tower with the footprint area averaged flux using a mosaic approach (Avissar and Pielke, 1989) based on the measurements on both lower towers. A first test of this method by Markkanen and Göckede (2003, personal communication) was done during an experiment at the boundary layer measuring field of the German Meteorological Service near Lindenberg/Germany over grassland and field crops (Beyrich et al., 2002a). They found that the Lagrangian stochastic simulation (Rannik et al., 2000) better represented the flux contributions.

Fig. 3. Schematic layout for a footprint comparison experiment with natural tracers. The fluxes two contrasting surfaces are measured by single eddy covariance systems. A third system measures the flux from a footprint area, which includes different percentage of the fluxes from the two surfaces depending on the atmospheric stability.
from the different fields than the analytical model (Schmid, 1997).

A similar example was investigated during the LITFASS-98 experiment in Lindenberg/Germany. The diurnal cycle of the momentum flux measured using a 99 m tower on June 17, 1998 is presented in Fig. 4. The momentum flux is usually assumed to decrease with height. Contrary to this assumption, one of the most salient features is a significantly smaller momentum flux measured at 10 m than that at the other levels. The interpretation of fluxes measured on the tower has to include a detailed footprint analysis, since the turbulence measured at different levels is likely to originate from different source areas (surface types) in the inhomogeneous landscape around this tower. Here, the source area was determined in relation to the underlying surface characteristics and atmospheric stability using a two-dimensional footprint model (Schmid, 1997). Stability was estimated using local surface layer measurements and roughness length surrounding the tower was estimated for a 250 m grid size according to the European Wind Atlas procedure (Petersen and Troen, 1990). The mean roughness length in the footprint area of the different tower levels on June 17 is shown in Fig. 5. It becomes obvious that the comparatively small momentum flux at 10 m noted above can be explained by a significantly smaller surface roughness in the corresponding footprint area compared to those for the footprint areas of the higher measurements. It should be noted that this example can only illustrate the influence of roughness on momentum flux, since the Schmid model (1997) is unable to simulate momentum flux footprints.

2.4. Isolated heterogeneities

Since isolated heterogeneities within or outside the footprint areas can influence the measurements at a point above the surface, they can also be used to assess the size of the footprint area. DeBruin et al. (1991) classified sites according to the type of heterogeneities, e.g. sites with heterogeneities in the surface roughness, and sites with heterogeneities in the surface temperature or other scalars. To identify these heterogeneities, they used normalized standard deviations (integral turbulence characteristics) of the wind.

\[
\frac{\sigma_{w,u,v}}{u_*} = f\left(\frac{z}{L}\right) \ldots
\]

and temperature

\[
\frac{\sigma_T}{T_*} = f\left(\frac{z}{L}\right) \ldots
\]

or of other scalars, where \(\sigma_{u,v,w,T}\) are the standard deviations of the three wind components and the temperature, \(u_*\) the friction velocity, \(T_*\) the dynamical temperature, \(z\) the height and \(L\) the Obukhov length. In the near-neutral range, these expressions are nearly constant and for temperature, these are not defined because of \(T_* \rightarrow 0\). Typical empirical functions are given in several textbooks (Arya, 2001; Foken, 2003; Lumley and Panofsky, 1964; Panofsky and Dutton, 1984; Stull, 1988). These values are only valid for homogeneous surfaces and significant differences can be found when these expressions are extrapolated to other more complex surfaces. DeBruin et al. (1991) used these differences between modelled values and
experimental results to define heterogeneities in surface roughness (Eq. (1)) and scalars (Eq. (2)).

These differences between modelled and measured integral turbulence characteristics were also used by Foken and Wichura (1996) to check the data quality of eddy–covariance measurements. This based on the fact that the theory of eddy–covariance measurements assuming homogeneous surface conditions. The degree of data quality, determined as the ratio of the measured to modelled integral turbulence characteristics, should be significantly lower when there are spatial changes in the surface properties within the footprint area due to either roughness characteristics or the presence of obstacles.

Inspection of data quality and subsequent signal processing which form necessary steps in the analysis of micrometeorological flux information (Foken et al., 2004), can also be applied to provide an ‘in situ’ validation of footprint models: since the footprint is changing due to surface roughness and atmospheric stability. Heterogeneities and obstacles in the landscape introduce short-lived flow perturbations within the footprint and hence variations in the measured fluxes. A footprint-dependent analysis of the data quality (Göckede et al., 2004) has recently shown the data quality of fluxes to degrade when measurements are made over heterogeneous surfaces contained within the footprint region, when compared against data collected over homogeneous surfaces. Thus this suggests that the effect of significant obstacles or heterogeneities can be used to validate the footprint model.

Using the ratio of modelled to measured integral turbulence characteristics as a validation method is illustrated for the Weidenbrunnen/Waldstein (Gerstberger, 2001) site (50°09′N, 11°52′E), it is a 18 m high (in 1998) spruce forest FLUXNET site at 775 m a.s.l. used in European carbon exchange programmes (GE1): for a 2-month experiment in 1998 (Foken et al., 1999). The footprint for different wind directions and atmospheric stabilities was determined for sensors placed at 32 m. Results from the footprint model by Schmid (1997) are shown in Fig. 6. Two significant heterogeneous areas can be identified. The first such heterogeneous area is represented by a sharp step change in a surface going from a tall forest to a clearing in the west to south-west direction at a distance of about 250 m. The second spatial heterogeneity consists of the presence of the ‘Großer Waldstein’ mountain exerting a large drag on the flow near the surface; that flow obstacle is located in the south to south-west direction at a distance of about 1.5 km and 870 m a.s.l. Both effects can be identified in these wind sectors when the footprint area includes the disturbance region. This suggests that the effect can only be found in selected conditions, such as in night time conditions.

Fig. 7 illustrates the standard deviation of wind direction in unstable and stable conditions as a function of wind direction. This variable is used in

Fig. 6. Footprint areas for the Waldstein/Weidenbrunnen site in Germany for different wind directions and atmospheric stabilities (Foken et al., 2000). Contours at 10 m intervals.
Fig. 7. The standard deviation of wind direction ($\sigma_\psi$) for the Waldstein/Weidenbrunnen site (see Fig. 6) for unstable and stable conditions as a function of wind direction (Foken et al., 2000).

Fig. 8. With the friction velocity ($u_*$) normalized standard deviations of the vertical wind velocity ($\sigma_{u_z}$) for the Waldstein/Weidenbrunnen site (see Fig. 6 in (a) unstable and (b) stable conditions as a function of wind direction (Foken et al., 1999).
several models to determine atmospheric stratification (Hicks et al., 1987) or to classify diffusion in air pollution studies (Blackadar, 1997). The observations show that the standard deviation of the wind direction is significantly higher for winds for the sector 225° to 270 than for other wind directions. This is a result of the step change between the forest height and the clear cut at a distance of about 250 m and occurs within the main source region of the measured flux.

The investigation of the dependence of the normalized standard deviation of the vertical wind velocity on wind direction is shown in Fig. 8. In unstable stratification, a good agreement between data and the parameterized values was found (Fig. 8a). In contrast, in stable conditions with large footprint areas (Fig. 8b) a significant difference was found in the wind sector 180–225°. For this situation, the source area of the flux includes the peaks of ‘Großer Waldstein’, which produce significant mechanical turbulence.

If isolated heterogeneities occur within the footprint area of an experimental site, investigations should be done, either to assess the overall data quality for different footprint areas according to Göckede et al. (2004) or to identify spatial heterogeneities using stability-dependent footprint analyses together with data quality checks using integral turbulence characteristics. The latter method does not only help understand the site conditions; they can also be used to assess the size of the footprint area.

Table 1
Comparison of validation methods

<table>
<thead>
<tr>
<th>Validation method</th>
<th>Artificial tracer</th>
<th>Natural tracer</th>
<th>Isolated heterogeneity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental design</td>
<td>Special experimental design</td>
<td>Special structure of the natural surface</td>
<td>Clear isolated heterogeneities or obstacles</td>
</tr>
<tr>
<td>Conditions</td>
<td>Mostly ideal conditions \textsuperscript{a}</td>
<td>Often ideal conditions \textsuperscript{a}</td>
<td>Non-ideal conditions</td>
</tr>
<tr>
<td>Test of assumptions of footprint models</td>
<td>In agreement with the footprint model</td>
<td>Often in agreement with the footprint model</td>
<td>Not in agreement with most footprint models; determination of the range of validity</td>
</tr>
<tr>
<td>In situ test/use of running systems</td>
<td>For fundamental research only</td>
<td>Possible in special conditions of running systems</td>
<td>Possible in special conditions of running systems</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Ideal conditions in the framework of similarity theory such as horizontal homogeneity.

3. Concluding remarks

This paper has demonstrated that while a considerable number of analytical and Lagrangian footprint models have been developed and subsequently widely used, these models have not been validated in many of the experimental conditions in which they are being used. It was therefore our aim to classify footprint validation methods and to present currently available results from both the literature and from our own measurements. Since footprint models are widely used by experimentalists outside the micrometeorologists community, who are often unfamiliar with the assumptions and limitations of such models, this issue is one of great importance.

The three methods discussed in paragraphs 2.2–2.4 are compared in Table 1. The criteria used here to intercompare different footprint models include (1) characteristics of the experimental design (measurement level and location with respect to surface properties), (2) characteristics of the underlying surface, (3) test criteria conform to assumptions of the footprint model and (4) possibility of validation for a running system.

While experiments with artificial tracers are often cost-prohibitive, the natural tracer method is inexpensive and easier to use, and represents a considerable attraction. Until now, such experiments have been few; but will hopefully become more common in the future. The proposed experimental design for footprint model validations should be transferable to other experiments with similar conditions. This method is in excellent agreement with practical cases and should be used whenever possible, since footprint models are often used in these conditions to provide a better interpretation of flux measurements.

The following topics should be included in future research programs:

1. Further development in the area of artificial tracer studies should include using multiple tracer techni-
ques in three-dimensional footprint studies, with tracers placed at several positions on the soil surface, in the understory and in the crown space. Tracer studies represent powerful tools that should be used to investigate the influence of non-homogeneous surfaces on the footprint of fluxes or concentrations.

2. Well designed experiments with natural tracers should be done to investigate the application range for different footprint models. Often such studies can be included into on-going flux field campaigns.

3. Further studies should also include the routine application of footprint models as part of signal processing package in the field for ‘in situ’ determination of the reliability of the dataset.

4. Greater consideration ought to be given to the presence of discontinuities upward beyond the footprint region, particularly in calm conditions or in conditions in which the upward patch/discontinuity exhibits a large thermal contrast.

5. Gaps in canopies, flow obstacles such as isolated trees or distant tall man-made structures, and their effect on footprint functions (and measured fluxes) should be investigated, with special precautions taken under nighttime conditions.

6. The Large-Eddy simulation is a formidable tool which should be used to investigate complex flux footprints originating from patchy terrain and other three-dimensional sources and sinks. The formulation of flow statistics in the LES makes it an ideal tool as an alternative to expensive and time-consuming experiments, and other footprint model formulations should be tested against this method.

7. The closer to the canopy footprint validation experiments are done, the more critical it is to measure and describe actual detailed flow statistics in flux footprint models, given that roughness sublayer flow statistics differ from those above. Also in the roughness sublayer the wind profile departs from its logarithmic behavior, even in neutral conditions. Sensitivity analyses are needed to help quantify the response of models to different parameterization of flow statistics.

8. The treatment of horizontal turbulent diffusion, in particular within the vegetation should be incorporated into footprint models.

9. Differences in footprints for scalars and fluxes and specially the footprint for the momentum flux should be investigated.

Many questions still remain unanswered. In spite of this, footprint models are very useful albeit indispensible to most eddy-covariance flux studies.

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