Chapter 1
History and Definition

This chapter describes the challenges and the history of micrometeorology. For sake of comprehensiveness, it also provides an overview of essential definitions that the reader might consider becoming familiar with before delving deeper into the present volume. Furthermore, this chapter provides the historical perspective of the evolution of a rapidly maturing field right up to the development of recent footprint tools used in research as in applications. It should be apparent to all that such an overview can only scratch the surface while some of the details will be described in the following chapters. It goes without saying that this overview is tinted by the experiences of the authors.

1.1 Micrometeorological Measurements

At the beginning of the last century, much progress was made in hydrodynamics beginning with the fundamental papers by Taylor (1915), Richardson (1920), and Prandtl (1925). The transition to micrometeorology was done by Schmidt (1925) in Vienna, who formulated the 'austausch coefficient' while in Munich, Geiger (1927) summarized microclimatological works in his famous book (still in print) 'The climate near the ground' (Geiger et al. 2009). A few years later in Leipzig, Lettau (1939) pioneered atmospheric turbulence investigations. Most experimental studies of that time were influenced by Albrecht, who wrote the first paper about the energy balance of the earth (Albrecht 1940). Those marked the beginning of micrometeorological studies seeking to measure and understand the energy exchange between the atmosphere and the earth surface, a field that flourished after the Second World War.

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Therefore, first large field experiments were planned in quasi-ideal site conditions without large heterogeneities or obstacles. Examples include the famous O'Neill experiment in 1953 (Lettau and Davidson 1957) and several experiments at the Australian field sites like Kerang (Garratt and Hicks 1990), and the Tsimlijansk site in Russia. While the first experiments used mainly the profile approach in later experiments in the 60s, the eddy-covariance method rapidly grew in popularity. Above and beyond providing a means to provide a direct mass balance of scalar exchanged to/from a surface, it also enabled to determine universal functions of the Monin and Obukhov (1954) similarity theory and the turbulent Prandtl and Schmidt numbers.

This direct measurement method for turbulent fluxes, now known as the eddy–covariance method, was developed probably independently by Montgomery (1948), Swinbank (1951), and Obukhov (1951). This method only emerged after the development of the sonic anemometer for which the basic equations are given by Schotland (1955). After the development of a sonic thermometer (Barrett and Suomi 1949) during the O'Neill experiment in 1953 (Lettau and Davidson 1957), a vertical sonic anemometer with a 1-m path length (Suomi 1957) was already used. The design of today's anemometers was developed by Bovscheverov and Voronov (1960), and later by Kaimal and Businger (1963) and Mitsuta (1966). The phase-shift anemometers have now been replaced by running time anemometers with time measurements (Hanafusa et al. 1982). These anemometers produced by the Japanese company Kaijo-Denki were the first commercially available sonic anemometers. This history is discussed in greater detail by Moncrieff (2004).

These findings were the basis for many famous experiments (Table 1.1), including turbulence sensors intercomparison experiments along with experiments delving into the study of turbulent exchange processes (i.e. KANSAS 1968 experiment (Izumi 1971) which was the basis for the widely used universal function by Businger et al. (1971). The Minnesota experiment followed in 1973 to investigate the validity of the function (Kaimal and Wyngaard 1990). An important summary about the status of the knowledge of turbulent exchange processes between the atmosphere and the surface was given in 1973 at the Workshop on Micrometeorology (Haugen 1973). Following the workshop and inspired by a seminal paper by Elliott (1958), the transition of investigations away from homogeneous to heterogeneous surfaces was made: The arrival of studies demonstrating a step change in surface roughness and its related internal boundary layer concept marked an important development in modern micrometeorology (Busch and Panofsky 1968; Peterson 1969; Taylor 1969; Shir 1972).

Rare are measurements inside low vegetation. Most of our knowledge (Cionco 1978; Wilson et al. 1982), also applied to footprint analysis, is based on measurements made by Silversides (1974) using a split-film anemometer. Inside tall vegetation, such profiles were more often measured (see Chap. 2).

The extension to more complex surfaces first came through the FIFE experiment in the USA (Sellers et al. 1988) followed by similar experiments in France (HAPEX-MOBILHY, André et al. 1990) and in Russia KUREX-88 (Tsvang et al.

Table 1.1 Important micrometeorological experiments up to the beginning of the 80s according to Foken (2006) based on McBean et al. (1979), Garratt and Hicks (1990), and Foken (1990)

Year	Place	Surface	Type, name	References
1953	O'Neill, USA	Step	Boundary-layer experiment	Lettau and Davidson (1957)
1962	Kerang, Australia	Step	Surface-layer experiment	Swinbank and Dyer (1968)
1964	Hay, Australia	Step	Surface-layer experiment	
1965	Hanford, USA	Sage	Anemometer comparison	Businger et al. (1969)
1968	Kansas, USA	Step	Micrometeorological experiment, KANSAS 1968	Izumi (1971)
1968	Vancouver, Canada	Water	ITCE-1968	Miyake et al. (1971)
1970	Tsimlyansk, Russia	Step	ITCE-1970	Tsvang et al. (1973)
1973	Minnesota, USA	Harvested crop	Boundary-layer experiment Minnesota 1973	Readings et al. (1974)
1976	Conargo, Australia	Step	ITCE-1976	Dyer (1981); Dyer and Bradley (1982)
1981	Tsimlyansk, Russia	Step	ITCE-1961	Tsvang et al. (1985)

For experiments after 1980, see Foken (2008). ITCE: International Turbulence Comparison Experiment

1991). During these experiments, aircraft overpass were also included in these experiments raising further questions regarding the interpretation and incorporation of fluxes over different (adjoining) surfaces together to a common picture.

T. F. remembers that time: When P. Sellers visited in the KUREX-88 about 500 km South of Moscow we discussed together with L.R. Tsvang, J. Ross, J. Fazu, J. Zelený and others the problems of the heterogeneous surfaces and the limitations of the eddy-covariance method for these conditions, later on used as a data quality test method (Foken and Wichura 1996). We decided that many gaps must be filled to fully understand the processes. Zubkovskij and Sushko (1987) investigated the limits of the frozen turbulence hypothesis as a measure of how long a surface can influence the turbulence structure. Ross (1981) underlined the importance of the plant structure and the radiation distribution. Finally we decided to repeat an internal boundary layer experiment over typical agricultural fields in 1990 in Estonia (TARTEX-90, Foken et al. 1993) at the time when the former Soviet Union was dismantled and Germany was unified. This was unfortunately also the end of a successful cooperation spanning more than a ten-year period between East European groups (Foken and Bernhardt 1994).

At the end of the 80s, analytical and numerical solutions to diffusion equations proliferate in the literature for many source configurations, initial and boundary conditions and levels of idealization of diffusivity and velocity profiles (Calder 1952; Sutton 1953; Rao et al. 1974; Wilson et al. 1982; Gash 1986; Arya 1999). From these solutions, vertical scalar profiles obtained as a function of downwind distance became the basis used in footprint modeling.

1.2 Towards the Footprint Definition

The 80s marked a period in which tools aiming at improving the development of the interpretation of micrometeorological measurements. Before the advent of footprint models, other tools were used which approximated in some way the concept of the footprint. As already mentioned above, the internal boundary-layer concept was also used to define a necessary fetch for micrometeorological measurements. For more details, the reader is referred to Sect. 2.3.

In the 80s, Czech scientists made measurements on an 80-m-tower in the very complex mine area of Northern Bohemia. To assist with the interpretation of the dataset, they developed a so-called macro roughness (Zelený and Pretel 1986), which was something akin to a weighted standard deviation of the heterogeneities of the underlying surface. The number of grids was chosen using logarithmical distances. Foken and Zelený (1988) investigated different definitions of such a macro roughness and found that they are significantly correlated to different turbulence characteristics like normalized standard deviations of the wind components at different heights. This was similar to the dependence of turbulence characteristics on the footprint area presented by Foken and Leclerc (2004).

M.Y.L. remembers that time: The history of 'footprints' studies goes back to the late eighties when Peter Schuepp of McGill University visited M.Y, Leclerc at Utah State Univ. in February 1988 to see whether she could not model, using the Lagrangian stochastic simulation something both interesting and, at the time, something considered rather puzzling: The CO_2 flux uptake seen by the Canadian National Aeronautical Establishment's Twin-Otter aircraft as it passed over Ile Royale, an island located in Lake Superior, gave fluxes which peaked, not above the forested island itself, but rather downwind from it. That explicit connection of a source/sink to a point flux measurement was then coined 'footprint' in the first paper by Leclerc and Thurtell (1989). That paper was entitled 'Footprint Predictions of Scalar Fluxes and Concentration Profiles using a Markovian Analysis' presented at the American Meteorological Society at the 19th Conference of Agricultural and Forest Meteorology Conference in Charleston, South Carolina (March 7th–10th, 1989). Shortly after, in the refereed articles by Schuepp et al. (1990) and Leclerc and Thurtell (1990).

The two original companion papers, by Schuepp et al. (1990) and Leclerc and Thurtell (1990) respectively, were simultaneously written and meant to be presented as a paper series. Because of small delays in the figure preparation of the final draft of one of the papers, it was decided that the Schuepp et al. (1990) paper would be incorporated in the memory of Hans Panofsky's special issue of Boundary-Layer Meteorology, while the Leclerc and Thurtell (1990) would follow a couple of months later. The Schuepp et al. (1990) article, based on the compact analytical solution by Gash (1986), provided a quick and effective way to model footprints since the latter presented a simple method to provide a rough estimate of the sampling error which would result from an upwind step-change in evaporation rate in limited fetch conditions. It used Calder's (1952) approximation of a uniform wind field and neutral atmospheric stability. The Schuepp et al. (1990) and Leclerc and Thurtell (1990) papers explicitly provided a method to identify the portion of the flux contributed by different sources upwind, with the Schuepp et al. (1990) contribution allowing experimentalists to incorporate into signal processing routines the nearly instantaneous 'field-of-view' assessment of their measurements while the Leclerc and Thurtell (1990) study incorporated real wind profiles, the effect of atmospheric stability, and different surface roughnesses.

On the basis of these two original papers alone, the NASA FIFE field campaign (Sellers et al. 1988) was entirely redesigned using footprint predictions from these models as a tool to reconcile observations and measurements at different scales and across different towers and locations (Kanemasu et al. 1992). For the first time in micrometeorology, experimentalists could now plan upcoming experiments and intercompare measurements from different platforms: flux measurements from aircrafts flying at different altitudes could be intercompared with their respective fluxes over the *Konza prairie* (FIFE) while tower fluxes could be intercompared using a quantitative tool assessing the amount of upwind fetch contributed to the measured flux. Measurements taken at different scales, became, almost overnight, more easily discussed during their daily intercomparison sessions. The 'footprint' concept had then received its baptism by the micrometeorologists and had become well entrenched into micrometeorology. The Schuepp et al. (1990) paper provided a quick, effective, if crude, idea of the surface sensed by a flux platform while the Leclerc and Thurtell (1990) paper, laying out the Lagrangian simulation of particle trajectories in inhomogeneous turbulence, lent sophistication to the footprint concept, by expressing explicitly a more realistic wind profile, the atmospheric stability, and expanded this work to a wide range of surface roughnesses. Furthermore, it depicted the behavior of the footprint peak as a function of both surface roughness and stability and then showed the cumulative effect of adding upwind surface elements to the modeled fetch on flux results.

Nearly in parallel with the Schuepp-Leclerc-Thurtell's efforts, Tim Oke with graduate student Hans Peter Schmid had begun working on a related concept, that of the source area influencing measurements, an adaptation from Pasquill's early efforts (1972). They presented their results at the 8th Symposium on Turbulence and Diffusion, San Diego, CA. in 1988 (Schmid and Oke 1988) which led to Hans Peter Schmid's doctoral dissertation that year. Oke and Schmid defined the 'source area of an eddy-covariance measurement as the surface area containing heat sources and/or sinks influencing those air parcels carried past the sensor under given external conditions'. Schmid later changed the Oke and Schmid's source area term to the use of the term 'footprint', more in line with the original footprint papers. Schmid and Oke (1990) discussed the concept of a source area model (SAM) using a plume-diffusion model to estimate the source region. This concept, borrowed from Pasquill's work (1972) which traditionally applied to air pollution purposes (Taylor 1915; Schmid 1994). The subsequent paper by Schmid (1997) explores the matching of scales of observations and fluxes and defines criteria of representativeness of several distinct measurement methods (Schmid 1997, 2002; Schmid and Lloyd 1999).

Two years later, Horst and Weil (1992) published analytical solutions to the diffusion equation presented in a form describing the footprint. The original solution to the diffusion equation had been presented earlier by van Ulden (1978) and by Horst (1979). The Horst and Weil (1992) solution had the advantage that it provided more realism to existing analytical solutions to the advection-diffusion equation by providing a realistic wind profile and the effect of atmospheric stability in the solution. This constituted a significant step in the evolution of analytical footprint models. The following paper by the same authors (Horst and Weil 1992) brought subsequent refinement to their original paper. That article was based on the work of Horst and Weil (1992) with the concentration-source area model by Schmid and Oke (1990) extended to include conditions of stable thermal stratification and the model's solution improved.

Footprint definition: The early papers by Schuepp et al. (1990) and Leclerc and Thurtell (1990) coined the word 'footprint' to 'the effective upwind source area sensed by the observation', with 'source' understood to include negative flux densities. Formally, Horst and Weil (1992) describe the flux footprint in a mathematical form: **The footprint encompassed by a point flux measurement is the influence of the properties of the upwind source area weighted with the footprint function.** That definition, however, has been evolving more toward 'not so much an effective upwind source area' than the original definition warrants it and which implies a two-dimensional source but rather an effective upwind source volume to reflect measurements over complex tall canopies characterized with vertical distribution of sources and sinks. This has become more apparent when the footprints are examined in the light of flux measurement above a tall canopy with say, an understory and soil emissions.

Based on this definition Horst and Weil (1992) made also the mathematical formulation for the footprint: The footprint function f combines the source area Q_η of a measuring signal η (scalar, flux) in relation to its spatial extent and its distribution of intensity, as illustrated in Fig. 1.1, and is given by:

$$\eta(x_m, y_m, z_m) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} Q_\eta(x', y', z' = z_0) \cdot f(x_m - x', y_m - y', z_m - z_0) dx' dy' \tag{1.1}$$

Hereby the source area is in the height $z' = z_0$ (z_0: roughness height) and the footprint is calculated for the sensor height z_m. From this follows two further definitions: one about concentration and flux footprint and one about the dimension of the footprint.

Schmid (1994) defined different source area functions Q_η for scalar or concentration footprints and for flux footprints. For scalar footprints, the source function is simply the concentration distribution

$$Q_\eta(x, y, z = z_0) = \chi(x, y, z = z_0), \tag{1.2}$$

while for flux footprints, the source function must be replaced by a flux distribution

$$Q_\eta(x, y, z = z_0) = K(z) \frac{\partial \chi(x, y)}{\partial z}, \tag{1.3}$$

where $K(z)$ is the turbulent diffusion coefficient. He found that the extension of the flux footprint is much shorter than for the concentration footprint. This separation is not always carefully done in all models. In the case of concentration footprints, the footprint function is always between 0 and 1 while the flux footprint may also be negative in complex terrain (Finnigan 2004).

Furthermore, footprint models can be separated according to their dimension (Table 1.2). To preclude any misunderstanding, we make a distinction between the definition of the source area and that of the footprint for various dimensions.

1.3 Footprint Modeling

This chapter expands on the description of modeling concepts after the basic definitions about footprints were developed at the beginning of the 90s.

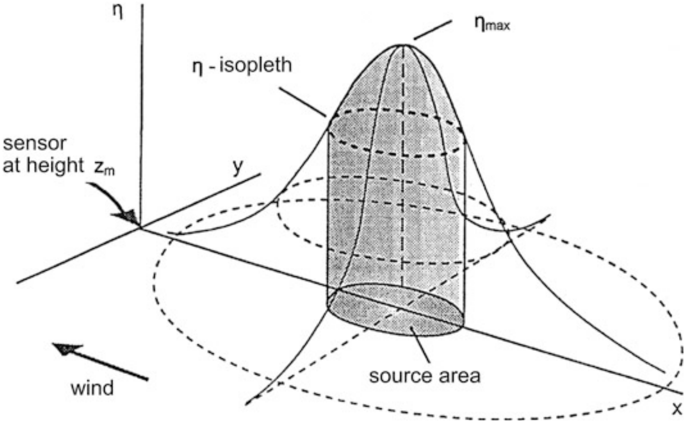

Fig. 1.1 Schematic picture of the footprint function according to Schmid (1994)

Table 1.2 Definition of dimensions of source area and footprint

Dimension	1-dimensional (1D)	2-dimensional (2D)	3-dimensional (3D)
Source area	Line source $Q_\eta(x)$	Two dimensional source in x and y, while z is constant, $Q_\eta(x,y)$	Three dimensional source, $Q_\eta(x,y,z)$
Footprint	Distribution of the concentration or flux density along a horizontal line, $\eta(x)$	Distribution of the concentration or flux density along a horizontal plane, $\eta(x,y)$	Distribution of the concentration or flux density in a non-horizontal plane like in a hilly region, $\eta(x,y,z)$

The footprint idea was extended from the surface layer to the lower convective boundary layer by Leclerc et al. (1997) with the use of Large Eddy Simulation (LES). This study quantified the degree of connection between the surface and an airborne flux platform in the lower convective boundary layer.

Footprint climatologies added to the body of work on footprints (Amiro 1998). The Amiro study was the starting point to estimate the footprint climatology in the FACE (Free-Air Carbon Dioxide Enrichment) experiment at the Duke forest (Stoughton et al. 2000). Footprint climatologies were also the basis used to screen the eddy-covariance data of about twenty European FLUXNET stations by Rebmann et al. (2005). This was subsequently broadened to most European FLUXNET stations by Göckede et al. (2008).

Wilson and Swaters (1991) derived analytical solutions to derive the footprint functions using one and two layers within which the dispersion was parameterized using *K*-theory. They calculated both the 'footprint' and the contact distance of a particle since it last touched the surface. The solutions, simple in nature, rely on the fact that travel times of the particles are large compared with the characteristic turbulence timescale, so that the error in this simplification is small. The method, which uses Monin-Obukhov similarity, has, as of today, not yet been tested. Related to this approach, backward Lagrangian stochastic models came about in the nineties (Flesch 1996). That study used backward Lagrangian stochastic models to provide a measure of the footprint given a measured atmospheric flux. In a manner analogous to that of Flesch (1996), Kljun et al. (2002) used a three-dimensional backward Lagrangian footprint for a wide range of atmospheric stabilities to determine the source area, which was presented also as an analytical approximation for homogeneous surfaces (Kljun et al. 2004b). Kljun et al. (2003) subsequently compared the three-dimensional Lagrangian footprint model by Kljun et al. (2002) against an analytical model of Kormann and Meixner (2001). Shortly after, Kljun et al. (2004a) introduced a scaling procedure for flux footprint functions over a wide range of stabilities with receptor heights ranging from the surface to the middle of the boundary layer. Kljun et al. (2004a), using SF_6 tracer release experiments in a wind tunnel, tested the three-dimensional Lagrangian stochastic footprint model and obtained a general agreement of both the peak location and shape of the resulting footprint functions between modeled and measured fluxes.

Further refinements in our understanding of footprints occur with Luhar and Rao (1994). That study integrated both approaches, analytical and stochastic, into a study involving a step-change in surface roughness and scalar fluxes and its influence on footprint fluxes.

Countless special sessions at meetings, workshops, and scholarly articles have appeared on the subject of footprints, including a recent special issue edited by Vesala, Rannik, Leclerc, Foken and Sabelfeld in Agricultural and Forest Meteorology (Vesala et al. 2004). Testing of these models (Rannik et al. 2000) have been taking place in parallel with the refinement or development of several models (Kurbanmuradov et al. 1999). Several scientific workshops based on footprints have been the subject of an INTAS (International association for the promotion of cooperation with scientists from the independent states of the former Soviet Union) project (2000, 2001, 2003), a European effort aimed at bringing together Eastern and Western scientists in the pursuit of advanced research.

It is with the rise of the Vesala group in Helsinki that the explicit effect of leaf area distributions and canopy density on footprint have been examined (Markkanen et al. 2003). Furthermore, this group further studied the influence of turbulence statistics inside and above a forest canopy as a source of variability on the footprint behavior in a Scots pine forest canopy in Finland (Rannik et al. 2000, 2003). To this end, the Vesala group used a 3D Lagrangian stochastic simulation based on the Thomson (1987) approach. They also, most interestingly, studied flux footprints over simple and complex terrain covered by heterogeneous forests using a canopy—atmospheric boundary layer and scalar transport one-and-half order closure model (Sogachev and Lloyd 2004).

A significant extension to the footprint work came with the application of flux footprints within and over forest canopies by Baldocchi (1998). In this study, the Lagrangian simulation technique was used to calculate footprints at different levels within the canopy. These in-canopy footprint results have been subsequently tested by Leclerc and her group in 2002 for short diffusion times, and in 2004 for longer diffusion distances and a wider range of atmospheric stabilities in the pine canopy of the Florida AmeriFlux site (US-Akn).

Lee (2003) used a combination of both the Raupach's (1989) localized near-field (LNF) theory and parameterization of the turbulence inside a canopy to investigate how atmospheric stability and source configuration influence the flux footprint over the canopy. Lee (2004) extended the above model to examine scalar advection from elevated sources inside plant canopies and used it to describe the behavior of footprints inside plant canopies.

If footprint modeling had been deemed a success, the need for validating these models, in particular those using the analytical solutions to the diffusion equation, would stand the 'litmus test' of flux footprints evaluated when flux sensors are placed both above rough surfaces close to sources and sinks or right amongst sources and sinks as inside a canopy layer.

Soegaard et al. (2003) applied the Schuepp et al. (1990) analytical solution as part of a large experimental campaign in Denmark to quantify the carbon dioxide budget within an intensive, highly heterogeneous agricultural area of Denmark. That footprint study was embedded in a large project involving carbon dioxide exchange measurements throughout the landscape, a scaling up to the landscape effort using satellite land-use maps, a validation of an aerial integration technique, and a quantification of the annual carbon budget from an agricultural landscape.

Falk and Gryning (2000) did a footprint analysis using a stochastic 1D model and validated their results against convective water tank experiments for atmospheric dispersion for the planetary boundary layer. Furthermore they investigated the sensitivity of the footprints to the model boundary conditions. They concluded that, if the turbulence is skewed at the ground, the footprints calculated from backward trajectories are very sensitive to the surface reflection scheme.

Kaharabata et al. (1999) applied the footprint concept to the interpretation of above-canopy sampling of trace gases to interpret VOC emissions data. Strong et al. (2004) incorporated active chemistry into a footprint Lagrangian stochastic model to which prescribed vertical profiles of required turbulence statistics were obtained using a 1D atmospheric turbulence model. It was concluded that active scalar flux estimates can be substantially improved by incorporating an active chemistry term to footprint modeling of a canopy in active defoliation.

Hsieh et al. (2000) developed an analytical model based on Ley and Thomson (1983), Gash (1986), and Horst and Weil (1992) models and tested their data against footprint data and latent heat fluxes downwind from a desert into an irrigated potato site.

Kormann and Meixner (2001) proposed a generalization of the Schuepp et al. (1990) model. They used power-law profiles of the mean velocity and eddy diffusivity based on the model by Huang (1979). Their method is based on profiles described by the Monin-Obukhov similarity theory. It has the advantage of predicting flux footprints for a wide range of atmospheric stabilities while preserving the property of remaining simple and thus well suited to online analysis of flux data. This model was made available in a simplified way for users (Neftel et al. 2008). The other advantage of their analytical solution is that it bypasses the use of the shape factor taking into consideration the related remarks of Haenel and Grünhage (1999) on the shape parameter used in Horst and Weil (1994). Their study examined the possible departure from Monin-Obukhov similarity profiles made using power-law profiles and found the deviations from Monin-Obukhov profiles to be less than 15 % in most conditions.

A novel and creative approach was more recently proposed by Kim et al. (2005) to address the issue of spatial and temporal variability in the scaling-up of tower flux measurements to the landscape. That study used high-resolution satellite maps of surface cover to which flux footprint model outputs were superimposed. The footprint model calculations were based on the Horst and Weil (1994) model. Their study is of importance since they showed that, using semi-variograms and window size techniques, this approach can be a useful tool to select the best tower location for a particular site and to analyze spatial heterogeneousness without a detailed knowledge of site meteorological information.

Finnigan (2004) also examined the footprint concept in complex terrain. In discussing footprint functions, he showed that, using Eulerian and Lagrangian arguments, the concentration footprint can be viewed as the Green function of the Eulerian mass conservation equation or as a Lagrangian transition probability but that the flux footprint cannot be described by the Green function of the flux-transport equation. Finnigan (2004) further argued that the flux footprint is a construction from both the scalar conservation equation and the concentration footprint. He also showed that, in complex flows, such as those encountered in vegetated covers on hilly terrain, an anomalous behavior is expected of the flux footprint so that it is an unreliable guide to the source area affecting tower flux measurements.

The versatility of the Large Eddy Simulation (LES) has been recognized as a potential tool to describe the flow over (Chandrasekar et al. 2003), near (Shen and Leclerc 1997) or inside very strongly sheared atmospheric flows such as within plant canopies (Shen and Leclerc 1997; Su et al. 1998; Watanabe 2009) and urban canopies (Letzel et al. 2008). Prabha et al. (2008) compared the in-canopy footprints obtained using a Lagrangian simulation with those obtained against a LES. In that model, the Lagrangian stochastic model was driven by flow statistics derived from the LES. Recently Steinfeld et al. (2008) embedded a Lagrangian footprint model into a LES model and compared the results with the calculations by Leclerc et al. (1997).

More recently, several overview papers were written (Schmid 2002; Vesala et al. 2004, 2008, 2010; Rannik et al. 2012) to complete this overview. The most important models are shown in Table 1.3.

Table 1.3 Overview about some of the most important footprint models with their dimension (if no remark: analytical model), adapted from Foken (2008) and Vesala et al. (2010) and updated

Author	Remarks
Schuepp et al. (1990)	Analytical footprint model; use of source areas, but neutral stratification and averaged wind velocity (1D)
Leclerc and Thurtell (1990)	Lagrangian footprint model (1D)
Horst and Weil (1992)	Analytical footprint model (1D)
Schmid (1994)	Separation of footprints for scalars and fluxes (1D)
Schmid (1997)	2D version of Horst and Weil (1992)
Kaharabata et al. (1997)	Analytical footprint model (2D)
Leclerc et al. (1997)	LES model for footprints (1D)
Baldocchi (1997)	Lagrangian footprint model within forests (1D)
Rannik et al. (2000; 2003)	Lagrangian model for forests (2D)
Hsieh et al. (2000)	Analytical footprint model (1D)
Kormann and Meixner (2001)	Analytical model with exponential wind profile (1D)
Kljun et al. (2002)	Back trajectories Lagrangian model for varying stratifications and heterogeneous surfaces (3D), 1D analytical version by Kljun et al. (2004b)
Sogachev and Lloyd (2004)	Boundary-layer model with 1.5 order closure (2 and 3D)
Cai and Leclerc (2007)	Concentration footprints from backward and forward in-time particle simulations driven with LES data (3D)
Prabha et al. (2008)	Footprint inside a canopy using LES (3D)
Steinfeld et al. (2008)	Footprint model with LES embedded particles (3D)
Hsieh and Katul (2009)	Second order closure model for heterogeneous surfaces (2D)

1.4 Validation of Footprint Models

Despite the body of works on predictions quantifying source-receptor relations, footprint models and their effectiveness, realism and applicability had not been tested. B. Lamb and M. Y. Leclerc, in collaboration with J. Businger, performed a SF_6 flux experiment with the logistical support of the National Center for Atmospheric Research (NCAR). In 1992, this experiment took place on the premises of the Battelle National Laboratory at the Hanford facility with the help of J. Allwine, a senior scientist at Battelle. D. Finn, a Washington State University PhD student supervised jointly by B. Lamb and by M. Y. Leclerc, not only participated in that experiment but also took a key role in the experimental data analysis that ensued and the subsequent use of the various models available. He visited M. Y. Leclerc several times in Montreal to discuss the 'insides' of the different models and their respective formulations. After several years of painstaking data analysis of the 'rambunctious' fast response continuous tracer analyzers, the group published the Finn et al. (1996) paper. With T. Horst on board, that team took advantage of their dataset to validate the shape-function (see Sect. 2.4.1) derived from Gryning et al. (1983), a necessary shape parameter used in the Horst and Weil (1992, 1994) papers, and whose formulation was found to be in general agreement with the experimental results. The results from the experiment were found to be in very good agreement with predictions from those models.

Table 1.4 Important footprint validation experiments

Year	Place	Surface	Type, name	Reference
1992	Hanford Diffusion Grid	Sagebrush	Artificial tracer (SF_6)	Finn et al. (1996)
1997	Boreal forest, Canada	Mixed sparse forest canopy	Artificial tracer (SF_6)	Kaharabata et al. (1997)
1998	Hollonville, Georgia	Peach orchard	Artificial tracer (SF_6)	Leclerc et al. (2003a)
1998	Waldstein Weidenbrunnen, Germany	Spruce	EUROFLUX site measurements 'natural tracers'	Foken et al. (1999), Foken and Leclerc (2004)
2000	Gainesville, Florida	Pine forest canopy	AmeriFlux site measurements, artificial tracer (SF_6)	Leclerc et al. (2003b)
2000	Socorro, New Mexico	Salt cedar canopy	'Natural tracer'	Cooper et al. (2003)
2000	Vielsam, Belgium	Mixed forest canopy	EUROFLUX site measurements	Rannik et al. (2000)
2002	Gainesville, Florida	Within pine canopy	AmeriFlux site measurements, six different Perfluorocarbon tracers (PFT)	Leclerc et al., unpublished
2003	Lindenberg, Germany	Grass, bare soil	LITFASS-2003, 'natural tracers'	Göckede et al. (2005)
2004	Gainesville, Florida	Within pine canopy	AmeriFlux site measurements, PFT	Leclerc et al., unpublished
2004	Karlshruhe, Germany	Wind tunnel experiment	Artificial tracer (SF_6)	Kljun et al. (2004a)

In a manner similar to that used earlier in the FIFE experiment, the BOREAS study used footprint predictions using not only analytical solutions to the diffusion equation and tracer experiments but also outputs to the LES to help improve the assessment, understanding and intercomparison of fluxes between the different tower sites and the different locations within the boreal forest (Kaharabata et al. 1997), see Table 1.4.

M. Y. Leclerc, with graduate student N. Meskidze, performed a tracer experiment, this time over a surface of intermediate roughness as found in a peach orchard. Initially, the data were collected to examine the robustness of these models when the flux system was outside the roughness sub-layer of that rough canopy. Using to their advantage the fact that peach orchard canopies are not only of intermediate roughness but that they also grow rather quickly throughout the summer, they collected additional data, this time with the same flux system transitioning into that rough sublayer close to sources and sinks. They placed two line sources perpendicular to a horizontal array of flux towers and collected data in such a way that experiments could be carried out when the wind came from one of two directions. That data formed the basis for the Leclerc et al. (2003a) paper. If they had found thus far that these models had demonstrated robustness within the range of applicability prescribed, it was not at all clear that these models, and in particular those using analytical solutions, would withstand one of the regimes where they were most needed: over extremely rough surfaces and within the roughness sublayer. There, the team built no less than a dozen of prototypes of line sources which had to be strong enough to sustain the strong winds, storms, and tail ends of hurricanes and the twisting and turning of the line sources and the battering of the latter in those conditions. The first prototype of line sources was the one that had been used previously both in the Hanford Diffusion Grid (sagebrush) experiment and in the peach orchard experiment and putting a 400 m long line source, tied at treetops onto the trees themselves. By the time the flux towers were built into the forest, mobile laboratories and gas cylinders had been brought to each site, while instrumentation shelters were built and installed on each tower, gas chromatographs working in good order, the sonic and the fast response continuous analyzers set up and data loggers programmed and in operating condition, along with other supporting instrumentation, that line source had experienced fatigue. Leclerc, accompanied by several undergraduate students, build several line sources prototypes. Either the ultra-violet radiation would weaken the lines quickly enough before the experiment could unfold or strong winds would tear the line source down. The building and withstanding of a sturdy line capable of withstanding the harsh sunny and stormy conditions of the Florida climate and weather was a daunting challenge. The basic idea of the new fully functioning line source was born. In January 2000, A. Karipot and T. Prabha, both former PhD students of Inge Dirmhirn and Erich Mursch-Radlgruber in Vienna, who some years ago had also been in contact with Foken's group, joined Leclerc's team and participated in the experiment. The new prototype of the line source was then fully built, orifices mounted on old ports from the original copper line source of the Hanford Diffusion Grid and peach orchard experiments, and flow rates checked across the line. The data collection, high quality data, had begun in earnest and now, the Leclerc group was waiting and praying for the wind direction to be favorable. Finally, with much persistence, the data was collected which formed the basis for the paper by Leclerc et al. (2003b).

If, for a short time, the Leclerc group relished in their accomplishments, at the time of data analysis and proposal writing, Leclerc, after hours of examining what appeared to be noisy sodar data burning the midnight oil in the wee hours of the night preparing for a proposal, noticed that some of the apparent scatter in the flux footprint might be connected in some form, to patterns in the sodar data. Curious, she then examined the many plots from the sodar placed above the group's mobile laboratory and started to reconstruct the puzzle. What was happening almost every morning around 10:00 at that site? Recreating the experimental scene at the site, she could hear in her ears the sudden shift in wind direction for the better part of the day. With a vector analysis of the synoptic wind and the observed wind, there must have been some forcing that skewed the flow when the winds came from the west. She then remembered having seen logging trucks in the fall of 1999. Intrigued, she investigated and found a large, very large freshly logged area about

300 m west of the tower. From then on, the data was re-examined in the light of wind direction, and the footprint predictions were found to be in very good agreement when the wind came from the east and departed by several orders of magnitude when the wind came from the west (clearing). The sodar data was double checked to make sure that the unusual signal could be trusted. That was then demonstrated in a guest paper written in the honor of G. W. Thurtell in a special issue of Agricultural and Forest Meteorology (Leclerc et al. 2003b).

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