3.1 USE OF FOOTPRINT MODELLING FOR THE CHARACTERISATION OF COMPLEX MEASUREMENT SITES

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1 INTRODUCTION

The adoption of the eddy covariance technique to estimate surface exchange is based on the assumption that certain conditions are valid. The most important of these are horizontal homogeneity, steady-state, and non-advective conditions. As these are often violated under complex terrain conditions, e.g. at flux monitoring sites over forests, this study aims to evaluate the influence of surface heterogeneity in order to allow a correct interpretation of the measurement results.

An approach has been developed which combines existing quality assessment tools for eddy covariance measurements with footprint modelling. For the determination of the spatial context of the measurements, a forward Lagrangian stochastic trajectory model is used. In a pre-processing step, effective roughness lengths are determined with a flux aggregation model (Hasager and Jensen, 1999). This way, the land use features of the surrounding terrain can be included in the analysis. The approach allows the determination of the dominating flux data quality for different wind sectors and varying meteorological conditions, so that the most suitable situations for the collection of high-quality data sets can be identified. Additionally, the flux contributions of the different land use types present in the footprint area are calculated.

The results can be visualised in two-dimensional graphs, which show the spatial distribution of the quality of different fluxes. These graphs help to identify terrain influences affecting the flux data quality, such as dominating obstacles in the fetch, slopes biasing the wind field, or even flow distortion or misalignment of the sensor itself. The evaluation is especially useful for checking to what extent the measured fluxes at a site are representative for a specific type of land use.

2 BASIC FEATURES OF THE APPROACH

2.1 *Input data set*

The quality assessment of the flux measurements is based on the analysis of high-frequency raw data of vertical and longitudinal wind components, air temperature, and water- and CO_2-concentrations. The required meteorological input dataset to run the footprint analyses comprises Obukhov-length and wind direction. Terrain information on the land use structure is provided by discrete matrices of high resolution, at best obtained with remote sensing methods.

2.2 *Data quality assessment*

The quality assessment of the measured fluxes of momentum, sensible and latent heat, and carbon dioxide is performed with a modified version of the method by Foken and Wichura (1996). Individual quality flags are used to rate the stationarity of the data, and to test for development of the turbulent flow field with integral turbulence characteristics. For the stationarity test, 30 minute covariances are compared with the mean covariance derived from six 5 minute covariances obtained for the same period. According to the deviations found between the values, quality flags ranging from 1 (best) to 9 (worst) are assigned. For example, deviations lower than 15 percent were rated with flag 1 (Foken, 2003; Foken et al., 2004). To test the integral turbulence characteristics, values parameterised with standard functions are compared to the measurement results. Deviations found between measured and parameterised values indicate a not fully developed turbulent flow field. These deviations are used to assign a quality flag ranging from 1 to 9, corresponding to a range of percentage deviations from below 15% (class 1) through greater than 1000% (class 9), with a non-linear partition of the range in between. The combination of these two ratings yields the overall quality of the measurement, indicated by a quality flag for each of the fluxes observed (Table 1). The vertical wind component is analysed in a separate procedure.

Table 1: Derivation of final quality flags from flags for stationarity (Stat. flag) and integral turbulence characteristics (ITC flag). Adapted from Foken et al. (2004).

Stat. flag	1	2	1-2	3-4	1-4	5	≤6	≤8	≤9
ITC flag	1-2	1-2	3-4	1-2	3-5	≤5	≤6	≤8	≤9
Final flag	1	2	3	4	5	6	7	8	9

2.3 *Footprint analysis*

The footprint analyses are performed with the Thomson (1987) forward Lagrangian stochastic (LS) trajectory model of Langevin type (e.g. Wilson and Sawford, 1996), in the version as parameterised by Rannik et al. (2003). It can be applied to diabatic conditions, and also considers within-canopy flow effects. Like all LS models, this model can also treat 3D turbulent diffusion (e.g. Reynolds, 1998). As a forward approach relying on the inverted plume assumption, it is

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restricted to horizontally homogeneous flow conditions. The simulations were performed releasing $5 \cdot 10^4$ particles from a height close to the ground, which are tracked until the upwind distance accounts for approximately 90 percent of the total flux. To save computation time, the flux footprint estimators were precalculated for a fixed set of stability classes, roughness lengths, and observation heights.

2.4 Flux aggregation model

To provide areally-averaged z_0 values as input for the footprint model, the microscale aggregation model by Hasager and Jensen (1999) is used. This approach aggregates surface properties under consideration of local advection effects in real terrain, taking into account the response of the atmospheric flow for every roughness step change. The physics consists of a linearised version of the atmospheric momentum equation in which only the advective term and the vertical flux divergence are assumed to be of importance, while all other terms such as the Coriolis term are neglected (Hasager et al., 2003). The algorithms are solved by Fast Fourier Transformation (FFT), which allows the time-efficient computation of the effective roughness parameter in consistence with the average stress for a given background flow. Terrain information must be provided by two-dimensional land use maps, with a fixed z_0 value assigned to each land use class. The aggregation model is run for a set of combinations of wind direction, atmospheric stability, and air temperature, in order to provide an effective z_0 value for different flow conditions.

3 SOURCE AREA ANALYSIS

To link the meteorological measurements with the terrain information, a footprint analysis is performed for each individual measurement of the observation period. The obtained source weight function is projected onto the land use matrix by assigning weighting factors ranging from zero to one to all matrix cells. These weighting factors are sorted by the different land use classes and subsequently summed up, yielding the relative flux contribution of each class to the total flux. This simplified aggregation process is based on the assumption of a uniform flux over all the parts of the terrain that have been assigned to the same land use class.

For the site evaluation concept presented, the individual results of the flux data quality assessment and the footprint analyses have to be combined for the complete observation period. This is obtained by collecting the results for single measurements in a database, specifying the individually assigned source weight for each matrix cell, as well as the quality flags for each of the six different quantities observed. The quantities considered are momentum flux, sensible heat flux, latent heat flux, CO_2-flux, vertical wind speed, and the contribution of the land use type to be observed within the source area to the total flux measured.

Finally, for each matrix cell, the entries in the database are evaluated in order to reveal the relative flux contribution to the total flux over the whole observation period, and the mean data quality for each of the six different quantities observed. To get the relative flux contribution for the cell, all entered weighting factors are summed up and subsequently normalised with the highest sum found in the entire matrix. To assess the overall data quality, the weighting factors are summed up for each observed quantity and then sorted according to the quality flag. As the final quality flag for each cell, the median of the distribution of these sums is used.

4 RESULTS

All result examples shown in this section were obtained with data from the Waldstein Weidenbrunnen site, which is located in the Fichtelgebirge mountains near Bayreuth, Germany. The flux measurement tower (50°08'32''N, 11°52'03''E, 775 m a.s.l.) has a height of 33 m and is part of the FLUXNET network. The surrounding terrain is hilly with moderate slopes, mainly covered by spruce forest with a mean tree height of 19 m for the nearest surrounding area. For the footprint analysis, a matrix covering 7.1 km in an east-west direction and 5.1 km in a north-south direction was prepared with a resolution of 15 m. The meteorological dataset employed for this analysis covers the period 21st May to 31st July, 2003.

Usually, a target land use type, for which the measurements shall be representative is specified for each flux monitoring site. Thus, the evaluation of the relative flux contribution of this land use type to the total flux can serve as a measure of quality. This can be obtained with the approach presented, as shown in Figure 1.

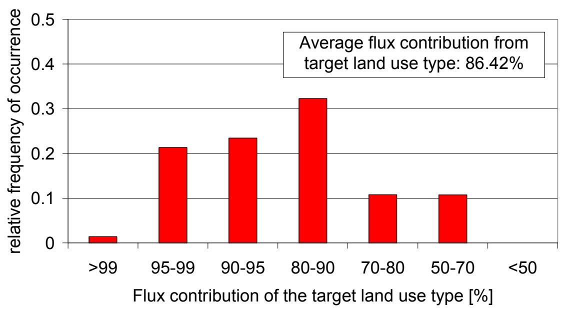

Figure 1: Classified distribution of the relative flux contribution of the target land use type to the total flux measured.

Figure 1 indicates that for the Waldstein Weidenbrunnen site, the flux contribution of the target land use type (spruce forest) is dominant during this observation period. About 78 percent of the measurements have a flux contribution from spruce forest of more than 80 percent. However, other land use types (e.g. clearings) also have a significant influence, so that on average about 86 percent of the flux was emitted by the target land use type.

The accumulation of all source weight functions for individual measurements for the total observation period yields the so-called 'footprint climatology' for the specific period. In Figure 2, this is shown as an example for stable stratification.

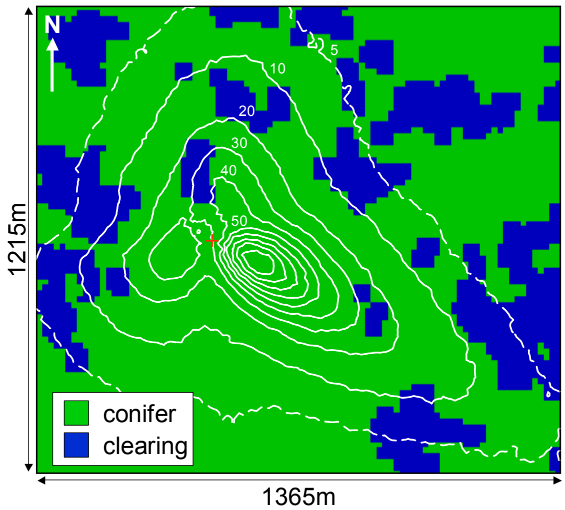

Figure 2: Footprint climatology for the Waldstein Weidenbrunnen site for stable stratification. The three dimensional weighting function is indicated by the white lines. Values are in percentages to the peak of the function, with solid lines ranging from 90 to 10 percent, and the dashed line as 5 percent of the maximum. The red cross marks the tower position.

In Figure 2, the white lines are isopleths, which reproduce the three-dimensional structure of the accumulated source weight function. The isopleths show the percentage contribution to the total flux, so that all matrix cells lying within the '90'-isopleth each have accumulated flux contributions ranging between 90 and 100 percent of the maximum value within the entire matrix. Isopleths for cells with an accumulated flux contribution below the threshold of 5 percent of the maximum value are not displayed because of the large areas covered, even though these cells are considered in the evaluations. The figures reveal that, for the chosen observation period at the Waldstein Weidenbrunnen site, during stable stratification the region to the south east of the mast was of principal importance for the measurement site. This is in contrast to the results for all stratifications (as shown in Figures 3 to 5), when the peak of the accumulated source weight function is situated very close to the west of the tower position. The principal part of the fluxes measured under stable stratification conditions was emitted within an area of about 1400 m x 1200 m.

In order to also include a visualisation of the overall data quality of the quantities observed, different colours can be used in the background of the figures to indicate the results of the data quality assessment (Figures 3 to 5). In Figure 3, the colours show the dominant data quality flag for the sensible heat flux. The white isopleths, specifying the relative flux contributions for the Waldstein Weidenbrunnen site for all stratification conditions, are included to highlight the region of highest influence on the observations. For most parts of the measurement site, the overall quality of the latent heat flux was rather low (class 7). This is due to the fact that the integral turbulence characteristics for temperature are not valid for neutral conditions, so that the deviations between modelled and measured values are frequently large. However, the overall data quality for the sensible heat flux is very high (class 2-3) in the region closest to the tower, which is dominated by the source area entries for cases with unstable stratification. In addition, there are two wind sectors in the south east and in the north-west of the tower position with a higher data quality for the sensible heat flux. In this case, the better results for these two sectors indicate a reduced number of data sets under stable stratification, so that the overall data quality is mostly influenced by the high quality data under unstable stratification.

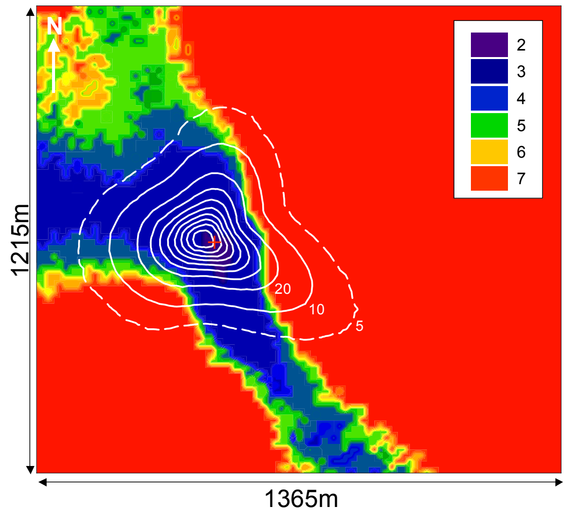

Figure 3: Spatial distribution of the quality assessment results for the sensible heat flux. The footprint climatology for all stratification cases is indicated by the white isolines, with the tower position marked by the red cross. Colours indicate the average data quality for each matrix cell, ranging from 1 (best) to 9 (worst).

In Figure 4, the quality assessment results for the vertical wind component *w* are shown. For this rating, measurements with an unrotated value of the mean *w* exceeding 0.35 m s^{-1} were flagged as 'bad', and for each matrix cell the percentage of flagged data was determined. The results displayed in Figure 4 indicate an overall low level of disturbance of the vertical wind speed for this site, with a maximum of about 20 percent of flagged measurements for individual matrix cells. However, the analysis also reveals a distinct sector with minor disturbances in the south west of the mast position. A possible explanation for these disturbances of the vertical wind component may be that the summit of the 'Großer Waldstein' lies at a distance of about 1700 m in this direction.

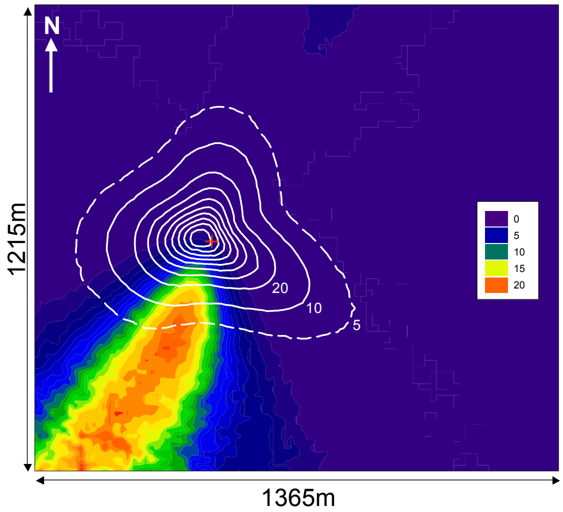

Figure 4: Spatial distribution of the quality assessment results for the vertical wind component. The footprint climatology for all stratification cases is indicated by the white isolines, with the tower position marked by the red cross. Colours indicate the percentage of unrotated mean vertical wind speeds exceeding the threshold of 0.35 m s^{-1}.

However, by using the Planar-Fit rotation method (Wilczac et al., 2001), the coordinate system can be tilted in order to adjust it to the average wind field, so that high values of the mean vertical wind speed such as shown in Figure 4 are usually eliminated. Nevertheless, the approach presented can also be adopted to evaluate the performance of this method at complex measurement sites (Figure 5).

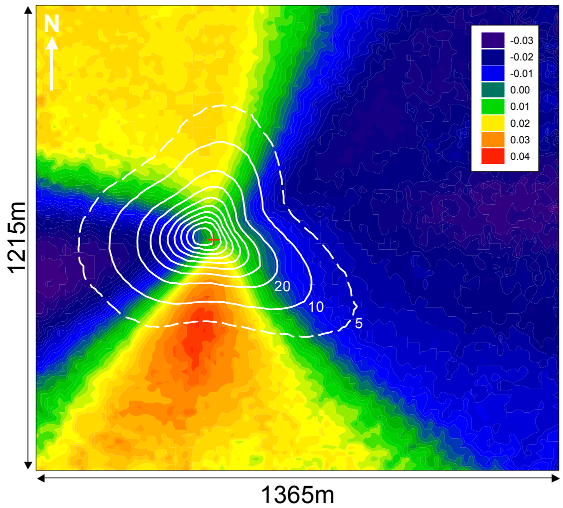

Figure 5: Mean value of the vertical wind component *w* [m/s] after performing the Planar Fit rotation method (Wilczac el al., 2001). The footprint climatology for all stratification cases is indicated by the white isolines, with the tower position marked by the red cross.

In Figure 5, for each matrix cell a footprint weighted average value of the mean vertical wind speed after performing the Planar Fit rotation method was calculated. This example for the Waldstein Weidenbrunnen site demonstrates that even after the rotation, small mean values for *w* may remain in case the average wind field is not an even plain, but in different wind sectors the plane is individually tilted. The highest deviations shown in Figure 5 are again to be found in the south westerly sector, and are probably also caused by the summit of the 'Großer Waldstein'. The positive deviations found within the northern wind sector are induced by a steep slope in the topography in this direction. In cases of higher values of the mean vertical wind component in some areas after performing the Planar Fit rotation, results as shown in Figure 5 can be employed to identify different wind sectors for which an individual rotation will be performed.

5 DISCUSSION

The approach presented is based on certain simplifications in order to provide a site evaluation tool that is practical and easy to use. The most important of these concern the application of footprint models in flow conditions over complex terrain. As already stated in Section 2.3, the forward LS footprint approach applied here assumes horizontally homogeneous flow, thus the accuracy of the modelling results obtained in terrain with large step changes in roughness is reduced (e.g. Schmid and Oke, 1990). In addition, the use of pre-calculated source weight functions does not allow the adaptation of the flow statistics to the conditions found at specific sites, thus generalisations are required that induce further uncertainty. However, to avoid these shortcomings, the adoption of a backward LS model and intensive measurements to adapt it to individual sites would be necessary, so that a practical application would no longer be possible.

Furthermore, the operation of footprint models for flow within or above tall canopies poses special problems as only a few generally valid characteristics are known for these conditions (e.g. Kaimal and Finnigan, 1994; Finnigan, 2000). Thus, the canopy turbulence has to be described with crude generalisations and certain ad hoc assumptions (Schmid, 2002). The problem of transport processes and footprints in and above high vegetation has been analysed in several detailed studies within the last years (e.g. Baldocchi, 1997; Lee, 2003; Marcolla et al., 2003; Markkanen et al., 2003). However, to date no unified theoretical framework exists for this type of flow.

The results obtained by the approach can indicate influences on the flow that are caused by meteorological effects on different scales. As a result, the practical consequences of the findings may be twofold. Mesoscale effects, for example the influence of the local topography on the vertical wind speed as shown in Figure 4 for the Waldstein Weidenbrunnen site, could in principle be avoided by choosing a better tower position. Thus, this kind of result is especially useful for the identification of the optimal location for a flux monitoring site. Synoptical events such as advected air masses with high humidity, which may reduce the quality of the measurements for the latent heat flux, are usually constant for a larger area.

Therefore, in this case the choice of the tower position is insignificant, and the findings can be applied to identify unsuitable measurement conditions in a post-processing analysis.

6 CONCLUSIONS

An approach has been developed to produce a flux data quality evaluation for meteorological measurement sites in complex terrain. It combines the quality assessment tools for eddy covariance measurements of Foken and Wichura (1996) with the forward Lagrangian stochastic footprint model of Rannik et al. (2003). In a pre-processing step, the microscale aggregation model of Hasager and Jensen (1999) is implemented to provide effective roughness lengths as input for the footprint analyses. This combination yields the dominating quality flag for the different observed fluxes and the relative flux contribution of each cell to the total measured flux. The contribution of each land use type to the measured flux is also determined.

The procedure presented is especially useful for the interpretation of results from monitoring stations situated in heterogeneous terrain, e.g. FLUXNET sites. The contribution of the target land use type to the total flux can be assessed for any user-defined period, indicating how representative the measurements are for that specific kind of surface cover. The approach proves to be a powerful tool for the identification and visualisation of factors distorting the measurements. The method can also be used to reveal differences between footprint algorithms for evaluation purposes.

7 ACKNOWLEDGMENTS

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