JP5.4 ON THE SENSITIVITY OF LAGRANGIAN STOCHASTIC FOOTPRINT MODELING TO WITHIN CANOPY FLOW STATISTICS DERIVED FROM WAVELET ANALYSIS

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1 INTRODUCTION

Sites for flux towers such as organized in the FLUXNET network (e.g. Baldocchi et al., 2001) are often chosen according to their ecological importance and micrometeorological aspects play only a minor role in many cases. As a result, sites are often located in complex terrain and are characterized by heterogeneous land cover with short fetches over the target land use type, i.e. conditions that compromise the collection of high quality meteorological data sets. The application of the eddy-covariance technique, which is commonly used for flux determination (e.g. Aubinet et al., 2000; Baldocchi et al., 2000), requires therefore a site dependent quality control to allow for a robust interpretation of the flux measurements (Foken et al., 2004). A key component in the data quality protocol are footprint models that determine the spatial context of a measurement by defining a transfer function between sources or sinks of the signal and the sensor position. The derived source area is crucial for the interpretation of micrometeorological data sets, e.g. by determining the fetch requirements under changing atmospheric stability regimes or by assessing the influence of distorting terrain elements on the measurements.

A powerful tool to model source areas over forest are Lagrangian Stochastic (hereafter referred to as LS) footprint models (e.g. Baldocchi, 1997; Rannik et al., 2000; Kljun et al., 2002; Rannik et al., 2003), because this technique allows the consideration of effects of canopy flow on the measured fluxes, and a more realistic treatment of diffusion. As drivers, Lagrangian stochastic models use characteristics of prevailing turbulence to calculate trajectories of individual air parcels, such as the profiles of the mean wind speed u, the wind fluctuations (σ_u; σ_v; σ_w), or the dissipation rate of turbulent kinetic energy ε. However, as only few generally valid theories are known for the flow in the canopy space (e.g. Lee, 1998; Finnigan, 2000), for within canopy flow these parameters often have to be approximated with crude generalizations and certain ad hoc assumptions (Schmid, 2002).

This study aims at testing the sensitivity of a Lagrangian Stochastic footprint model to the input parameters describing the turbulent flow field, with a focus on the within canopy flow processes. A high-quality long-term dataset of turbulence measurements within and above a tall spruce canopy was used to extract detailed turbulence statistics as input parameters for the footprint model. From these measurements, representative profiles of the input parameters required for the footprint modeling are derived by application of different filters to the original data set. We deployed spectral analysis using a wavelet analysis tool (Thomas and Foken, 2005) to extract and detect single coherent structures along the vertical profile. Based on this analysis, typical exchange regimes are determined to characterize the degree of coupling between the canopy space, the atmosphere and the ground surface. The resulting description of the turbulent flow field varies in both the spatial and temporal context, as statistics are derived specifically for each exchange regimes and corresponding wind direction.

Two additional simpler methods to describe the canopy flow regime will be applied for means of comparison. First, the parameterization of the flow statistics presented by Rannik et al. (2003) will be used, which have been tested thoroughly for Lagrangian Stochastic footprint modeling. This dataset was derived by measurements at the Hyytiälä site in Finland, for a forest architecture that has characteristics significantly different from those at our testing site. Second, a model by Massman and Weil (1999) to parameterize the profiles of the flow statistics based on profiles of the leaf area index will be employed. The impact of the application of these different descriptions of canopy flow will be tested by comparing size and position of the source areas computed by the footprint model, as well as by the determined composition of land cover types within the source area and their correlation to the measured eddy-covariance fluxes.

2 DATA SOURCES

2.1 *The WALDATEM-2003 dataset*

A long-term dataset of turbulence measurements collected during the WALDATEM-2003 (WAveLet Detection and Atmospheric TurbulencE Measurements, see Thomas et al., 2004) experiment within and above a tall spruce canopy was used to extract detailed turbulence statistics as input parameters for the footprint model. This experiment was conducted at the Waldstein Weidenbrunnen FLUXNET measuring site (Gerstberger et al., 2004) of the University of

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Bayreuth, Germany, which is located in the Fichtelgebirge mountains (50°09' N, 11°52' E, 775 m a.s.l.). The terrain in the vicinity of the tower is hilly with moderate slopes, mainly covered by spruce forest with a mean canopy height (h_c) of 19 m for the nearest surrounding area. The experiment was conducted in the period April 28 to August 03, 2003, whereas this study used the data collected from June 24 to July 17 only.

The WALDATEM dataset includes a profile of five sonic anemometers, installed at 5.5m, 13.6m, 17.7m, 22.4m, and 33m above ground level. Figure 1 shows these measurements heights, normalized with h_c, and the vertical profile of the plant area index (PAI) measured at the Waldstein Weidenbrunnen site (Thomas and Foken, 2006a).

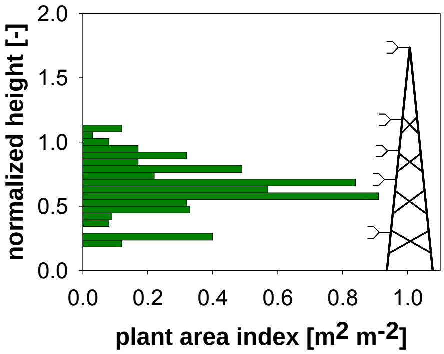

Figure 1: Vertical profile of the plant area index measured at the Waldstein Weidenbrunnen site. The total plant area index is 5.2 [m^2 m^{-2}]. The tower on the right-hand side of the figure indicates the positions of the five sonic anemometers. Heights were normalized by the mean canopy height h_c.

The sonic anemometers were used to obtain high-frequency time series of turbulent variables and to compute the turbulent exchange. In addition to the turbulence measurements, vertical profile measurements of wind speed, temperature and humidity were performed with slow-response sensors. The above-canopy turbulence measurements were supplemented by a SODAR-RASS system located in a clearing 200 m away from the main tower (Thomas et al., 2006). Details of the experimental setup can be found in Thomas and Foken (2006b).

2.2 Profile data by Rannik et al. (2003)

Rannik et al. (2003) used observations of wind statistics within and above a Scots pine forest to drive their forward LS footprint model. Extending their original LS footprint algorithm (Rannik et al., 2000), they also considered the effect of diabatic stratification on the footprint predictions. Their profiles are based on measurements at the Hyytiälä site, which is located in southern Finland (61°51' N, 24°17" E, 181 m a.s.l.), with a mean canopy height of 14 m close to the tower. Measurement levels of the sonic anemometers employed to derive the profiles of the flow statistics were 2.0 m, 9.5 m, 23.3 m, and 46 m. The profiles used within the context of this study are shown in Figure 2. Please refer to Rannik et al. (2003) for details on instrumentation and profile parameterization.

2.3 Second order closure model by Massman and Weil (1999)

The one-and-half order closure model by Massman and Weil (1999) predicts the turbulence statistics (i.e. σ_u, σ_v and σ_w) inside the forest canopy under neutral stratification according to the plant area distribution of the study site. It builds on an analytical one dimensional model by Massman (1997) of momentum transfer to predict the profiles of the vertical momentum flux (u'w') and mean wind speed (u). In addition to plant area distribution the model requires the leaf drag coefficient C_d and the foliage sheltering factor P_m in determining the profiles of the flow statistics. We used constant values of C_d = 0.2 and P_m = 2 for these parameters the latter having inverse value of the clumping index of 0.5, which is appropriate for coniferous species (e.g. Marcolla et al., 2003).

Representative profiles for the Waldstein Weidenbrunnen site were computed using the PAI profile shown in Figure 1. The normalized profiles used to drive the LS footprint model are shown in Figure 2, together with the profiles parameterized by Rannik et al. (2003) based on measured data.

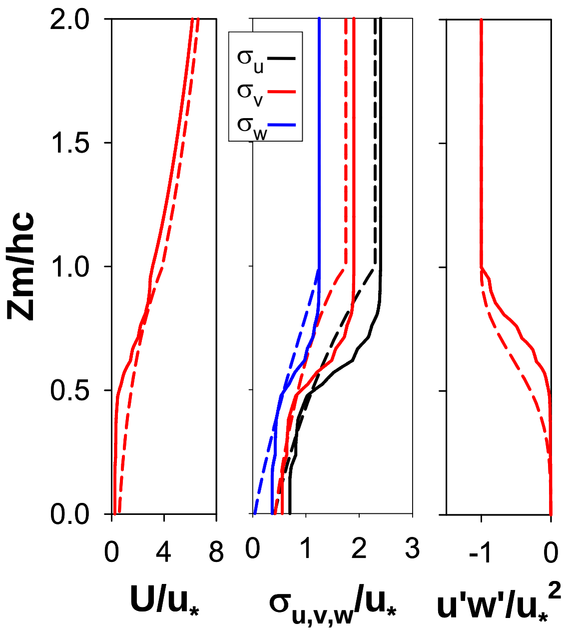

Figure 2: Profiles of the flow statistics required to drive the LS footprint model. All data shown have been produced for neutral stability of atmospheric stratification. Results were derived from the Massman and Weil (1999) second order closure model (solid lines), and taken from the measurements published by Rannik et al. (2003) (dashed lines), respectively. Zm: measurement height [m]; hc: canopy height [m]; U: Horizontal wind speed [m s^{-1}]; u*: Friction velocity [m s^{-1}]; $\sigma_{u,v,w}$: Standard deviations of alongwind (u), crosswind (v), and vertical wind (w) component [m s^{-1}]; u'w': vertical momentum flux [m^2 s^{-2}].

3 LAGRANGIAN STOCHASTIC FOOTPRINT MODELING

Lagrangian stochastic footprint approaches assume that the dispersion of a passive scalar in turbulent flow can be described by tracking the trajectories of a finite number of independent particles on their passage through the model domain (e.g. Sawford, 1985; Leclerc and Thurtell, 1990). The performance of any LS model is therefore based on the definition of the flow field within this model domain, which is described by the imposed profiles of turbulence statistics.

In contrast to the Eulerian analytical footprint models (e.g. Schuepp et al., 1990; Horst and Weil, 1992; Schmid, 1997), LS models are able to simulate non-Gaussian inhomogeneous turbulence, and three-dimensional turbulent diffusion (e.g. Reynolds, 1998). A further important advantage of LS footprint models is the option to apply vertically inhomogeneous flow statistics (Baldocchi, 1997; Rannik et al., 2000; 2003). Furthermore, the applicability of LS footprint models is not restricted to the atmospheric surface layer as is the case for the analytical models, and an arbitrary vertical distribution of source locations for the quantity to observe can be implemented. However, the LS models also demand the stationarity of the turbulent flow field as a basic requirement (Wilson and Sawford, 1996). Also, all LS footprint models operated in forward mode are based on the inverted plume assumption (e.g. Schmid and Oke, 1988; Schmid, 2002); thus they are restricted to horizontally homogeneous flow conditions.

In this study, we used the Thomson (1987) three dimensional forward LS trajectory model of Langevin type (e.g. Wilson et al., 1983; Wilson and Sawford, 1996). In this approach, in addition to being carried downwind by horizontal advection, the particles are dispersed by turbulent diffusion in vertical, along mean wind and cross mean wind directions. The particles tending downwards near to the surface are perfectly reflected at the height z_r. The required flow statistics within the canopy space are profiles of the mean wind speed $\overline{u}$, the wind fluctuations (σ_u; σ_v; σ_w), and the vertical momentum flux u'w' and the dissipation rate of the turbulent kinetic energy, ε. These can either be measured, or parameterized with closure models such as proposed by Massman and Weil (1999). The effect of stability on the profiles can be accounted for. Besides the description of the turbulence statistics, the atmospheric stability (using the Obukhov length, *L)*, surface roughness length z_0, and measurement height z_m need to be specified. In the setup chosen for this study, the simulations were performed releasing particles from a height equal to 0.005 times the canopy height, which was also the height of perfect reflection (z_r), and tracked until an upwind distance accounting for approximately 90 percent of the total flux. To examine influence of source heights on the footprints under different decoupling conditions, additional runs were performed with particle release from the heights of 0.5 and 0.9 times the canopy height.

To link the meteorological measurements with the terrain information for evaluation purposes, a concept described by Göckede et al. (2004; 2006) was applied.

4 ANALYSIS OF COHERENT STRUCTURES

The determination of exchange regimes was based on the analysis of coherent structures along the vertical profile. Coherent structures were extracted from the sampled time series using the wavelet transform (Thomas and Foken, 2005). Characteristic time scales of coherent structures were computed from the spectral peak in the wavelet variance spectrum for each sampling interval and for each variable separately. The characteristic time scale was then used to detect individual coherent structures throughout the sampling interval.

The relative contribution of coherent structures to the total flux was determined by conditionally sampling the coherent structures. This method uses a triple decomposition (Antonia et al., 1987) of a turbulent variable into high-frequency part, part attributed to the occurrence of coherent structures, and time-averaged mean over the sampling interval to partition fluxes attributed to different eddy sizes.

4.1 Exchange regimes determined with the wavelet tool

The flux contribution of coherent structures to the exchange of sensible heat was used to track coherent structures along the vertical profile of sonic anemometers as described in Thomas and Foken (2006a). As a result, it was determined how deep coherent structures penetrate into the canopy and which volume of the canopy participates in the mixing. We differentiated five exchange regimes (Figure 3) for the WALDATEM-2003 dataset:

Wave motion (W). The flow above the canopy is dominated by wave motion rather than by turbulence (Figure 3a). These periods can be detected by analyzing the phase angle in the cross-spectrum between velocity and scalar variables. We assume the atmosphere to be decoupled from the canopy and subcanopy spaces and thus the exchange of energy and matter to be negligible.

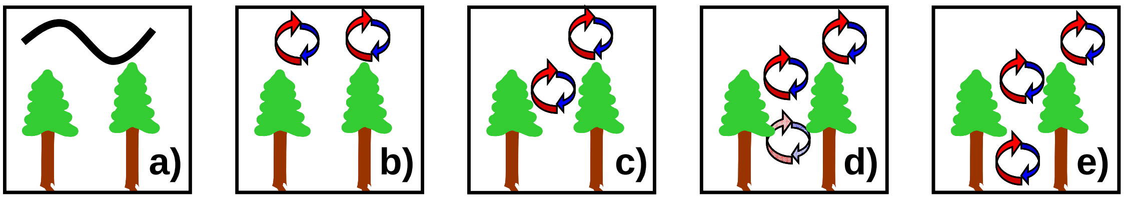

Figure 3: Sketches depicting the exchange regimes determined with the wavelet tool, indicating how deep coherent structures penetrate into the canopy according to the volume of the canopy that is coupled with the atmosphere. a) Waves (W); b) Decoupled canopy (Dc); c) Decoupled subcanopy (Ds); d) Partly coupled subcanopy (Cs); e) Fully coupled canopy (C). Please refer to the text for a more detailed description.

Decoupled canopy (Dc). The atmospheric layer above the canopy is decoupled from the canopy and sub-canopy layers (Figure 3b). The direction of the fluxes by the sweep and ejection phases of coherent structures are opposite to those in the overlying atmosphere. In general, there is no transfer of energy and matter into or out of the canopy.

Decoupled subcanopy (Ds). The atmosphere is coupled with the canopy but decoupled from the subcanopy space (Figure 3c). The volume which participates in the exchange is limited to the canopy layer. The flux contribution of the sweep and ejection phases of coherent structures at the 'bottleneck' of the canopy indicates either fluxes opposite in sign or negligible flux fractions in relation to the canopy top and the overlying atmosphere.

Partly coupled subcanopy (Cs). The exchange between the atmosphere and the subcanopy is forced by the strong sweep motion of coherent structures only (Figure 3d). The ejection phases either do not contribute significantly to the transport or are have fluxes opposite in sign in relation to the canopy top and the atmosphere. This exchange regime is a transition regime between Ds and C.

Fully coupled canopy (C). The atmosphere, the canopy and the subcanopy spaces are in a fully coupled state (Figure 3e). Both ejection and sweep phases of coherent structures significantly contribute to the exchange of energy and matter throughout the entire volume of the roughness sublayer.

Figure 4 gives the distribution of the Monin-Obukhov stability parameter $\zeta = z\,L^{-1}$ for the 5 different exchange regimes, and the percentage of 30-min averages that were assigned the specific exchange regime.

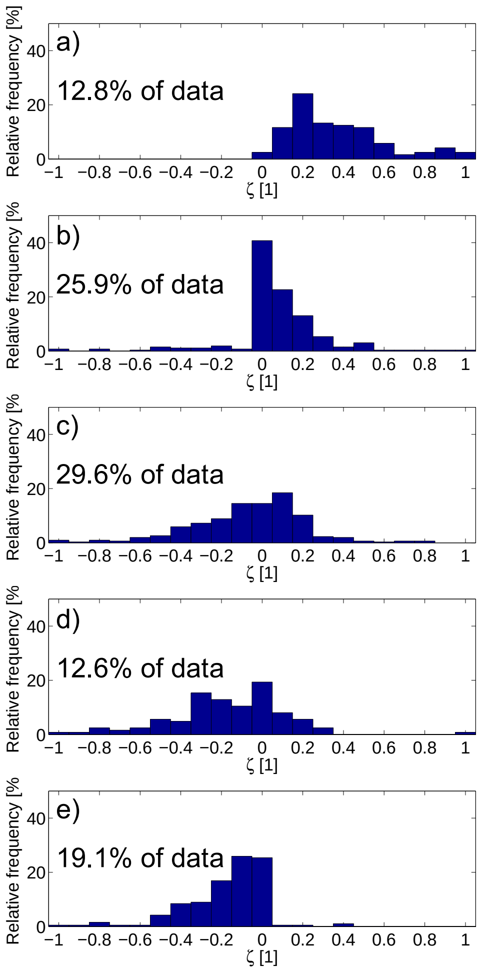

Figure 4: Distribution of the Monin-Obukhov stability parameter $\zeta = z\,L^{-1}$ for the 5 different exchange regimes: W (a), Dc (b), Ds (c), Cs (e), and C (e). Numbers give the percentage of 30-min averages that were assigned the specific exchange regime.

5 RESULTS

5.1 *Representative profile measurements for the different exchange regimes*

One representative sampling interval of 30-min length for each of the five exchange regimes was selected to characterize the turbulent flow field (Figure 5). Please note that the single, but representative sample cases will be replaced by the mean statistics for each exchange regime in a later project stage.

For the wave motion (W) regime, both high absolute values and a strong gradient of the normalized wind speed are observed above the canopy. The normalized vertical momentum flux also has a relatively large gradient in this region, but low absolute values, especially close to and within the canopy space. Normalized standard variations of the wind components are generally low, except of the cross-wind component which shows a strong gradient above the canopy.

For situations with a decoupled canopy (Dc), the highest level of variation is found in the profiles shown in Figure 5. The very strong gradient of the normalized horizontal wind speed close to the canopy top leads to a very strong gradient of the vertical momentum flux at this level. This results in very high absolute values of the shear stress above the canopy (see Figure 5b), while within the canopy the profile quickly drops to a level close to zero. The standard deviations of the wind components follow the same pattern showing the strongest gradients close to the canopy top, with a particularly large increase for the alongwind component.

The exchange regimes decoupled subcanopy (Ds) and partly coupled subcanopy (Cs) show similar general patterns in the measured profile data, although at different levels of the absolute values. For both regimes, the turbulence is more developed in the canopy space compared to the Dc regime, so that the strongest gradients are found at the height of the LAI maximum ($\approx$0.75 h_c). This particularly applies in case of the vertical momentum flux, which is at very high absolute values in the upper canopy space, and then quickly drops to low levels with decreasing heights. In general, except for the trunk space region both the average gradients in the canopy space and the absolute values of the profile data are larger for the Ds regime than those for the Cs regime. This observation may be attributed to the fact that only a single case is considered rather than mean statistics for the entire experiment.

For the fully coupled canopy (C), a pronounced local maximum (in absolute values) of the vertical momentum flux was observed. According to the high abundance of cases with unstable stratification (see Figure 4e) and the corresponding intensive turbulent mixing, the normalized standard deviations of the wind components are generally higher than for any other exchange regime. As expected, only for the C regime significant turbulent mixing can be observed down to the trunk space region

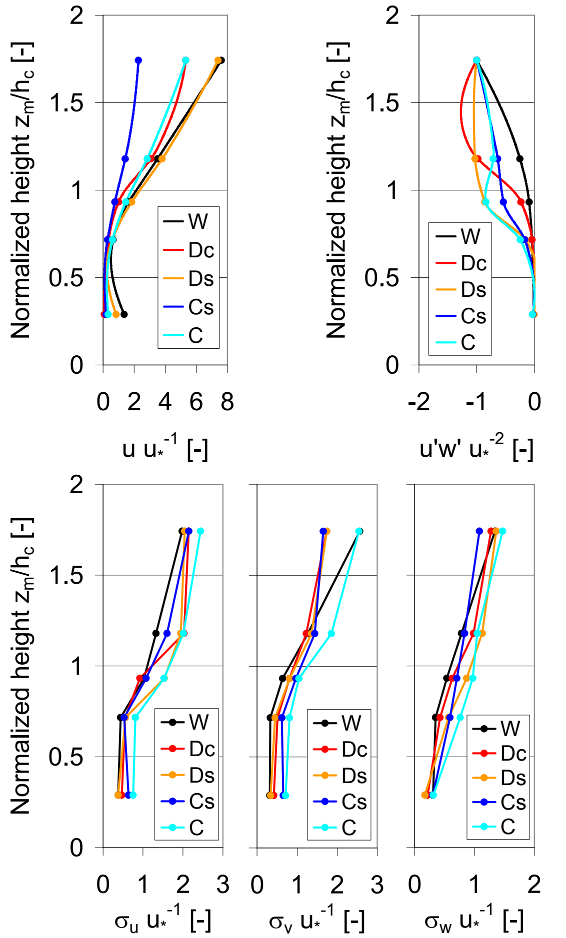

Figure 5: Representative profiles of measured turbulence statistics for the 5 exchange regimes: wind speed (a), vertical momentum flux, (b), standard deviation of alongwind (c), crosswind (d), and vertical wind (e). All values normalized with friction velocity. Figures (a) and (b) show AKIMA-interpolated profiles, (c) to (e) are linearly interpolated between measurement levels.

5.2 *Footprint functions under different exchange regimes*

Lagrangian stochastic footprints were calculated for all five exchange regimes specified above. These footprints are based on the profiles of the turbulence statistics modeled with the approach by Massman and Weil (1999) as shown in Figure 2, and the measured statistics based on the WALDATEM-2003 data presented in Figure 5. Above the highest measurement height and above the canopy space in the case of the modeled profiles, Monin-Obukhov similarity was used to extend the profiles in the atmospheric surface layer. Results for footprints and cumulative footprints are shown in Figures 6 and 7, respectively. For means of conciseness, no footprints derived with the parameterized profiles of Rannik et al. (2003) were included in this extended abstract.

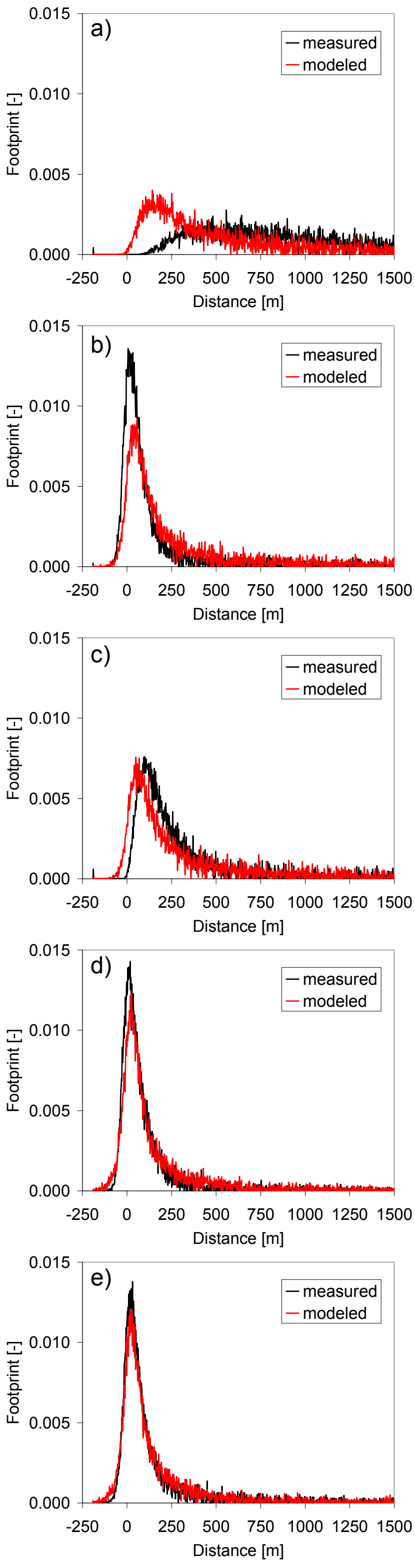

Figure 6: Footprints calculated with the forward LS trajectory model based on measured (black lines) and modeled (red lines) profiles of the turbulence statistics. Panels show footprint function for exchange regimes W (a), Dc (b), Ds (c), Cs (d), and C (e).

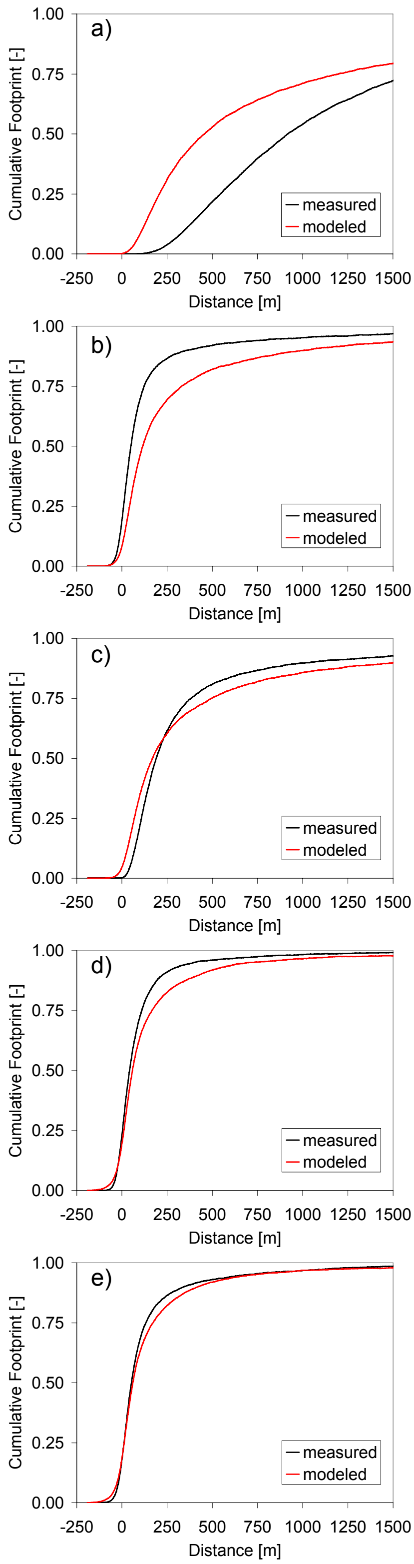

Figure 7: Cumulative footprints calculated with the forward LS trajectory model based on measured (black lines) and modeled (red lines) profiles of the turbulence statistics. Panels show cumulative footprint function for exchange regimes W (a), Dc (b), Ds (c), Cs (d), and C (e).

In Figures 6 and 7, the differences between footprints in different exchange regimes are largely influenced by differences in atmospheric stability. The stability parameter □ ranges from very stabile (W) over stable (Ds) and near-neutral (Dc) to unstable (Cs, C). As Monin-Obukhov theory was used for extrapolation purposes in the atmospheric boundary layer, atmospheric stability has a dominant impact on the shape of the modeled profile.

The differences in the footprints computed from measured and modeled turbulence statistics decrease with increasing coupling of the canopy space to the ASL. There are significant deviations to be observed for the wave motion regime (W) concerning both position and level of the footprint peak. For the decoupled canopy case (Dc), the footprint functions differ mainly in the more pronounced peak derived with the measured profiles, which causes the cumulative footprint function to reach the maximum level at a much closer distance to the tower. For the decoupled subcanopy (Ds), the peak of the footprints based on measured profiles is shifted for about 50 m in upwind direction; however, looking at the cumulative footprint function, this shift is balanced soon further upwind as the footprint based on modeled profiles drops more quickly to a lower level. For the regimes with partly decoupled subcanopy (Cs) and fully coupled canopy (C), the differences between the two footprint functions are small.

For any exchange regime, two additional footprint calculations with particle release heights at 0.5 and 0.9 h_c were calculated in addition to the model runs with release heights close to the ground. The influence of the particle release height on footprint calculations was found to be significantly larger for the footprints based on measured profiles than on those based on modeled profiles. This finding was observed for all five exchange regimes (results not shown here); however, differences in the influence of the particle release height between footprints based on measured and modeled profile data were smaller for exchange regimes with unstable atmospheric stratification (Cs, C), which are characterized by a relatively high level of turbulent exchange throughout the canopy space.

6 DISCUSSION

The results presented in the preceding section emphasize that the use of locally measured profiles of the turbulence statistics as input for an LS footprint model may have significant influence on the computed source areas. Moreover, for the five different coupling regimes between ground surface, canopy and, atmosphere as determined by spectral wavelet analysis, individual characteristics of the flow statistics within and above the canopy were found which influenced the shape and position of the computed source areas in many ways. This suggests that it may not be sufficient to run a footprint analysis for a given site with only a single set of flow statistics to describe the model domain; however, the compatibility of the specified conditions of turbulent exchange with the requirements to operate an LS footprint model needs to be discussed in more detail.

The wave motion (W) profiles are possibly not truly representative for the transport process in the model domain, as the case probably is not stationary as assumed for the footprint modeling. This is particularly true for the parts of the profile within the sub-canopy domain. The resulting large footprints are mainly due to high stability assigned to this exchange regime (see Figure 3a). The comparison between the footprints based on measured and modeled profiles indicate that the modeled turbulence overestimates the effectiveness in carrying the signal upwards toward the measurement level as the peak position is closer to the measurement point in the modeled case. These findings suggest that footprint calculations for this exchange regime are unreliable, as neither measured nor modeled turbulence statistics allow to describe the model domain in an adequate way for footprint modeling.

The exchange regimes decoupled canopy (Dc) and decoupled subcanopy (Ds) are discussed as a pair. For both regimes, the profiles of turbulence statistics are split in two sections, a well-mixed upper part and a decoupled lower part, which differs in the degree of coupling between Dc and Ds only. In the case of a particle release height at 0.9 times the canopy height, which reduces the influence of the lower canopy space on the model runs significantly, the results for both regimes are fairly similar. The most significant difference found for this release height is that the measured profiles produce more pronounced peaks than the modeled ones, indicating an underestimation of vertical transport in the modeled profiles.

Release of particles from the forest floor, however, reveals considerable differences between the Dc and the Ds regime. In the case of a decoupled canopy (Dc), the results are similar as for the case with sources in the upper parts of the canopy – the measured profiles cause the peak to be more pronounced than for modeled profiles. This may be caused by a reduced horizontal mobility of the particles due to low turbulence levels in the canopy space, so that the trajectories are still very close to the source location when they finally leave the canopy. However, also the vertical turbulence is very weak, which may balance the weak horizontal mobility of the particles, so that further analyses are required here to clarify these observations. In addition, further investigation is required to see if this description adequately represents the exchange processes, or if the decoupled canopy is rather subject to intermittent ejections of sweeps to exchange particles with the ASL.

On the contrary, in the decoupled subcanopy (Ds) regime the measured and modeled profiles produce similar peak heights with obvious differences in their locations. As shown in Figure 6c, the footprints based on measured profiles peak approximately 75 m further downwind those based on the modeled profiles. As the transport of the particles in the trunk space is based on very similar turbulence statistics for both the Dc and the Ds regime, this indicates a very effective horizontal transport within the upper part of the canopy. This interpretation is supported by the fact that for the Ds regime, very strong gradients of normalized wind speed, standard deviation of the alongwind component, and vertical momentum flux were observed (see Figure 5).

Both examples for deviations between footprints based on measured or modeled turbulence statistics, respectively, indicate that locally measured profiles are especially useful in case of a partly decoupling of the vertical model domain from the ASL. In this case, very strong gradients or even local maxima or minima of the parameters describing the turbulent flow field frequently occur, which cannot be reproduced by modeling approaches. Furthermore, these characteristics of the profile data may have significant influence on the footprint calculations, so that the use of a single modeled profile as input data to run LS footprint models will result in high uncertainties especially in Dc or Ds situations.

Measured and modeled footprints for the exchange regimes partly coupled subcanopy (Cs) and fully coupled canopy (C) are fairly similar with the exception that the Cs regime shows a closer peak location to the observation point than the C regime. This finding suggests that the use of modeled profiles of the turbulence statistics produces accurate results as long as there are no strong gradients within the profiles, and all areas are well-mixed due to a sufficient level of turbulence intensity throughout the canopy space.

The interpretation of the influence of the specific profile characteristics for different exchange regimes is compromised by the fact that they represent different stabilities which also significantly influence the shape and position of the footprint. A direct comparison is only possible between the cases Cs and C, which both have a stability parameter $\zeta = -0.285$. Differences are only small between both model runs; however, the influence of the different turbulence statistics can clearly be seen in the cumulative footprint functions (Figures 7d and 7e). For the measured profiles, the 90%-footprint has an extension of only $\approx$230 m for the Cs regime, while for the C regime this distance is $\approx$340 m, thus the footprint is $\approx$50% larger. In both cases, the 90% footprint based on the modeled profiles has a maximum distance of $\approx$420 m from the tower.

In this study we did not consider possible turning of the mean wind direction as the flow penetrates into the canopy space. That may have considerable influence on the dispersion especially under low wind speeds above the canopy, and will be addressed by using a more advanced footprint algorithm in subsequent studies.

7 SUMMARY

In this study, we tested the influence of measured profiles of turbulence statistics on Lagrangian Stochastic footprint modeling within and above a tall canopy. A wavelet tool (Thomas and Foken, 2005) was used to differentiate between five different regimes of coupling between ground surface, canopy and atmospheric surface layer (Thomas and Foken, 2006a). Each exchange regime has individual characteristics of the turbulent flow field. Comparison of the results based on these locally measured profiles with those based on the one-and-half order closure model by Massman and Weil (1999) revealed significant differences in the form and the position of footprint functions. These differences could be linked to the different exchange regimes, indicating that it may not be sufficient to run a footprint analysis with just a single set of profiles.

Concerning the effect of the exchange regime on the footprint calculations, results can be organized in three groups. First, in case of wave motions (W), footprint calculations are generally unreliable, as the turbulence is not well organized, and the flow is most probably not stationary as required for footprint modeling. Second, for exchange regimes with the lower section of the profiles decoupled from the atmospheric surface layer (Dc, Ds), significant differences between footprints based on measured or modeled profiles were observed. These can be attributed to characteristics of the turbulence profiles such as strong gradients or the occurrence of local maxima or minima, which cannot be reproduced by the modeling approaches. As a decoupling of the lower profile sections was observed for more the 50 percent of the WALDATEM-2003 dataset analyzed in this study, we conclude that conditions as such are likely to be important for sites with tall canopies of at least medium density. Consequently, profiles of the flow statistics considering this effect could significantly enhance the accuracy of LS footprint modeling. Third, for exchange regimes which at least partly couple the full canopy space to the atmospheric surface layer (Cs, C), well-mixed conditions are observed throughout the canopy space, and footprints based on profiles of modeled turbulence statistics are very similar to those based on the measured flow statistics.

Future work on this project will include the derivation of mean profiles of flow statistics for each exchange regime. It will also analyze how atmospheric stability influences the profiles, and will discuss the flow of the turbulent field in the spatial context of the experimental site, where surface conditions vary with wind direction. In footprint modeling, three-dimensional footprints will be calculated to assess the effect of the locally measured profiles on the composition of land cover types within the source weight function. In addition, we will use the improved profiles in an advanced version of the LS footprint model which allows for changing wind directions within the canopy space.

8 ACKNOWLEDGMENTS

We greatly acknowledge the contributions of Teresa Bertolini (Dept. Scienze Ambientali, Univ. Naples, Italy), Johannes Lüers, Johannes Olesch (both Dept. Micrometeorology, Univ. Bayreuth, Germany), Jens-Christopher Mayer (Max-Planck Institute for Chemistry, Mainz, Germany), and Joel Schröter (Meteorology and Air Quality Section, Univ. Wageningen, The Netherlands) in the WALDATEM-2003 experiment. This investigation was funded in part by the German Federal Ministry for Education and Research (BMBF), DFG Fo 226/10-1 and the Finnish Academy of Science.

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