Chapter 9
Looking Forward to the Next Generation of Footprint Models

When we surveyed the exhaustive list of developments in footprint modeling (Foken and Leclerc 2004) ten years ago, we were most enthusiastic to see the rapid and vigorous progress in the footprint specialty of micrometeorology. Owing to the technical challenges of tracer methods, further progress related to footprint validation has slowed. This may bode well for the present volume given that a certain level of knowledge can be recognized and the book was not written in a period of fast progress. We are not suggesting that all aspects of footprint research have been addressed but instead the major developments have already been achieved. New developments in this arena are expected to lie in the field of applications. Let us underline this with key statements:

We had hoped that differences between analytical and Lagrangian type of footprint models (Kljun et al. 2003; Vesala et al. 2008a), can be solved with advances in the field of artificial tracer studies. The latter should include multiple tracer techniques in three-dimensional footprint studies, with tracers placed at several positions on the soil surface, in the understory and in the crown space of a forest canopy. Tracer studies are undoubtedly a powerful but also an expensive tool to study many influences on flux or concentration footprints. Such studies are always very specific and costly but practical relevance failed in the last years for such studies. We had also hoped that natural tracers (Foken and Leclerc 2004), this means the identification of heterogeneities in the footprint area by the measured fluxes, can be a less expensive tool because they can be included into on-going flux field campaigns. But this was only applied in a study by Göckede et al. (2005) and was on the brink of some other experiments. The really problem was the missing reference for model comparison like etalon instruments in sensor calibration

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technique. The Lagrangian footprint model embedded into a LES model (Steinfeld et al. 2008) was probably one step in this direction. It was used by Markkanen et al. (2009) as a reference for the validation of forward and backward Lagrangian models. The result was the same as for the comparison of analytical and Lagrangian models (Kljun et al. 2003), not only as a visual result but as a quantitative result with quality flagging. Therefore, one must conclude that both the footprint peak and the different factors influencing the footprint behavior are similar amongst the various models though the level of sophistication may impact the results though only slightly. This is more relevant in stable then in unstable stratification. All further applications and developments will be based on this statement.

The main progress in the coming years is expected to revolve around the practical application of footprint models. Already simple footprint models are implemented into software tools like for eddy covariance measurements. These are the analytical footprint model applied to the neutral atmospheric surface layer by Schuepp et al. (1990) or for the diabatic surface layer and lower atmospheric boundary layer by Korman and Meixner (2001). The latter is also available as a easily to handle tool (Neftel et al. 2008, see also Sect. 3.1.3.5). The significant better Lagrangian models are too expensive in handling for general users. Therefore it was a great progress by Kljun et al. (2004) to make her backward Lagrangian model (Kljun et al. 2002) online available (see Sect. 3.1.4), unfortunately only as a 1-dimensional version. Mauder et al. (2008) made a 2D version of this model and also H.P. Schmid made a proposal how to make a two dimensional extension (Metzger et al. 2012). Hopefully this version will soon also be online available. The higher order closure model by Sogachev and Lloyd (2004) was also free available (Vesala et al. 2010) but can now only be commercially applied. From the availability of easy to use Lagrangian or higher order closure models the progress in practical footprint application depends. 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 would gain increasing importance. Nowadays the footprint tool is mainly familiar to the flux community, but as shown in Chaps. 7 and 8 and a myriad of possibilities are emerging. This may be a wide area in atmospheric measurements, air pollution, use of renewable energies etc. The consulting and the ideas of the footprint community are necessary to make this important widely known and applicable.

Nevertheless some developments in footprint modeling are still necessary, primarily in the application of the interpretation of fluxes over heterogeneous areas. Small heterogeneities in thermal (Markkanen et al. 2010) and roughness conditions including possible internal boundary layers have not really a significant effect on the calculated footprint of the backward Lagrangian model by Kljun et al. (2002). More important are probably forest areas (Foken and Leclerc 2004; Vesala et al. 2008a). Here the turbulence structure of the roughness sublayer, i.e. the layer of air influenced by the presence of a neighboring rough surface, as in a canopy layer, violates similarity principles used in surface-layer scaling. Yet, most eddy-covariance measurements over forests are contained within the roughness sublayer

(Raupach and Thom 1981), a layer which exhibits some departure from surface-layer similarity. Hence the mean wind speed does not follow a log-linear profile and the observed eddy-diffusivity can be two to four times greater than the similarity value (Raupach et al. 1986; Su et al. 1998). Inside tall forest canopies, the treatment required to derive footprint functions derived from realistic analytical solutions become even more a distant possibility because of the added complexity of having to contend with the presence of multiple vertically distributed sources and sinks. Yet, even approximate solutions would be helpful as increasingly experimentalists seek to determine in-canopy footprints (Göckede et al. 2007). Not only these basic studies in and above idealized tall vegetation are necessary. Gaps in canopies, flow obstacles such as isolated trees or distant tall man-made or pest and wind throw structures, and their effect on footprint functions (and measured fluxes) should be investigated, with special precautions taken under nighttime conditions. Here are only a few studies available at forest edges (Klaassen and Sogatchev 2006; Sogachev and Leclerc 2011).

A similar problem are footprints in urban canopies (Vesala et al. 2010). Here the footprint problem is up to now only addressed (Vesala et al. 2008b) and even large recent urban experiments did not applied footprint technology (Rotach et al. 2005). The reason lies in the difficult definitions of the source area and the height or zero-plane displacement. We are not sure, if footprint technology or better LES will solve the problems of source areas and its footprint in urban meteorology in the future.

The application of footprint technology in air chemistry, mainly for the transport of particles or of reactive trace gases is only presented by few studies (Strong et al. 2004; Rinne et al. 2007). Often backward trajectories are applied in this field, like for the interpretation of the footprint of tall towers (Gloor et al. 2001).

There are still some meteorological situations where the application of footprint models is difficult. Greater consideration ought to be given to the presence of discontinuities upwind beyond the footprint region, particularly in calm conditions or very stable conditions. Recent efforts along the lines of quantifying atmospheric stability effects inside a canopy are being made (Zhang et al. 2010). These new developments should provide a step forward toward the future development and use of analytical footprint models describing in-canopy flux footprints.

As it was already shown in recent studies (Steinfeld et al. 2008) that 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 could be tested against this method like in Markkanen et al. (2009). Numerical closure models (Belcher et al. 2012) and LES (Schlegel et al. 2012) are nowadays able to solve problems in hilly terrain and forests, which were addressed above as deficits of footprint models. Therefore we can finally state that the future of footprint models will not be a further improvement of the classical footprint models (as it was the issue in this book), but the development of adequate

LES models, which need now no high sophisticated computer centre because of much faster processors, will be the future.

Summarizing these remarks, we believe that the main thrust of the development in footprint technology is now done and made this technology to an in most cases easily applicable method. This gives us the opportunity that the book will give the basics for footprints in micrometeorology and ecology also for the future. Some improvements are possible but without significant changes. The challenge over the next years will either be to make footprint technology more applicable to applied technologies of atmospheric gas exchange and to develop the next generation of models used in the interpretation of experimental data with LES and higher-order closure technology.

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