Monique Y. Leclerc
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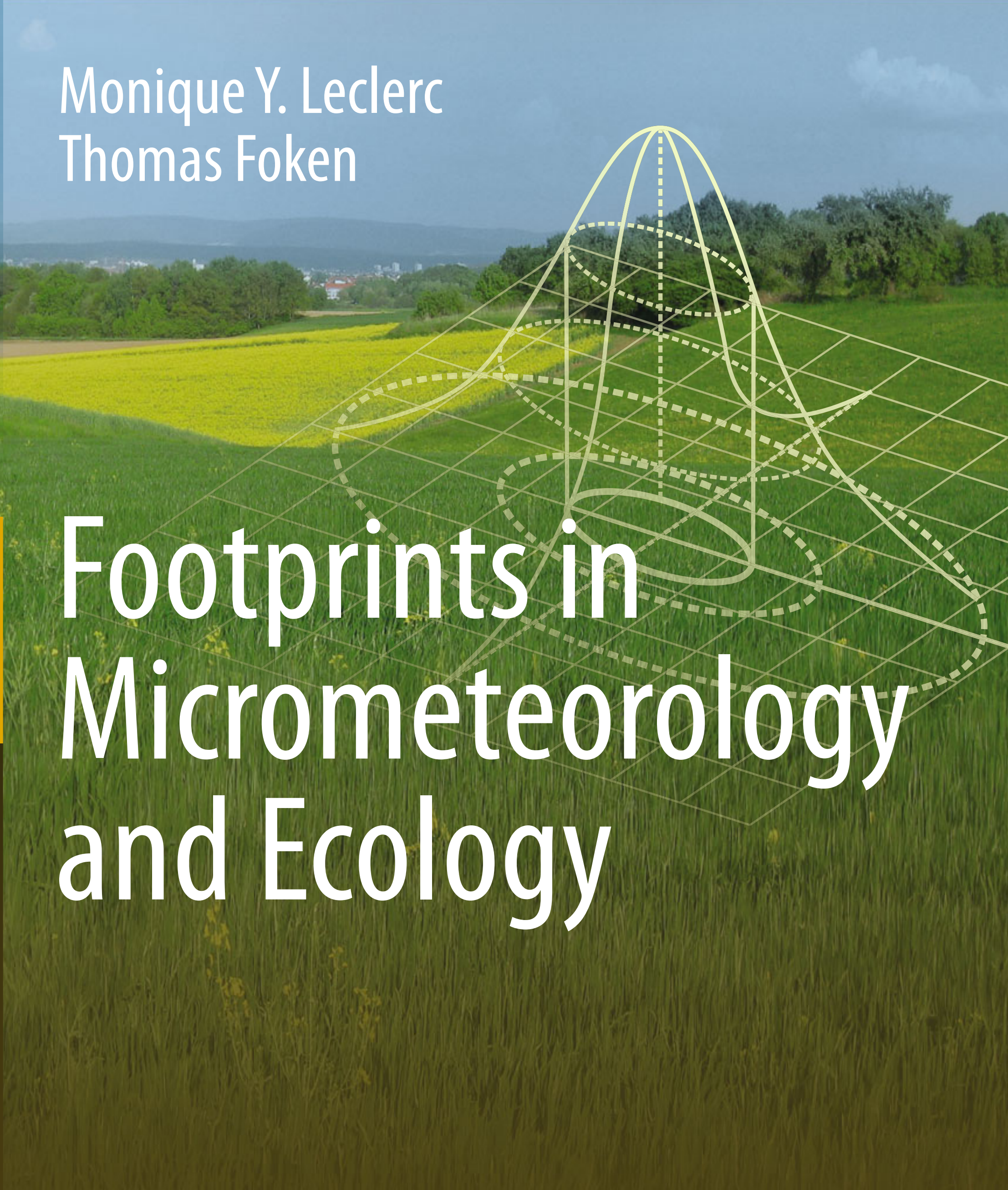
Footprints in Micrometeorology and Ecology



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With Contributions by M. J. Savage and M. Göckede

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Preface

Ever since the humble beginnings of micrometeorology over 50 years ago, micrometeorologists have pondered over ways in which to best measure surface-atmosphere exchange at non-ideal sites. In setting up their instrumentation to ensure the highest integrity of data quality, micrometeorologists went to great lengths seeking to eliminate upwind obstacles suspected to adversely degrade the quality of their dataset. Constantly present in the mind of these early pioneers, the problematic determination of the range of the upwind coverage covered by an atmospheric measurement was an ever present concern on their mind. Pasquill however, in his groundbreaking work of 1961 developed a series of empirical guidelines aimed at identifying the source area.

While *a priori* this may appear to be a moot point for non-micrometeorologists, a sensor in the atmosphere does not measure the properties at the point where the sensor is located. Indeed, the sensor measurement reflects the scalar and dynamic properties of eddies embedded in the flow advected past an atmospheric sensor, while an atmospheric flux represents the correlation of the properties of eddies going past the flux system and their vertical wind velocity. Both concentration and flux measurements are the product of a spatial average over the path length of the sensor/flux system and a temporal average dictated by the measurement period (typically 30-min period).

Since the inception of micrometeorological research up until the 1980s, experimentalists limited the scope of their measurements to smooth, flat terrain covering extending homogeneous areas. This state-of-affairs was then to undergo a profound transformation in the mid-1980s with the arrival of a fortuitous combination of cheap computers, the production of affordable data acquisition systems and data loggers and, above all, with the arrival of affordable, fast response sonic anemometers/thermometers that the common use as we know it today surfaced. These modern measurement systems then opened the door to a vast and rapid expansion of the field of micrometeorology, leading experimentalists to move into forays of considerable challenge: the scientific community relaxed their restrictions of limiting their efforts to quasi-idealized terrain to then shift their focus to frequently encountered terrain or over surfaces presenting much need in assessing atmosphere-exchange. It is then that, for the first time, measurements over tall forested canopies and over mosaic-like terrain grew to become the norm rather than the exception.

Furthermore, these techniques were soon adopted by scientists outside the meteorological community: the deceptive ease of use of the eddy-covariance technique opened the door to a myriad of experiments in the field of ecology and became extensively used at difficult sites. The footprint concept was developed in an attempt to provide leadership in this rapidly expanding field.

Why are we writing this book, the reader might well ask: With the recent and rapid proliferation of papers in the field of eddy-covariance essential, either pertaining to or resorting to the use of eddy-covariance, there has yet to be a full comprehensive 'manual' summarizing from the ground up the plethora of ways estimating footprints. We have wanted to provide a comprehensive yet easy-to-use guide to those unfamiliar with the concept. We have thus included the rudiments of micrometeorology along with measurement methods. Furthermore, the present book also offers a fresh insight into practical applications like tall tower measurements, wind power investigations, and air pollution issues.

The idea of writing this 'field manual' was spurred by the preparation of the special issue of *Agricultural and Forest Meteorology* in 2004 edited by Timo Vesala, Ullar Rannik, and colleagues including but not limited to John Finnigan, Dennis Baldocchi, Xuhui Lee, and many others; this special issue, along with the recent productions of three overviews by Vesala et al. (2008, 2010) and Rannik et al. (2012) into non-traditional readership further demonstrated the relevance of the present endeavor. This manual on footprints should provide a solid well-rounded foundation establishing the basis for robust flux experiments (tower positioning, height of measurements, difficulties with upstream inhomogeneous surfaces, and related errors) and their subsequent interpretation especially when used with the *Handbook on Micrometeorology* (Lee et al. 2004) and the recently published book on *Eddy-Covariance* (Aubinet et al. 2012).

The reader should forgive a personal note of Chap. 1. These views have formed after more than 25 years in the field. Despite this, one point should be emphasized: Writing this book was only possible thanks to the wonderful cooperation of many scientists in common projects and in the preparation of joint papers, overview papers, and book chapters. We want to thank them all; the list is extremely long as the references sections will attest.

We are particularly grateful to M. J. Savage and M. Göckede for their unwavering support, mainly for Chaps. 1, 3, 6 and 8. One of the authors (M. Y. Leclerc) wishes to sincerely express her appreciation and gratitude to Prof. Joon Kim of Seoul National University for his hospitality during a portion of the book writing. Professor Kim provided the conditions needed to foster useful discussions, concentration, and solitude. The preparation of the book was supported by the states of Georgia and Bavaria mainly by the funding of technological cooperation (BayCaTEC-Georgia) to whom we are most indebted.

Griffin, Bayreuth, January 2014

Monique Y. Leclerc
Thomas Foken

References

Aubinet M, Vesala T, Papale D (2012) Eddy covariance: apractical guide to measurement and data analysis. Springer, Dordrecht, p 438

Lee X, Massman WJ, Law B (eds) (2004) Handbook of micrometeorology: a guide for surface flux measurement and analysis. Kluwer, Dordrecht, p 250

Pasquill F (1961) Estimation of dispersion of windborne material. Meteorol Mag 90:33–49

Rannik Ü, Sogachev A, Foken T, Göckede M, Kljun N, Leclerc MY, Vesala T (2012) Footprint analysis. In: Aubinet M, et al (eds) Eddy covariance: A practical guide to measurement and data analysis. Springer, Berlin, pp 211–261

Vesala T, Kljun N, Rannik U, Rinne J, Sogachev A, Markkanen T, Sabelfeld K, Foken T, Leclerc MY (2008) Flux and concentration footprint modelling: state of the art. Environ Pollut 152:653–666

Vesala T, Kljun N, Rannik Ü, Rinne J, et al (2010) Flux and concentration footprint modelling. In: Hanrahan G (ed) Modelling of pollutants in complex environmental systems, vol II. ILM Publications, St. Albans, Glendale, pp 339–355

Contents

Abbreviations

AmeriFlux	Research Network of the Americas
ASTER	Advanced Spaceborne Thermal Emission and Reflection radiometer
BOREAS	Experiment in the boreal forests of Northern America
CCGD	Carbon Cycle Greenhouse Gases Group
CCSM	Community Climate System Model
CHIOTTO	Continuous high-precision tall tower observations of greenhouse gases
CPU	Central processing unit
DBSAS	Displaced beam small aperture scintillometer
ERF	Environmental response function
ESDU	Engineering Sciences Data Unit
ESRL	NOAA Earth System Research Laboratory
EUROFLUX	European part of FLUXNET
EVI	Enhanced Vegetation Index
FACE	Free-Air Carbon Dioxide Enrichment
FIFE	First ISLSCP Field Experiment
FLUXNET	Flux network
FSAM	Flux footprint model by Schmid (1994, 1997)
GEWEX	Global Energy and Water Cycle Experiment
GIS	Geographical Information System
GMD	Geoscientific Model Development
HAPEX-MOBILHY	Hydrological Atmospheric Pilot Experiment—Modelisation du BiLan Hydrique
HERC	Helsinki Environment Research Centre
HYSPLIT4	Hybrid Single Particle Lagrangian Integrated Trajectory model by Draxler (1997)
IBL	Internal boundary layer
ID	Identification document
IKONOS	Commercial earth observation satellite
INSTAAR	Institute of Arctic and Alpine Research
INTAS	International association for the promotion of cooperation with scientists from the independent states of the former Soviet Union

IR	Infrared
ISLSCP	International Satellite Land Surface Climatology Project
ITCE	International Turbulence Comparison Experiment
KUREX	Kursk experiment
Landsat	Programme for acquisition of satellite imagery of Earth
LAS	Large aperture scintillometer
LES	Large Eddy Simulation
LITFASS	Lindenberg Inhomogeneous Terrain Fluxes between Atmosphere and Surface: a long-term Study
LNF	Localized near-field theory by Raupach (1989)
LPDM-B	Lagrangian footprint model by Kljun et al. (2002)
LS	Lagrangian simulation
LST	Land surface temperature
MAGS	Mackenzie Area GEWEX Study
MODIS	Moderate-resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NEL	New equilibrium layer
NIR	Near IR
NOAA	National Oceanic and Atmospheric Administration
NOPEX	Northern Hemisphere Climate Processes *Experiment*
PALM	LES model according to Raasch and Schröter (2001)
PFT	Perfluorocarbon tracer
SAM	Footprint model according to Schmid and Oke (1990)
SCADIS	1.5-order closure model by Sogachev and Lloyd (2004)
SGS	Sub-grid scale
SRNL	Savannah River National Laboratory
STILT	Model for tall tower data according to Lin et al. (2004)
SVAT	Surface-Vegetation-Atmosphere-Transfer
TK	Turbulence knight
TKE	Turbulent kinetic energy
VOC	Volatile organic compound

Symbols

a	Footprint fraction related to the target area
a_i	Normalized footprint
Bo	Bowen ratio
C_n^2	Refraction structure-function parameter ($m^{-2/3}$)
C_T^2	Temperature structure-function parameter ($K\ m^{-2/3}$)
c	Concentration (general) (*)
c_*	Concentration scale (*)
c'	Fluctuation of the concentration (general) (*)
c_p	Specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
C	Weighting factor for aircraft data
C_0	Kolmogorov constant
$C_{k,j}$	Weighting function
d	Displacement height (m)
D_{ext}	Extended fetch (m)
D_{min}	Minimal fetch (m)
e	Water vapor pressure (hPa)
E	Power spectra (general) (*)
E	Turbulent kinetic energy (*)
EVI	Enhanced vegetation index
f	Frequency (s^{-1})
f	Coriolis parameter (s^{-1})
f	Footprint function*
$\bar{f}^y$	Crosswind-integrated flux footprint (*)
f^P	Footprint function of the effect level (*)
$F(x)$	Distribution density function
F	Flux (general) (*)
F_T	Total flux (*)
F_e	Flux in an elevated level (*)
F_{obs}	Observed flux (*)
F_{tar}	Flux of the target area (*)

F_{surf}	Flux of a surface (not target area) (*)
g	Acceleration due to gravity (m s^{-2})
$G(y)$	Gaussian distribution function
h	Canopy height (m)
h_c	Canopy height (m)
$H(z)$	Gaussian distribution function
H/L	Hill slope (H: hill height, L: length scale)
K	Turbulent diffusion coefficient (general) (m^2 s^{-1})
K_c	Turbulent diffusion coefficient of mass transfer (m^2 s^{-1})
K_H	Turbulent diffusion coefficient of sensible heat (m^2 s^{-1})
K_m	Turbulent diffusion coefficient of momentum (m^2 s^{-1})
$K_{x,y,z}$	Component of the turbulent diffusion Coefficient (m^2 s^{-1})
K_χ	Turbulent diffusion coefficient of mass transfer (m^2 s^{-1})
l_b	Blending height (m)
L	Obukhov length (m)
L_c	Canopy drag scale (m)
L_R	Resolution of a matrix size (m)
L_v	Obukhov length with buoyancy flux (m)
L_s	Shear scale (m)
LAI	Leaf area index (m^2 m^{-2})
$NDVI$	Normalized difference vegetation index
O_p	Photosynthetically active radiation (μmol m^{-2} s^{-1})
p	Air pressure (hPa)
p	Exponent of the power law
P	Portion of the total integrated footprint effect (*)
P	Path length of a scintillometer (m)
Pr_t	Turbulent Prandtl number
q	Specific humidity (kg kg^{-1})
q'	Fluctuation of specific humidity (kg kg^{-1})
q_*	Scale of the specific humidity (kg kg^{-1})
Q	Source density (general) (*)
Q_χ	Dry deposition (kg m^{-2} s^{-1})
Q_E	Latent heat flux (W m^{-2})
Q_G	Ground heat flux (W m^{-2})
Q_H	Sensible heat flux (W m^{-2})
Q_{Hv}	Buoyancy flux (W m^{-2})
Q_N	Normalized flux (m s^{-1})
Q_s^*	Net radiation (W m^{-2})
Q_η	Source density of the η parameter (*)
Q_0	Source density at the surface (*)
Q_χ	Concentration or mixing ratio flux (*)
r	Shape parameter
R	Number of pixel in a fly segment

R_L	Gas constant of dry air (J kg^{-1} K^{-1})
RN	Parameter of relative non-stationarity
$\mathrm{Ri_f}$	Flux Richardson number
Ri_g	Gradient richardson number
Ri_b	Bulk Richardson number
Ri_c	Critical Richardson number
$\mathrm{Sc_t}$	Turbulent Schmidt number
S_c	Concentration sources and sinks (*)
t	Time (s)
T	Temperature (K)
T'	Fluctuation of the temperature (K)
T_*	Temperature scale (K)
U	Mean wind speed (m s^{-1})
u	Longitudinal component of the wind velocity (m s^{-1})
u'	Fluctuation of the longitudinal component of the wind velocity (m s^{-1})
u_*	Friction velocity (m s^{-1})
v	Lateral component of the wind velocity (m s^{-1})
v'	Fluctuation of the lateral component of the wind velocity (m s^{-1})
w	Vertical component of the wind velocity (m s^{-1})
w'	Fluctuation of the vertical component of the wind velocity (m s^{-1})
w_*	Convective (Deardorff) velocity (m s^{-1})
W	Weighting factor for scintillometers
X	Dimensionless distance $X = w_* x/Uh$
x	Fetch (m)
x	Horizontal direction (length) (m)
x,	Measuring variable (general) (*)
x'	Fluctuation of a measuring variable (general) (*)
y	Horizontal direction (length, perpendicular to x) (m)
z	Height (general, geometric) (m)
z_i	Mixed-layer height (m)
z_m	Measuring height (m)
z_0	Roughness parameter, roughness height (m)
z_{0q}	Roughness height for water vapor pressure (m)
z_{0T}	Roughness height for temperature (m)
z'	Height (aerodynamic) (m)
$\overline{Z_H}$	Averaged building height (m)
δ	Depth of the internal boundary layer (m)
δ_T	Thickness of the thermal internal boundary layer (m)
$\delta\varphi$	Accuracy of the universal function
Δe	Water vapor pressure difference (hPa)
ΔT	Temperature difference (K)
Δu	Wind velocity difference (m s^{-1})
Δz	Height difference (m)

$\Delta\chi$	Concentration or mixing ratio difference (*)
$\Delta_{\chi,min}$	Minimal concentration or mixing ratio difference (*)
ε	Energy dissipation (m^2 s^{-3})
ζ	Dimensionless height z/L
η	Quantity being measured at a location (footprint) (*)
η	Kolmogorov's micro scale (m)
θ	Potential temperature (K)
θ_v	Virtual potential temperature (K)
κ	Von-Kármán constant
κ	Wave number (m^{-1})
λ	Heat of evaporation for water (J kg^{-1})
λ_F	Frontal areal index
λ_P	Plain area fraction
Λ_u	Eulerian turbulent length scale for the horizontal wind (m)
ν	Kinematic viscosity (m^2 s^{-1})
ρ	Air density (kg m^{-3})
ρ	Autocorrelation function (*)
ρ_d	Density of dry air (kg m^{-3})
σ_u	Standard deviation of the longitudinal wind component (m s^{-1})
σ_v	Standard deviation of the lateral wind component (m s^{-1})
σ_w	Standard deviation of the vertical wind component (m s^{-1})
σ_T	Standard deviation of the temperature (K)
τ	Shear stress (kg m^{-1} s^{-2})
τ	Lagrangian integral time scale (s)
τ_c	Scalar eddy diffusivity (*)
Π	Coefficient of Buckingham's Π-Theorem
φ	Geographical latitude (°)
φ_m	Universal function for momentum exchange
φ_H	Universal function for sensible heat flux
φ_E	Universal function for latent heat flux
φ_*	Correction function for the roughness sublayer
χ	Concentration or mixing ratio (general)
$\chi_{\min}$	Accuracy of the measurement system (*)
χ'	Fluctuation of the concentration or mixing ratio (general) (*)
χ_y	Crosswind integrated concentration or mixing ratio (*)
ψ	Weighting function for the land cover type
ψ	Concentration function of reactive particles (*)
ψ_H	Integral of the universal function for sensible heat
ψ_m	Integral of the universal function for momentum
ψ_{ijk}	Weighting function in Eq. 7.28
ω	Dissipation of the turbulent kinetic energy (*)
ω	Weight distribution function, isopleths
ω_P	Weight distribution function, isopleths for level P

Ω_p Footprint effect level (*)
Ω Angular velocity of the rotation of the Earth (s^{-1})

Indices

m Measurement
r Special position in coordinate system

Remark

* Dimension according to the use of the parameter

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.

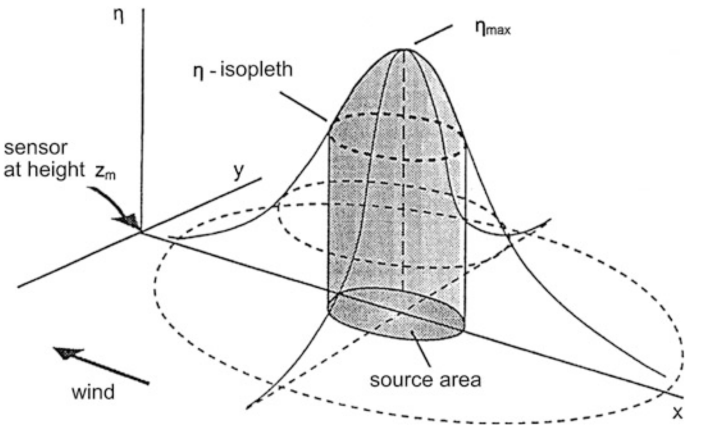

Fig. 1.1 Schematic picture of the footprint function according to Schmid (1994)

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