ADOPTION OF FOOTPRINT METHODS FOR THE QUALITY CONTROL OF EDDY-COVARIANCE MEASUREMENTS

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Contents

List of manuscripts

The thesis is presented in cumulative form consisting of seven manuscripts. Three of the manuscripts have been accepted for publication by specific journals and have been printed. One manuscript has been accepted and will be published in the near future. Two further manuscripts have been submitted and are still under review. One manuscript appears as a section in a textbook that has already been published.

Printed manuscripts

Göckede, M, Rebmann, C, Foken, T (2004) A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. Agric For Meteorol 127: 175-188 (Appendix B)

Rebmann, C, Göckede, M, Foken, T, Aubinet, M, Aurela, M, Berbigier, P, Bernhofer, C, Buchmann, N, Carrara, A, Cescatti, A, Ceulemans, R, Clement, R, Elbers, JA, Granier, A, Grünwald, T, Guyon, D, Havránková, K, Heinesch, B, Knohl, A, Laurila, T, Longdoz, B, Marcolla, B, Markkanen, T, Miglietta, F, Moncrieff, JB, Montagnani, L, Moors, E, Nardino, M, Ourcival, J-M, Rambal, S, Rannik, Ü, Rotenberg, E, Sedlak, P, Unterhuber, G, Vesala, T (2005) Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling. Theor Appl Climatol 80: 121-141 (Appendix C)

Reth, S, Göckede, M, Falge, E (2005) CO_2 efflux from agricultural soils in Eastern Germany - comparison of a closed chamber system with eddy covariance measurements. Theor Appl Climatol 80: 105-120 (Appendix H)

Accepted manuscript

Reithmaier, L, Göckede, M, Markkanen, T, Knohl, A, Churkina, G, Rebmann, C, Buchmann, N, Foken, T (2005) Use of remotely sensed land use classification to improve an approach for the evaluation of complex micrometeorological flux measurement sites. Theor Appl Climatol, accepted (Appendix E)

Submitted manuscripts

Göckede, M, Markkanen, T, Hasager, CB, Foken, T (2005a) Use of footprint modelling for the characterisation of complex measurement sites. Boundary-Layer Meteorol: submitted (Appendix F)

Göckede, M, Mauder, M, Markkanen, T, Arnold, K, Leps, J-P, Foken, T (2005b) Approaches to validate footprint models using natural tracer measurements from a field experiment. Agric For Meteorol, submitted (Appendix G)

Manuscript published as section of a textbook

Foken, T, Göckede, M, Mauder, M, Mahrt, L, Amiro, BD, Munger, JW (2004) Post-field data quality control. In: Lee, X, Massman, WJ, Law, BE (Eds.), Handbook of Micrometeorology: A guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp. 181-208 (Appendix D)

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Summary

Footprint models determine the spatial context of a measurement by defining a transfer function between sources or sinks of the signal and the sensor position. The resulting source area provides an important quality control tool to improve the interpretation of micrometeorological data sets, e.g. by assessing the influence of distorting terrain elements on the measurements. However, to date no approaches have been presented in the literature that provide a standardised footprint-based methodology that allows observers to include terrain characteristics into quality assessment and quality control strategies. Consequently, it has not yet been possible to conduct studies comparing the sites organised in flux monitoring networks such as FLUXNET (e.g. Baldocchi et al., 2001) while taking into account the influence of the local terrain structure on the data quality. One problem in this context is the small number of studies that concentrate on the validation of footprint models under the non-ideal conditions in which they are frequently being used (Foken and Leclerc, 2004). Therefore, for many applications, e.g. in aerodynamically inhomogeneous terrain, the accuracy of the source areas computed by the footprint models cannot be evaluated. To further increase the acceptance of footprint-based studies, a stronger focus on footprint validation studies for a wide variety of experimental designs is needed.

This dissertation focuses on the development of a footprint-based evaluation tool for complex measurement sites that allows the combination of quality assessment results for micrometeorological measurements with characteristics of the surrounding terrain. The standardised method is easy-to-use in order to encourage its application on a large number of sites. To improve the interpretation of the obtained results, a second objective of this thesis was to develop and test approaches to validation experiments for footprint models. In this context, several studies on natural tracer experiments for footprint validation purposes as a low-cost and practical alternative to footprint validation experiments using artificial trace gases were performed.

Göckede et al. (2004) presented an approach for the evaluation of micrometeorological measurement sites in complex terrain, which combined a method for quality assessment of eddy-covariance measurements (Foken and Wichura, 1996) with an analytic footprint model (Schmid, 1994; 1997). Their software package provided micrometeorologists, for the first time ever, a practical tool for determining the average flux contributions from the land use type intended to observe at a specific site, or to identify footprint areas for which a high data quality could be assumed, to name some examples. Rebmann et al. (2005) proved the efficiency of this evaluation approach for extensive studies on a large number of sites organised in a network by comparing 18 different sites of the CARBOEUROFLUX project. Although the average data quality for the sites tested was high, they were able to demonstrate negative effects of surface heterogeneity on the average flux data quality, and also problems caused by the instrumentation itself, such as misalignment of the sensor or flow distortion by the tower. These results may serve as a tool for an improved determination of yearly sums of the net ecosystem exchange, because fluxes originating from sectors of minor quality could be excluded from the analysis. Because of these important contributions to quality control, Foken et al. (2004) integrated the site evaluation approach into a comprehensive survey on micrometeorological post-field data quality control techniques. The experiences obtained during the extensive study by Rebmann et al. (2005) allowed us identification of the major weak points of the original site evaluation approach by Göckede et al. (2004), which we were able to improve in subsequent studies. Using remote sensing methods Reithmaier et al. (2005) studied the influence of the characteristics of the land use maps and different roughness length assignment schemes on the performance of the site evaluation approach. Finally, Göckede et al. (2005a) developed an updated version of the site evaluation approach, which improved the basic

method by replacing the analytic footprint model with a Lagrangian stochastic footprint model (Rannik et al., 2003) that is more suitable for studies above high vegetation, and by applying a more sophisticated microscale flux aggregation method (Hasager and Jensen, 1999) for the determination of areally-averaged roughness lengths. This software package forms an optimum compromise between the accuracy of the modelling results and an easy applicability to various sites. Although the implemented models are far more sophisticated than in the original version, the approach by Göckede et al. (2005a) still permits a practical application that allows for comparative studies of a large number of sites. A further improvement of the remaining conceptual weak points, such as the assumption of horizontally homogeneous flow conditions by the employed forward LS footprint model, would require extensive input data sets which could only be provided for detailed analyses of single selected study sites.

With respect to the development of validation methods for footprint models using natural tracer measurements from field scale experiments, Göckede et al. (2005b) presented two different experimental approaches. The first of these, a comparison of measured flux differences and modelled land use differences for pairs of measurement positions, revealed general correlations between measurement data and model results. However, a definite equation for a correlation analysis between flux measurements and source area composition could not be identified and, as a consequence, a quantitative evaluation of the results was not possible. Secondly, Göckede et al. (2005b) tested a correlation analysis between measured and modelled parameters using reference measurements and footprint results. Due to a clearly linear functional relationship between measured and modelled quantities, this approach resulted in an objective quantitative evaluation of the accuracy of the footprint model. The study by Reth et al. (2005), which among other objectives attempted to use soil chamber measurements and eddy-covariance data to evaluate footprint models, could not be employed for footprint validation purposes because of a large systemic scatter between these measurement systems. Overall, both the paper by Göckede et al. (2005b) and by Reth et al. (2005) provided successful methods to testing the suitability of natural tracer experiments in the validation of footprint models. Although experimental deficits prevented the working out of significant differences between the results of the employed footprint models, their studies developed an improved design for natural tracer experiments that are especially designed for footprint validation purposes. These results could form the basis for future experiments that may improve the application of footprint models in non-ideal terrain conditions.

Zusammenfassung

Footprint-Modelle bestimmen den Einfluss des umgebenden Geländes auf eine Messung durch die Definition einer Transferfunktion zwischen Quellen beziehungsweise Senken einer erfassten Größe und der Position des Sensors. Das auf diese Weise berechnete Quellgebiet stellt ein wichtiges Werkzeug für die Qualitätskontrolle mikrometeorologischer Datensätze dar. Mit ihm kann die Interpretation der Ergebnisse deutlich verbessert werden, beispielsweise durch die Bewertung des Einflusses störender Geländeelemente auf die Messungen. Allerdings wurde bislang noch kein Ansatz für ein standardisiertes Verfahren veröffentlicht, das mit Hilfe von Footprint-Modellen die Eigenschaften des Geländes bei der Bestimmung und Kontrolle der Datenqualität berücksichtigt. Als Konsequenz daraus war es bisher nicht möglich, Vergleichsstudien über den Einfluss des lokalen Geländes auf die Datenqualität für die Standorte umfangreicher Netzwerke (z.B. FLUXNET, Baldocchi et al., 2001) durchzuführen. Einen problematischen Aspekt stellt in diesem Zusammenhang die geringe Anzahl von Studien dar, die auf die Validierung von Footprint-Modellen unter den komplexen Bedingungen abzielen, in denen diese üblicherweise eingesetzt werden (Foken und Leclerc, 2004). Aus diesem Grunde kann die Qualität von Footprint-Berechnungen für viele Anwendungen, z.B. in aerodynamisch inhomogenem Gelände, nicht eindeutig bestimmt werden. Um die Akzeptanz von Footprint-Ergebnissen in mikrometeorologischen Studien weiter zu erhöhen, ist daher eine verstärkte Durchführung von Validierungsexperimenten für Footprint-Modelle unter Berücksichtigung einer Vielzahl verschiedener Messbedingungen notwendig.

Diese Dissertation konzentriert sich auf die Entwicklung eines Verfahrens zur Bewertung komplexer Mess-Standorte unter Verwendung von Footprint-Berechnungen. Dieses Verfahren ermöglicht die Verbindung von Ergebnissen der Qualitätsbewertung mikrometeorologischer Messungen mit den Eigenschaften des umliegenden Geländes. Als standardisiertes und praktisches Werkzeug ist es zur Bearbeitung einer großen Anzahl von Stationen einsetzbar. Um die Interpretation der berechneten Ergebnisse zu verbessern, wurden als zweiter Schwerpunkt dieser Arbeit Validierungsansätze für Footprint-Modelle entwickelt und getestet. Hierfür wurden mehrere Studien durchgeführt, welche die Verwendung von Messungen natürlicher Tracer aus Feldexperimenten zur Footprint-Validierung verfolgen. Diese Methode stellt eine kostengünstige und einfache Alternative zur Durchführung von Validierungs-Experimenten mit künstlichen Tracern dar.

Göckede et al. (2004) entwickelten ein Verfahrens zur Bewertung mikrometeorologischer Standorte in komplexem Gelände, das eine Methode zur Qualitätsbestimmung von Eddy-Kovarianz-Messungen (Foken und Wichura, 1996) mit einem analytischen Footprint-Modell (Schmid, 1994, 1997) verband. Das von ihnen entwickelte Programm ermöglichte unter anderem erstmals die einfache Berechnung der Flussanteile der Ziel-Landnutzungsart an einem beliebigen Standort oder die Identifikation von Teilen des umliegenden Geländes, aus denen eine generell hohe Datenqualität zu erwarten war. Rebmann et al. (2005) demonstrierten die Effizienz dieses Verfahrens für Studien mit einer hohen Anzahl von Stationen, indem sie 18 unterschiedliche Standorte des CARBOEUROFLUX Projekts miteinander verglichen. Obwohl die Datenqualität im Rahmen dieser Studie im Mittel sehr hoch war, zeigten sich für einige Standorte deutliche negative Auswirkungen der heterogenen Geländestruktur auf die Qualität der Messdaten. Außerdem konnten Störungen nachgewiesen werden, welche durch den Messaufbau selbst ausgelöst worden waren, wie zum Beispiel eine fehlerhafte Ausrichtung der Sensoren oder eine Beeinflussung des Strömungsfeldes durch die Instrumente selbst. Derartige Untersuchungen können eingesetzt werden zur verbesserten Bestimmung der jährlichen CO_2-Bilanz eines Ökosystems, indem fehlerhafte oder gestörte Messdaten von den Berechnungen ausgeschlossen werden. Aufgrund

dieses wichtigen Beitrags zur Interpretation von Messdaten integrierten Foken et al. (2004) dieses Verfahren zur Bewertung komplexer Standorte in eine umfassende Zusammenstellung mikrometeorologischer Ansätze zur Qualitätskontrolle von Datensätzen. Durch die Erfahrungen aus der umfangreichen Studie von Rebmann et al. (2005) konnten einige Schwachpunkte im Ansatz von Göckede et al. (2004) identifiziert werden, von denen die wichtigsten in nachfolgenden Studien verbessert wurden. Unter Verwendung von Fernerkundungsmethoden untersuchten Reithmaier et al. (2005) den Einfluss der Eigenschaften der Geländedaten sowie die Auswirkungen des Einsatzes verschiedener Rauhigkeits-Klassifikationen auf die Durchführung des Bewertungsverfahrens. Eine grundlegend überarbeitete Version des Ansatzes wurde schließlich von Göckede et al. (2005a) vorgelegt. Diese ersetzte das analytische Footprint-Modell durch ein Vorwärts-Trajektorienmodell mit Lagrange'scher Stochastik (Rannik et al., 2003), das zur Berechnung von Quellgebieten über hoher Vegetation besser geeignet ist. Zusätzlich wurde zur Bestimmung von flächengemittelten Rauhigkeitslängen das hochentwickelte mikroskalige Flächenmittelungsmodell von Hasager und Jensen (1999) eingesetzt. Somit stellt die Software von Göckede et al. (2005a) einen optimalen Kompromiss zwischen der Qualität der modellierten Ergebnisse und der einfachen Anwendbarkeit des Verfahrens auf beliebige Standorte dar. Obwohl die implementierten Modelle deutlich aufwändiger sind als in der Grundvariante des Ansatzes von Göckede et al. (2004), kann auch dieses Verfahren routinemäßig eingesetzt werden im Rahmen von vergleichenden Studien für eine große Anzahl von Standorten. Eine weitere Verbesserung bestehender konzeptioneller Schwachpunkte, wie zum Beispiel die Annahme horizontal homogener Strömungsbedingungen für das eingesetzte Vorwärts-Trajektorienmodell, würde sehr aufwändige Eingabedatensätze erfordern, welche lediglich für detaillierte Prozessstudien an ausgewählten einzelnen Standorten bereit gestellt werden könnten.

Göckede et al. (2005b) präsentierten zwei unterschiedliche experimentelle Ansätze zur Validierung von Footprint-Modellen mit Hilfe von Messungen natürlicher Tracer. Der erste dieser Ansätze, ein Vergleich zwischen gemessenen Fluss-Differenzen der betrachteten Größe und modellierten Landnutzungs-Differenzen, ermöglichte den Nachweis eines generellen Zusammenhangs zwischen Messdaten und Modellergebnissen. Da allerdings eine eindeutige funktionelle Beziehung zwischen den Fluss-Messungen und den Landnutzungs-Berechnungen nicht bestimmt werden konnte, war eine quantitative Bewertung der Ergebnisse über eine Korrelationsanalyse nicht möglich. Als zweiten Ansatz untersuchten Göckede et al. (2005b) den Zusammenhang zwischen gemessenen Daten und modellierten Daten, die mit Hilfe von Referenzmessungen und Footprint-Ergebnissen erstellt worden waren. Da in diesem Fall ein eindeutig linearer Zusammenhang zwischen gemessenen und modellierten Größen vorlag, konnte mit diesem Verfahren auch eine Korrelationsanalyse zur objektiven quantitativen Bewertung der Güte der Footprint-Ergebnisse durchgeführt werden. Eine Studie von Reth et al. (2005), welche als eine von mehreren Zielsetzungen die Verwendung von Bodenkammer-Messungen und Eddy-Kovarianz-Daten zur Evaluierung von Footprint-Modellen anstrebte, konnte durch eine starke Streuung der Ergebnisse aufgrund systemischer Unterschiede zwischen den eingesetzten Messtechniken nicht zur Footprint-Validierung eingesetzt werden. Generell untersuchten die Arbeiten von Göckede et al. (2005b) und Reth et al. (2005) erfolgreich die Eignung experimenteller Ansätze mit natürlichen Tracern zur Evaluierung von Footprint-Modellen. Obwohl es aufgrund von experimentellen Schwierigkeiten bisher nicht möglich war, signifikante Qualitätsunterschiede zwischen den Ergebnissen der beiden eingesetzten Footprint-Modellen nachzuweisen, bilden die gewonnenen Erfahrungen eine Grundlage für die Durchführung verbesserter Validierungsexperimente mit natürlichen Tracern, welche speziell für diese Zielstellung optimiert wurden. Die Durchführung derartiger Experimente kann die Qualität von Footprint-Ergebnissen, welche in komplexem Gelände angewendet werden, deutlich verbessern.

1 Introduction

1.1 Definition of the footprint

Micrometeorological measurements are not only influenced by the terrain directly underneath the sensor location. Indeed, the 'field of view' of the instruments stretches upwind of their position (Gash, 1986), and may include very large areas composed of many different types of sources or sinks. This spatial context is commonly defined as the 'footprint' of a measurement, a term that is also used here to summarise the terms 'effective fetch' (Pasquill, 1972) and 'source area of the sensor' (Schmid and Oke, 1990). Basically, the footprint of a measurement is a transfer function used to link the sensor signal and the characteristics of the surrounding terrain (Schmid, 2002), which can be expressed in an integral formulation (e.g. Pasquill and Smith, 1983) as given by Equation 1:

$$\eta(r) = \int_{\Re} Q_\eta(r + r') \cdot f(r, r')\, dr' \qquad (1)$$

where η is the measured value at location r, r' the position of the forcings, $Q_\eta(r+r')$ the distribution of sources and sinks, and $f(r, r')$ the footprint or transfer function between r and r'. $\Re$ is the integration domain for possible forcing positions. The footprint function, hereafter referred to as source weight function (Schmid, 1994), indicates the relative weight of the contribution of a source or sink at position r' to the measurements at the sensor location r. Its functional form is dependent on the type of the footprint model employed, which has to consider the diffusion and transport properties relevant for the distribution of the measured quantity η (Schmid, 1994, 1997).

First approaches to the estimation of the spatial context of measurements were made by Pasquill (1972), who extended the internal boundary-layer concept (e.g. Garratt, 1990, 1992) to surfaces with two-dimensional patchiness, and by Gash (1986), who calculated a cumulative fetch as an integral of the sources within a limited fetch contributing to the measured flux. This early work provided the basis for the first footprint models for concentration (Schmid and Oke, 1990) and for fluxes (Leclerc and Thurtell, 1990; Schuepp et al., 1990). Since then, many footprint methods using different mathematical concepts have been developed. Concerning the transfer function between source and sensor location, differences between the footprint approaches exist in the type of the modelled quantity η (e.g. scalar flux, or scalar gradient), the mathematical concept on which the transfer function is based (e.g. Eulerian analytical, Lagrangian stochastic trajectory simulation, or large eddy simulation model), the flow characteristics for which the model is valid (e.g. homogeneous or heterogeneous flow, neutral or diabatic stratification), and finally in the definition of the model domain (Schmid, 2002).

1.2 Analytical footprint models

Analytical footprint models use an Eulerian analytic approach to the advection-diffusion processes to calculate the mean distribution of a passive scalar in the turbulent flow field. They are all restricted to surface layer scaling, as their evaluations are based on imposed mean similarity profiles. In addition, they require horizontally homogeneous flow conditions due to the use of the inverted plume assumption (e.g. Schmid and Oke, 1990), which suggests an analogy between the developing zone of influence downwind from a surface element, and a diffusion plume of a passive scalar emitted from a point source at that specific surface position. In the crosswind direction, Gaussian distribution functions are assumed, while turbulent diffusion in the streamwise direction is considered to be small compared to advection, and thus is neglected. For most models developed to date, the equations can no longer be solved analytically due to the application of numerical algorithms, e.g. to produce realistic profiles of the eddy diffusivity K and the mean wind speed u. In general, analytical models simplify the actual flow physics in order to gain mathematical simplicity, and thus to decrease the computational expense (Schmid, 2002). Therefore, this type of footprint model is especially useful for practical footprint evaluations, or in application to large data sets. The most important approaches found in literature have been published by Schmid and Oke (1990), Schuepp et al. (1990), Leclerc and Thurtell (1990), Horst and Weil (1992) including subsequent updates of the approach (Horst and Weil, 1994, 1995; Finn et al., 1996; Horst, 1999), Schmid (1994; 1997), Haenel and Grünhage (1999), and Kormann and Meixner (2001).

1.3 Lagrangian stochastic footprint models

Lagrangian stochastic (hereafter referred to as LS) 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 (e.g. Sawford, 1985; Leclerc and Thurtell, 1990). The basic equation for the determination of the time evolution of trajectories is

$$dx_i = u_i \; dt \tag{2}$$

where x_i (i = 1, 2, 3) is the position of the particle in the i-direction, u_i the appendant Lagrangian velocity, and dt the time increment. The Lagrangian velocity in turbulent flow is usually determined by the so-called Langevin equation (e.g. Rodean, 1996)

$$du_i = a_i\left(x_i, t, u_i\right) dt + b_i\left(x_i, t, u_i\right) d\xi \tag{3}$$

In Equation 3, the parameters a_i and b_i are non-linear functions dependent on position, time, and velocity of the particle, while $d\xi$ is a Gaussian random process with zero mean and a variance of dt. The first term of the right hand side is responsible for the deterministic velocity variations, while the second term represents the stochastic influence on the increments of du_i. The correct formulation for a_i and b_i is a critical part in the design of LS footprint models, as the solutions must be able to simulate the stochastic nature of the turbulence field, and at the same time include a drift correction term to prevent mixed particles from becoming unmixed in time, e.g. using the well-mixed condition of Thomson (1987). Usually, the functions are derived from the budget equation for the Eulerian probability density function of u_i, the Fokker-Planck equation (e.g. Rodean, 1996). All evaluations of an LS model are based on imposed turbulence statistics.

In contrast to the Eulerian analytical footprint models, LS models are able to simulate non-Gaussian inhomogeneous turbulence, and three-dimensional turbulent diffusion (e.g. Reynolds, 1998). However, the LS models also demand the stationarity of the turbulent flow field as a basic requirement (Wilson and Sawford, 1996). An important advantage of LS footprint models in comparison with the analytical models is the option to separate the vertical model domain into several layers with different 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 (e.g. Rannik et al., 2000). Additionally, an arbitrary vertical distribution of sources and sinks for the quantity to observe can be implemented. Like analytical footprint models, all LS footprint models operated in forward mode (e.g. Leclerc and Thurtell, 1990; Baldocchi, 1997; Rannik et al., 2000; 2003) are based on the inverted plume assumption; thus they are restricted to horizontally homogeneous flow conditions.

This restriction can be averted by the use of backward LS footprint models (e.g. Flesch et al., 1995; Flesch, 1996; Kljun et al., 2002). However, the use of these approaches requires more sophistication than the forward mode. This method is also based on Equations 2 and 3, but using a simple linear coordinate transformation that can be derived by changing the sign of a term of the Fokker-Planck equation, and running the time interval t in backward mode $t' = T_0 - t$, where T_0 is an arbitrary transformation constant (Flesch et al., 1995). This approach allows the consideration of only those trajectories that pass through a pre-defined sensor location, because the particles are released right there, and move in an upwind direction backward in time towards the possible source locations. The critical task for the implementation of a backward LS footprint algorithm is the initialisation procedure for the vertical and streamwise velocity fluctuations, and individual parameterisations have to be found for different stability regimes.

1.4 Importance of footprint models as quality control tools

During the last decades, long-term measurement programs organised in the FLUXNET network, which aim at studying the exchange and the feedback mechanisms of greenhouse gases, have continuously been extended and gained importance. Providing measurement data for a wide range of ecosystems, these programs are an important instrument for the establishment of the global carbon budget (Houghton et al., 2001). To measure the exchange fluxes between biosphere and atmosphere, they most often make use of the eddy-covariance technique (e.g. Aubinet et al., 2000; Baldocchi et al., 2000). However, the increasing number of sites also implies that, because of their ecological importance, many sites had to be established in heterogeneous areas with naturally variable land cover. These terrain conditions violate the basic theoretic assumptions for eddy-covariance measurements, such as the need for horizontal homogeneity, steady-state, and non-advective conditions (e.g. Kaimal and Finnigan, 1994; Foken, 2003).

Due to the shift of observational focus from ideal, homogeneous sites to complex and heterogeneous conditions (e.g. Schmid, 2002), interest in algorithms that can link the measured data with the characteristics of the surrounding terrain has grown correspondingly. Neglecting the problems associated with heterogeneous terrain introduces additional uncertainties into the results obtained at the flux monitoring stations, e.g. in the assessment of the net carbon balance for a specific type of vegetation (e.g. Foken et al., 2004). Therefore, the computation of the source area by footprint models has become an important tool for the quality control of micrometeorological measurements. This information can, for example, be employed to assess the influence of distorting terrain elements on individual measurements. Footprint model results can also be applied to determine a representative composition of land use types in the fetch of the sensor in areas with a variable source and sink distribution, in order to define the spatial representativeness of the measurement site. Footprint calculations are also necessary to link measurements at different scales, such as tower measurements with remote sensing information, or eddy-covariance data with soil chamber measurements. Finally, the application of footprint models is gaining importance in the arrangement of field experiments (Horst and Weil, 1994, 1995; Schmid, 1997).

Consequently, approaches which combine quality assessment approaches for eddy-covariance measurements and footprint modelling to determine the flux data quality and the spatial representativeness of the measurements should be employed as a standard tool to allow for deeper levels of data interpretation. The fulfilment of the theoretical assumptions for the use of the eddy covariance technique can be analysed with a tool developed by Foken and Wichura (1996), which assigns quality flags to the measurements according to criteria such as the stationarity of the flow, or the state of development of the turbulent flow field. Concerning the spatial context of the measurements, a wide variety of footprint models that can be used to determine the source areas has been developed. However, to date, no quality assessment and quality control strategies have been presented in the literature that provide a standardised methodology to combine these two concepts, or to follow a comparable approach. Therefore, until now it has been impossible to conduct studies comparing the sites organised in flux monitoring networks according to the influence of the local terrain structure on the data quality.

1.5 Evaluation of footprint models

Despite the importance of footprint models for quality control purposes in micrometeorology, the issue of their validation remains an outstanding problem (Foken and Leclerc, 2004). Most of the existing footprint approaches have been compared either to measurement data or to existing footprint models as references (e.g. Horst and Weil, 1992; 1994; Flesch et al., 1995; Haenel and Grünhage, 1999; Rannik et al., 2000, 2003; Kljun et al., 2002). However, these studies typically assume idealised conditions, which do not correspond to the complex conditions at real sites where footprint models are frequently used (Foken and Leclerc, 2004). The effect of horizontally inhomogeneous flow on the accuracy of the footprint model results still remains widely unexplored, as does the presence of large step changes of surface properties in the source area of the sensor. This is due to a lack of experiments that seek to validate footprint models in natural, non-ideal conditions (e.g. Finn et al., 1996; Leclerc et al., 1997; Cooper et al., 2003; Leclerc et al., 2003a; 2003b).

Foken and Leclerc (2004) presented a thorough survey on possible concepts for footprint validation studies. In addition to a theoretical approach comparing footprint calculations with a data set generated by a large eddy simulation model (Leclerc et al., 1997), they discuss three approaches to footprint validation using experimental data sets: firstly, the use of artificial tracer gases to validate footprint estimates, adopted e.g. by Finn et al. (1996) and Leclerc et al. (2003a; 2003b); secondly, the use of natural tracer measurements (e.g. Rannik et al., 2000; Cooper et al., 2003); and thirdly, experiments in an area with isolated heterogeneities that influence the measurements (Foken et al., 1999; 2000). The term ‘natural tracer’ is used here to summarise all types of micrometeorological quantities that can be measured without releasing artificial trace gases. These may be measurements of either scalars or fluxes; however, one must take into account the fact that fluxes such as the sensible heat flux are not passive tracers.

The prerequisite for an experimental design that makes a footprint validation approach possible is the existence of variable sources or sinks of the quantity to observe in the terrain surrounding the sensor. An artificial tracer experiment is an ideal solution to this, e.g. by using sulphur hexafluoride (SF_6), with a defined point or line source, and no other sources or sinks in the environment. Besides the lack of natural sources or sinks, the use of SF_6 provides further advantages, e.g., chemical inertness, and no adherence to surfaces. For a footprint validation experiment with natural tracers, the use of standard instrumentation such as eddy-covariance measurement complexes implies that normally multiple sources or sinks are present for each quantity observed. Thus, the success of such a validation experiment is dependent on the differences of emission rates from the various types of sources, and also on the size and arrangement of the terrain parts with different source strengths in the terrain. Concerning the use of natural tracer experiments for footprint validation, Foken and Leclerc (2004), although pointing out the small number of studies published so far, highlight the possibilities of this approach; for example, the rather simple instrumental design allows for a cost-efficient realisation of such experiments. The observation of isolated heterogeneities for footprint validation purposes also offers a low-cost alternative to artificial tracer experiments, with a large number of existing data sets already available. However, these experiments are compromised by flow distortion effects induced by the heterogeneities to be monitored, which may cause the turbulent flow field not to be fully developed. Under these conditions, large additional scatter usually affects the results of the footprint models to such an extent that it is difficult to rate their performance.

1.6 Objectives of the thesis

This thesis focuses on the use of footprint modelling in the context of quality control studies in micrometeorology. It addresses two of the open questions listed by Foken and Leclerc (2004) as suggestions for future research on footprint models. As the first and principal objective, an approach has been developed, tested and further improved that includes footprint modelling as part of a software package used for a standardised post-field data quality control of micrometeorological measurements at complex sites. Secondly, to improve the interpretation of the site evaluation results based on footprint modelling, and to provide a basis for future experiments that allow evaluating footprint models under complex conditions, experimental approaches have been designed and tested to make use of simple and low-cost measurements of natural tracers for footprint validation purposes. The studies conducted to analyse these objectives have been published in seven manuscripts, which are presented in Appendices B to H. Sections 3.1 and 3.2 give a summary of the results for each topic.

The first group of papers, comprising the five manuscripts in the Appendices B to F, present an approach for the evaluation of micrometeorological measurement sites in complex terrain using footprint modelling. These studies, which are described in more detail in Section 3.1, aimed at the development of a new quality control tool for micrometeorological flux measurements. This tool should provide a standardised procedure allowing the user to link the meteorological observations with the characteristics of the terrain surrounding a flux tower in order to improve the interpretation of the data sets. For example, the approach should enable the computation of the flux contribution of the land use type intended to observe as a new quality control parameter to ensure that estimates of the yearly net ecosystem exchange are really representative for a specific type of vegetation. A further principal objective of this research was to calculate two-dimensional maps that separate the experimental site into footprint regions with a different mean data quality for various observed parameters, in order to identify sectors with disturbed measurements. An important requirement for the tool was an easy and practical applicability to different measurement sites to encourage extensive comparisons of a large number of measurement sites focusing on the influence of the local terrain on the quality of the measurements. Göckede et al. (2004, Appendix B) developed a basic version of the site evaluation approach, which combined a method for the quality assessment of eddy-covariance measurements (Foken and Wichura, 1996) with an analytic footprint model (Schmid, 1994; 1997). This concept was realised in a FORTRAN software package, which principally aimed at the identification of an averaged data quality for different footprint areas, and at the determination of the flux contributions from the various types of land use to the total flux measured. The approach was applied in an extensive study comparing 18 different sites of the CARBOEUROFLUX project (Rebmann et al., 2005, Appendix C), and integrated into a comprehensive survey on micrometeorological post-field data quality control techniques (Foken et al., 2004, Appendix D). Using remotely sensed data sets, Reithmaier et al. (2005, Appendix E) studied the influence of the characteristics of the land use maps and different roughness length assignment schemes on the performance of the site evaluation approach. Finally, Göckede et al. (2005a, Appendix F) developed an updated version of the site evaluation approach, which improved the basic method by replacing the analytic footprint model by a Lagrangian stochastic footprint model (Rannik et al., 2003) that is more suitable for studies above high vegetation, and by applying a more sophisticated flux aggregation method (Hasager and Jensen, 1999) for the determination of areally-averaged roughness lengths.

The two papers presented in appendices G and H form the second group of manuscripts, and present validation approaches for footprint models using natural tracer measurements from field scale experiments. The principal objective of these studies was to develop alternative approaches to the expensive and elaborate use of artificial trace gases for footprint validation purposes. These approaches should provide a basis for future validation experiments under real conditions in which footprint models are frequently being used, in order to improve the accuracy of the obtained results. However, as pointed out in Section 1.5, the advantages of natural tracer experiments, such as the cost-efficient realisation of such experiments, are accompanied by certain disadvantages, for example the presence of multiple sources or sinks for the quantity to observe in the experimental area. Therefore, by testing several measurement setups, various combinations of instrumentation, and different strategies to compare footprint models, the two studies presented here aimed at finding solutions to minimise the influence of disturbing factors on the footprint evaluations. Their results, which are summarised in Section 3.2, are based on the two measurement campaigns STINHO-1 and STINHO-2, in which the Department of Micrometeorology of the University of Bayreuth participated as one of several research teams. These extensive measurement campaigns were not especially designed for footprint validation purposes, but the general experimental design that was comprised of simultaneous measurements of a large number of sensors provided a suitable data basis for the studies. In Göckede et al. (2005b, Appendix G), two different footprint validation approaches were developed; firstly, a comparison of measured flux differences and modelled land use differences for pairs of measurement positions, and secondly, a correlation analysis between measured and modelled parameters using reference measurements. Both were successfully tested using field scale measurements of eddy-covariance instruments and scintillometers. The second manuscript presents a comparison study between soil chamber measurements and fluxes derived with the eddy-covariance technique (Reth et al., 2005, Appendix H). In this case, the use of the intended data set for footprint validation purposes had to be abandoned because of large systemic scatter induced by the different measurement techniques. As a consequence, this manuscript concentrates on improving the comparability of soil chamber and eddy-covariance measurements using footprint modelling. Additional results using different footprint models are provided in Section 3.2.

2 Experiments and data sets

The results presented in this thesis are based on data sets either obtained by the author's own experiments, or provided by the project partners involved in the specific studies. Concerning the author's own experiments, the Department of Micrometeorology of the University of Bayreuth participated in an extensive measurement program in two field scale campaigns of the STINHO project (STructure of Turbulent fluxes under INHOmogeneous conditions), which is a subproject of the VERTIKO (VERTIcal transports of energy and trace gases at anchor stations under COmplex natural conditions) research network. In addition, in summer 2003 the experiment WALDATEM-2003 (WAveLet Detection and Atmospheric TurbulencE Measurements) was organised in a spruce forest at the Waldstein Weidenbrunnen site in the Fichtelgebirge mountains near Bayreuth, Germany. Data sets measured by other research groups were provided for the study by Rebmann et al. (2005), who applied the site evaluation procedure by Göckede et al. (2004) on 18 flux sites organised in the CARBOEUROFLUX project.

The STINHO project studied the effect of heterogeneities in surface heating on the vertical turbulent heat exchange, and attempted to quantify the resulting horizontal heat fluxes and their divergences. The first of two field measurement campaigns organised in this context, STINHO-1, was carried out to check the capability of the combination of observation methods brought together by different participating research teams (e.g. Arnold et al., 2004). The campaign took place in the period September 24 to October 10, 2001, on the experiment site of the Leipzig Institute for Tropospheric Research, which is situated in a flat part of the Elbe valley in Melpitz near Torgau (51°31' N, 12°55' E, 86 m a.s.l.). The site itself is covered by short grass, with agricultural fields in the surrounding area. For the STINHO-1 experiment, this area was observed with several eddy-covariance complexes, small aperture scintillometers, an array for acoustic tomography, SODAR measurements, and a helicopter-borne container for flight observations, among other techniques. The University of Bayreuth team participated by using three eddy-covariance measurement complexes, a profile mast equipped with wind and temperature sensors, and instruments to monitor the surface radiation budget components (Göckede et al., 2002a).

The second field experiment, STINHO-2, constituted the main experiment of the STINHO project and was based on the experience gathered during STINHO-1. It took place in June and July 2002 at the Falkenberg Boundary-Layer measurement site of the Lindenberg observatory, which belongs to the German Meteorological Service. This site is situated at 52°10'N and 14°07'E at an altitude of 73 m a.s.l., and is embedded in a heterogeneous landscape with a slightly undulating orography formed by the inland glaciers of the last ice age (e.g. Beyrich et al., 2002). The Falkenberg Boundary-Layer measurement site itself is flat and consists of about 0.18 km² of managed meadow with short grass, while the surrounding agricultural areas are cultivated with various kinds of crops. The same techniques and observational methods as listed for the STINHO-1 experiment were used. The University of Bayreuth team participated in the period July 2 to 10, 2002, operating two eddy-covariance measurement complexes, an extensive array of instruments monitoring soil properties, instruments to monitor the surface radiation budget components, and a profile mast with wind and temperature sensors (Göckede et al., 2002b). Data from the STINHO-2 experiment were used to perform the studies presented by Göckede et al. (2005b) and Reth et al. (2005).

The experiment WALDATEM-2003 (Thomas et al., 2004) was conducted at the Waldstein Weidenbrunnen FLUXNET measuring site of the University of Bayreuth, Germany. This extensive measurement campaign was performed exclusively by members of the Department of Micrometeorology of the University of Bayreuth, under general supervision of Prof. Thomas Foken as the project manager. The experiment site was situated in the Fichtelgebirge mountains (50° 09' N, 11° 52' E, 775 m a.s.l.), with spruce as the dominant tree species and a canopy height of 19 m in the immediate vicinity of the main tower. A profile of sonic anemometers, with the highest instrument at 33 m above ground level, was used to monitor the turbulent exchange fluxes. In addition, CO_2 exchange was observed using a vertical trace-gas and isotope profile system, and a relaxed eddy accumulation (REA) system for ^{13}C and ^{18}O isotopes. The main tower was equipped with vertical profiles of cup-anemometers, as well as temperature and humidity probes. Three additional smaller towers 40 m away from the main tower measured wind speed and direction and CO_2 concentration in the sub-canopy space at 1 m and 2.25 m height. The turbulence structure in the lower atmospheric boundary layer was observed with a SO-DAR-RASS system located in a clearing 200 m away from the main tower. WALDATEM-2003 data were employed for the study presented by Göckede et al. (2005a).

For the study by Göckede et al. (2004), measurements obtained in the course of the diploma thesis by Mangold (1999) were used. Rebmann et al. (2005) and Reithmaier et al. (2005) analysed data sets from flux measuring sites organised in the CARBOEUROFLUX network. These data sets were provided by cooperating research teams responsible for the specific sites (Table 1).

Table 1: Data sets of CARBOEUROFLUX sites which were analysed in the presented thesis. Table taken from Rebmann et al. (2005), modified.

Site Code	Site Name	period with data available for footprint calculations	period for which quality tests were performed	Reference
BE-Vie	Vielsalm	01.05.-31.08.'00	01.05.-31.08.'00	Aubinet et al. (2002)
BE-Bra	Brasschaat	31.05.-01.09.'00	31.05.-17.08., 23.08.-31.08.'00	Carrara et al. (2003)
CZ-BKr1	Bily Kriz	01.07.-30.09.'00	01.07.-30.09.'00	Spunda et al. (1998)
FI-Hyy	Hyytiälä	01.05.-31.08.'01	07.05.-15.07.'01	Vesala et al. (1998)
FI-Sod	Sodankylä	01.05.-30.09.'01	02.06.-18.07.'01	Laurila et al. (2003)
FI-Kaa	Kaamanen	01.05.-30.09.'00	07.06.-22.08.'00	Aurela et al. (2002)
FR-Hes	Hesse	17.04.-31.12.'00	01.06.-28.08.'00	Granier et al. (2000)
FR-LBr	LeBray	07.05.-31.08.'00	01.07.-31.08.'00	Berbigier et al. (2001)
FR-Pue	Puechabon	03.05.-31.07.'01	03.05.-03.06.'01	Joffre et al. (2003)
DE-Wei	Waldstein	01.05.-31.08.'98	01.05.-31.08.'98	Rebmann et al. (2004)
DE-Tha	Tharandt	31.05.-30.08.'00	01.06.-30.06.'00	Bernhofer et al. (2003)
DE-Hai	Hainich	01.06.-31.08.'01	01.06.-31.08.'01	Knohl et al. (2003)
IL-Yat	Yatir	01.01.-31.03.'01	01.01.-31.03.'01	Grünzweig et al. (2003)
IT-Ren	Renon	05.10.-05.12.'01	04.10.-03.12.'01	Montagnani (cited in Rebmann et al., 2005)
IT-Non	Nonantola	01.04.-31.07.'01	01.06.-30.06.'01	Nardino et al. (cited in Rebmann et al., 2005)
IT-Lav	Lavarone	22.05.-30.09.'01	22.05.-30.09.'01	Marcolla et al. (2003)
NL-Loo	Loobos	31.05.-30.08.'00	02.06.-14.07.'00	Dolman et al. (2002)
UK-Gri	Griffin	09.01.-06.12.'00	18.06.-08.07.'00	

3 Results

3.1 Evaluation of complex micrometeorological measurement sites using footprint modelling

A basic version of an evaluation approach for complex micrometeorological sites (Göckede et al., 2004, Appendix B) was developed as a combination of existing quality assessment tools for eddy-covariance measurements (Foken and Wichura, 1996) and analytic footprint modelling (Schmid, 1994; 1997). Basically, this quality control approach strove to determine the average flux contributions from the land use type intended to observe at a specific site, and at the identification of footprint areas for which a high data quality can be assumed.

The software package determined the data quality of the eddy-covariance measurements for an observation period of several months, with a quality flag assigned to each half-hourly measurement of the fluxes of momentum, sensible and latent heat, and carbon dioxide according to a modified version of the scheme presented by Foken et al. (2004). These quality flags, which indicated whether or not the meteorological conditions fulfilled the theoretical assumptions required for the adoption of the eddy-covariance technique, were projected onto a discrete map using the source areas of the analytic flux source area model FSAM (Schmid, 1994; 1997). The footprint results were also employed to determine the flux contribution from different types of land use within the source areas, and to identify wind sectors where the averaged vertical wind component significantly deviates from the ideal value of zero. The software package collected the results for single measurements in a database, storing the individually assigned source weight for each matrix cell, as well as the quality evaluations for each of the quantities observed. After processing the complete data set, these results were aggregated to determine a two-dimensional map of the data quality structure for each observed quantity. In addition, the software package combined all individual source areas of the observation period, yielding an accumulated source area or 'footprint climatology' for the specific site.

Figure 1, as an example of a result from this basic version of the site evaluation approach, shows that the overall quality of the latent heat flux was very high for most parts of the Waldstein Weidenbrunnen site for the chosen observation period, but there were also regions to the west and to the north of the tower which were only of intermediate data quality. The relatively poor quality in these wind sectors can be attributed to fog events and air masses with high humidity or rain with winds blowing from westerly and northerly directions, which significantly influenced the closed-path analyser used for the measurement of the water concentrations necessary to determine the fluxes.

In the framework of the CARBOEUROFLUX project, Rebmann et al. (2005, Appendix C) applied the evaluation approach for complex micrometeorological sites by Göckede et al. (2004) on 18 participating sites. These study sites represented various forest ecosystems of the European continent, encompassing different species, community structures, management practices, terrain topographies, and distribution with respect to climatic change. As networks such as CARBOEUROFLUX often establish some of their measuring sites in non-ideal terrain because of their ecological importance, in some of the analysed cases significant disturbances for the eddy-covariance measurements were observed. As an example of a site with distinct structures in the computed horizontal map of the averaged data quality, Figure 2 displays the results obtained for the sensible heat flux H at the French site Hesse forest (FR-Hes).

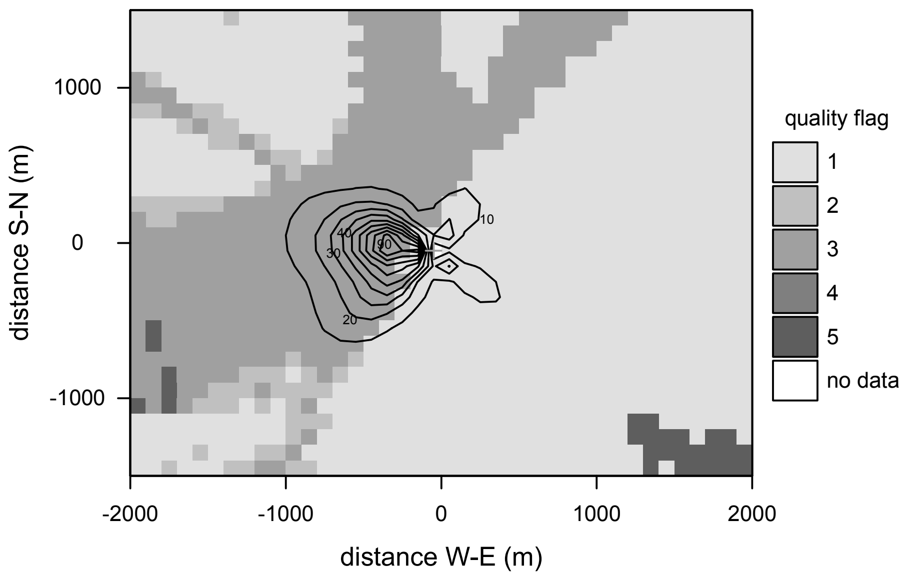


Figure 1: Aerial view of the quality control result for the latent heat flux in combination with the relative flux contribution for all stratification conditions. The results were obtained for the Waldstein Weidenbrunnen site, with measurements from the period 1 May to 31 August, 1998. The nine black isopleths indicate the normalised three-dimensional source weight function. The values represented by the isopleths are specified as percentages, and are normalised with the highest value found within the entire matrix. The area within each isopleth represents the contribution to the total flux. The '10'-isopleth, for example, follows the ring of matrix cells with an accumulated flux contribution of 10 % of the maximum flux contribution found within the entire matrix. The grey cross marks the tower position. For each matrix cell, the greyscale indicates the dominant quality flag for the latent heat flux during the observed measurement period. Figure taken from Göckede et al. (2004).

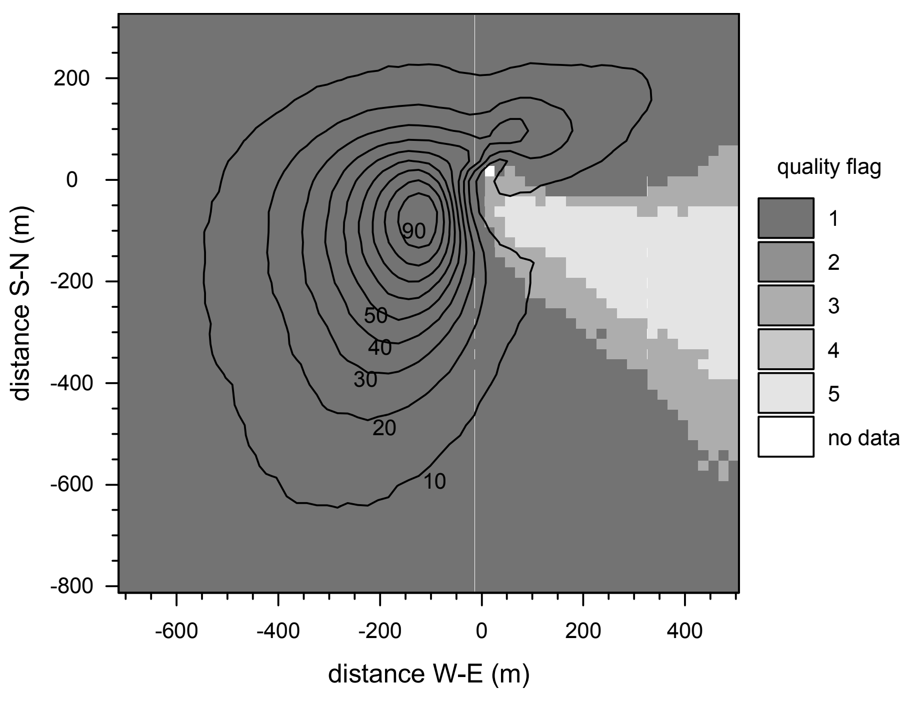


Figure 2: Spatial distribution of stationarity flags for sensible heat flux *H* with relative flux contribution for the site Hesse forest (FR-Hes). Results were obtained for the period 1 June to 28 August, 2000. See Figure 1 for more information. Figure taken from Rebmann et al. (2005).

The spatially varying mean data quality demonstrated in Figure 2 for the FR-Hes site was caused mainly by the reduction of the stationarity of *H* for easterly wind directions. This finding indicated the significant influence of an area further away consisting of crops and grasslands. These areas had very different roughness lengths than the forest areas intended for observation, and also different properties of heat exchange, which were the reasons for the instationarities of the measured fluxes. For the overall project, the quality control revealed that, on average, over all sites, 86 % of all half-hourly momentum fluxes were assigned a high quality concerning stationarity and integral turbulence characteristics. Concerning the stationarity of the fluxes, on average 83 % of all cases for the sensible heat flux and 80 % for the CO_2-flux were of high quality, whereas for the latent heat flux only 68 % could be assessed as high quality.

The investigations for the vertical wind component revealed a misalignment of the anemometer at some of the observed sites. For others, a significant influence of the local topography on the tilt of the wind field could be demonstrated. Both findings emphasised the need to apply coordinate rotation procedures such as the planar fit method (e.g. Wilczak et al., 2001) to eliminate systematically high values of the vertical wind component *w*. Figure 3 displays the results of the Italian site Renon (IT-Ren) as an example for a site with distorted *w* before the application of a coordinate rotation method.

The results shown in Figure 3 for the Renon site clearly indicate that the distribution of measurements of the vertical wind component *w* exceeding the threshold of 0.35 m s^{-1} was caused by local topography. The threshold was exceeded mainly because of the steep slope to the north of the tower position. Due to the local wind climatology, the distorted sectors had a high relative contribution to the total

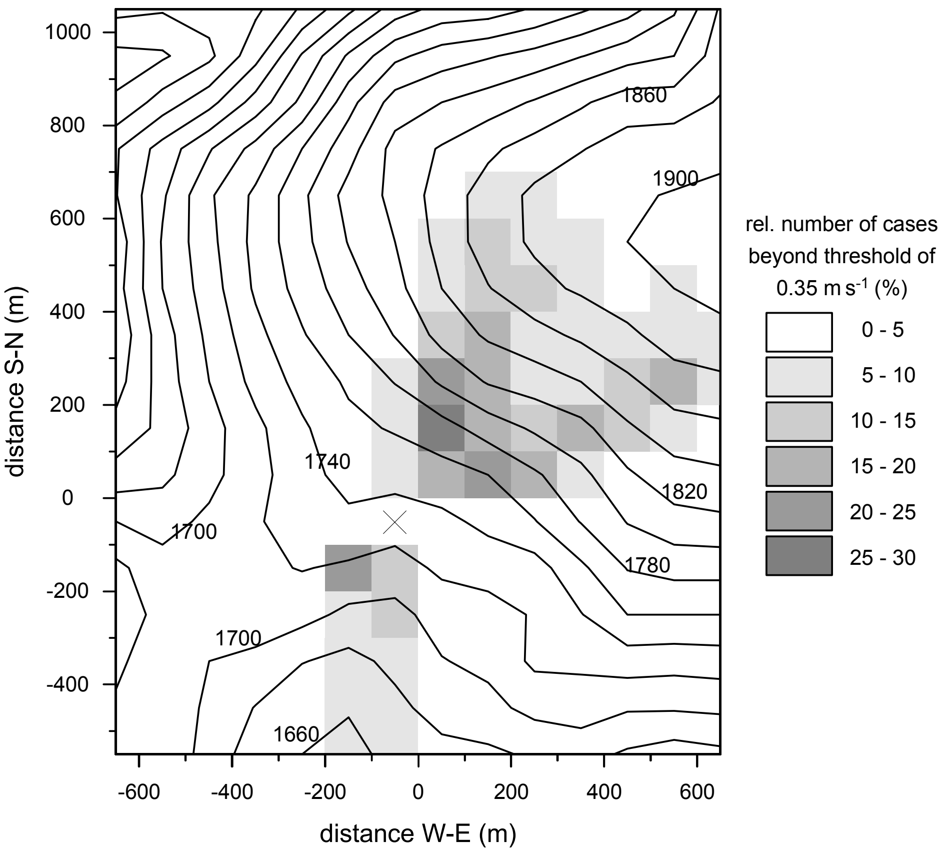


Figure 3: Spatial distribution of the quality of the vertical wind component *w* with topography (isopleths: height above sea level [m]) for the site Renon (IT-Ren). Data were measured in the period 4 October to 3 December, 2001. The cross marks the tower position. Dark greyscales indicate a high relative number of measurements of *w* exceeding the threshold of 0.35 m s^{-1}. Figure taken from Rebmann et al. (2005).

fluxes measured (results not shown). As an average result for all 18 participating sites, 95 % of the measurements of the vertical wind before application of a coordinate rotation method fall below the threshold of 0.35 m s^{-1}.

The study by Rebmann et al. (2005) proved that the evaluation approach for complex micrometeorological sites as presented by Göckede et al. (2004) provided a powerful tool for the identification of factors distorting the measurements. It permitted visualisation of the effects of surface heterogeneity on the average flux data quality, and also of problems caused by the instrumentation itself, such as misalignment of the sensor or flow distortion by the tower. Such effects, which were identified by structures in the computed two-dimensional data quality maps, could be analysed for arbitrary user-defined atmospheric conditions to refine the results. For sites situated in heterogeneous terrain, which is the case for most of the FLUXNET sites, the representativeness of a measurement position for the land use class intended to observe could be assessed. These results may serve as a tool for an improved determination of yearly sums of the net ecosystem exchange (NEE). The application of the site evaluation procedure could, for example, be used to reject fluxes originating from sectors of minor quality, or measurements with a low flux contribution from the land use type intended to observe. The replacement of these low quality data by gap-filling procedures, as is usually done for fluxes under low turbulence conditions, may significantly influence the calculation of yearly sums of the NEE. However, no studies concentrating on this issue have been conducted so far.

The incorporation of the quality control approach by Göckede et al. (2004) into the comprehensive survey on post-field data quality control by Foken et al. (2004, Appendix D) emphasises its significance for the classification of measurement sites. This section of a textbook on micrometeorological surface flux measurements summarises the steps taken to achieve quality assurance and quality control for the eddy-covariance method. The survey lists the test for site-dependant quality control by Göckede et al. (2004) among tests for spikes in the raw data (Højstrup, 1993; Vickers and Mahrt, 1997), statistical tests to determine sampling errors (e.g. Haugen, 1978; Finkelstein and Sims, 2001), and tests to analyse the fulfilment of the requirements for eddy-covariance measurements (Foken and Wichura, 1996). In this context, the approach by Göckede et al. (2004) provides an important element of a procedure designed to improve the interpretation of experimental data, and to simplify comparative studies between different measurement sites.

In spite of its successful application at a large number of measurement sites, the site evaluation concept by Göckede et al. (2004) had several weak characteristics that compromised the accuracy of the obtained results. First of all, the software package used the analytic flux source area model by Schmid (1994, 1997) to determine the source area of the measurements. FSAM is a very easy to use footprint model that allows for a fast computation of the two-dimensional source area for fluxes with reasonable computational expense and satisfying accuracy. However, the model was not designed for operation above tall vegetation, so that within-canopy flow and alongwind diffusion were neglected. The performance of the FSAM-algorithms was very sensitive to the input of the roughness length, because all input parameters were internally normalised by z_0. As a consequence, program breakdown was frequent for aerodynamically rough surfaces, especially when the Obukhov length had low positive values during stable stratification. This numerical instability of the algorithms lead to a discrimination against night time situations, with a large percentage of the cases with low friction velocities being excluded from the analysis. To minimise this effect when using FSAM in the context of the site evaluation approach, the roughness lengths had to be kept arbitrarily low for forest sites in order to avoid frequent model breakups. In addition, in some cases the characteristic dimensions of the source area calculated by the FSAM algorithms were incorrect (results not shown). These errors, which can be attributed to problems with an interpolation procedure embedded in FSAM (H.P. Schmid, personal communication), could be separated into two classes: jump discontinuities for specific combinations of the input parameters, and problems connected with very low measurement heights. In both cases, the calculated 90 % source area was much too large, inducing additional uncertainty to the results obtained by site evaluation approach using FSAM. A second weak characteristic to the approach of Göckede et al. (2004) was an oversimplified procedure introduced to derive a footprint-based average roughness length for individual measurements. This concept neglected the requirement for a non-linear flux aggregation to derive an effective value of the roughness length (e.g. Claussen, 1990), because it considered only the composition of land use types within the source area of a measurement, not their structure. A final weak characteristic to this approach was the use of very basic land use information, derived from topographical maps, to describe the characteristics of the terrain surrounding the flux tower.

To overcome the weak characteristics listed above, additional studies on these aspects of the site evaluation approach were conducted. Based on the diploma thesis by Reithmaier (2003), Reithmaier et al. (2005, Appendix E) presented a manuscript concentrating on the use of satellite remote sensing techniques to derive more accurate information on the land use structure at the observation sites. They showed that simple land use classification methods in combination with low-cost commercially available remote sensing data could not only replace the cumbersome reading of topographical maps without a loss of accuracy, but could improve the site evaluation results to a higher degree of detail. A test to determine the influence of the horizontal resolution of the maps revealed only a small influence of this parameter on the output of the model. However, the analysis also showed that a higher map resolution may improve the results by allowing a more accurate definition of the measurement position. Larger differences were found for a comparison of four different roughness length assignment schemes, but the results were not clear enough to allow the authors to recommend the most suitable scheme for the site evaluation approach. Overall, Reithmaier et al. (2005) demonstrated that the approach by Göckede et al. (2004) produced valid results even when the analysis was based on simple land use information of low resolution, while at the same time pointed out the enhanced possibilities that arise from the use of remote sensing methods in the context of the site evaluation approach.

Göckede et al. (2005a, Appendix F) conducted intensive studies on both footprint modelling and roughness length averaging procedures to improve the original site evaluation approach by Göckede et al. (2004). For the footprint calculations, the analytic FSAM (Schmid, 1994; 1997) was replaced by the forward LS trajectory model as proposed by Rannik et al. (2003). This LS model is more suitable than FSAM for modelling source areas for fluxes over tall vegetation, because it considers within-canopy transport processes and alongwind diffusion, and includes the roughness sublayer into the model domain. Furthermore, the LS model can treat high roughness lengths of more than one meter, which are more realistic for forest sites, without frequent model breakups that discriminate e.g. night-time situations. Concerning the determination of areally averaged effective roughness length values as input for the footprint model, Göckede et al. (2005a) tested several approaches according to their practicability within the context of the site evaluation approach, and for the quality of the results obtained. Based on these results, the former footprint-based computation of a roughness length for individual measurements was replaced by the application of the microscale flux aggregation model by Hasager and Jensen (1999). The physics of this model consist of a linearised and simplified version of the atmospheric momentum equation (Hasager et al., 2003), which can resolve local advection effects based on the analysis of high-resolution two-dimensional land use maps. This technique allows the time-efficient computation of effective roughness length values while considering the response of the atmospheric flow for every roughness step change in arbitrary surface conditions.

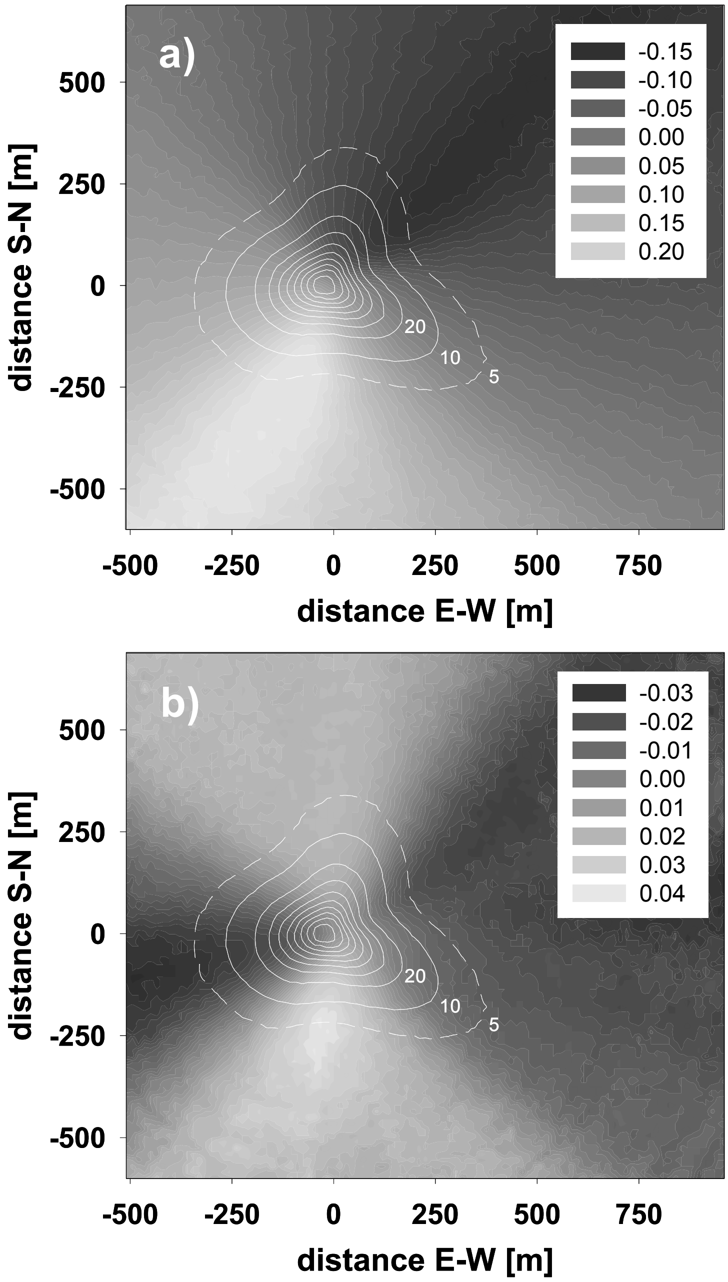


Figure 4: Spatial distribution of the averaged mean vertical wind component *w* [m s^{-1}], a) before and b) after performing the Planar-Fit correction. The results were obtained for the Waldstein Weidenbrunnen site, with measurements from the period 21 May to 31 July, 2003. The footprint climatology for all stratification cases is indicated by the white isolines. The greyscales show the mean *w* values that have been calculated for each matrix cell under consideration of the footprint results. Please note that the range of values varies between a) and b). Figures taken from Göckede et al. (2005a).

In addition to the visualisation of spatial structures of quality flags, the approach refined by Göckede et al. (2005a) can also produce maps of footprint-averaged continuous meteorological parameters. This method can be applied to show spatial structures of the average values of the vertical wind component *w*, in order to find out what kind of rotation method should be applied, and afterwards to check whether the coordinate rotation was performed correctly (Figure 4). As an example for this kind of analysis, the results for the Waldstein Weidenbrunnen site displayed in Figure 4a indicate a general tilt in the unrotated wind field, with high positive averaged values of *w* in the south-westerly wind sector, and a trend for negative values in the north-easterly direction. Along an axis stretching from the south-

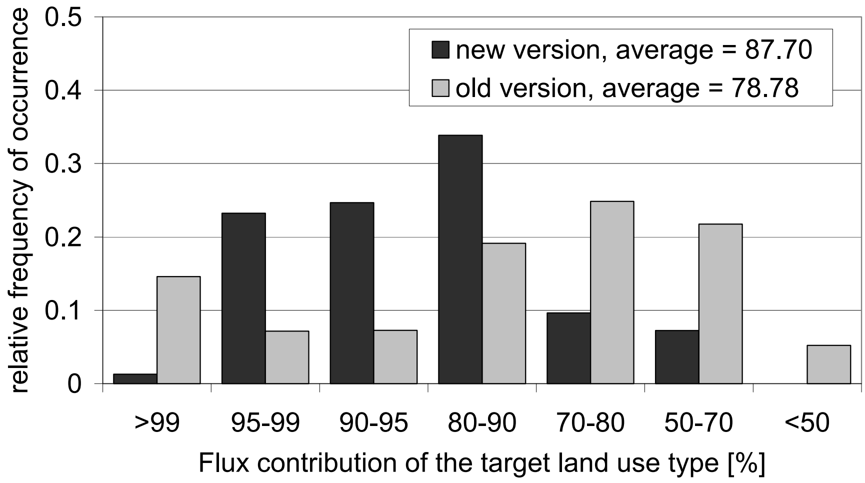


Figure 5: Comparison between results of the original site evaluation approach (Göckede et al., 2004) and of the updated version by Göckede et al. (2005a). The plot shows the classified distribution of the relative flux contribution of the target land use type to the total flux measured, computed with the different approaches. Measurements were taken from the site Waldstein Weidenbrunnen, 21 May to 31 July, 2003.

east to the northwest, the mean values for the unrotated *w* are approximately zero. These results indicate the need to apply a Planar-Fit coordinate rotation at this site, in order to minimise the effect of the general slope of the wind field that is induced by the local topography. After performing the Planar-Fit coordinate rotation (Figure 4b), the elimination of this general slope of the wind field has reduced the deviations to a level that is insignificant for the computation of the fluxes at this site.

A direct comparison between results obtained by the original site evaluation approach by Göckede et al. (2004) and the modified version by Göckede et al. (2005a) revealed significant differences (Figure 5), illustrating the important influence of the improvements implemented in the updated approach. To ensure the comparability of the results displayed in Figure 5, for both versions of the site evaluation approach the data set was reduced to about 83 % to avoid breakups of the analytic FSAM algorithm. These findings demonstrated that the use of the updated version of the site evaluation approach increased the average flux contribution of the target land use type significantly by about 9 %. The classified flux contributions of the target land use type concentrated on the range between 80 and 99 % of the total flux, while the principal part of the results of the original version was situated between 50 and 90 %. The deviations could be explained by the different shape of the source areas of both models, and by the use of higher roughness lengths when applying the LS footprint model in the updated version of the site evaluation approach. Both effects enhanced the computed flux contribution of the region close to the measurement position, which consisted almost exclusively of the target land use type in the case of the Waldstein Weidenbrunnen site. Although these findings could not be used to evaluate the different versions of the site evaluation approach, they emphasised that the use of more sophisticated footprint and flux aggregation models in the updated version of the approach, which are better adapted to the application above high vegetation, had a significant effect on the results.

3.2 Validation of footprint models with natural tracer experiments

The accuracy of micrometeorological studies based on footprint results, such as the site evaluation approach described in Section 3.1, is naturally closely connected with the quality of the performance of the employed footprint model. Therefore, it is essential to the interpretation of the results that the footprint model has been validated under the conditions chosen for the specific study. Without a thor-

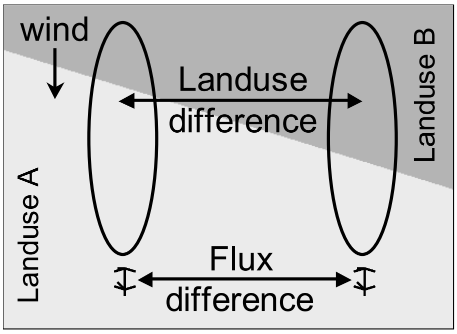


Figure 6: Sketch of the first footprint validation approach comparing the measured differences of the observed parameter between two sensor positions with the differences in the composition of their source areas as determined by a footprint model. Figure taken from Göckede et al. (2005b).

ough validation of the adopted footprint models under the conditions of the specific study, even for significantly deviating results as shown in Figure 5, it could only be speculated which of the models produced the better results. However, as already pointed out in Section 1.5, the number of footprint validation studies that have been published so far is small, and there are few available references that evaluate footprint models under the conditions in which they are frequently being used (Foken and Leclerc, 2004). Consequently, the site evaluation results obtained by the approach presented by Göckede et al. (2004; 2005a) have to be interpreted with care, as the real turbulent flow conditions at complex measurement sites might significantly deviate from those assumed by the footprint algorithms. The site evaluation approach would clearly benefit from footprint validation studies conducted in various types of complex terrain. For this reason, the second part of this thesis focuses on the development and testing of footprint validation approaches based on natural tracer measurements, intending to improve the interpretation of footprint results. These studies cannot yet be employed to improve the accuracy of the site evaluation approach, as they only analyse data sets obtained during field experiments without major disturbing elements in the direct surrounding of the sensors; however, the experience gained within the course of these studies might serve as a basis for future natural tracer experiments under complex conditions over tall vegetation.

Göckede et al. (2005b, Appendix G) presented approaches using natural tracer measurements to evaluate the performance of footprint models, with the intention of providing observers with an inexpensive and practical alternative to footprint evaluation experiments releasing artificial trace gases. The authors tested two different footprint validation approaches based on natural tracer measurements: firstly, a comparison of measured flux differences and modelled land use differences for pairs of measurement positions and secondly, a correlation analysis between measured and modelled quantities using reference measurements. Both approaches used data from either eddy-covariance measurement complexes or small aperture scintillometers operated during field experiments in an area of well-defined heterogeneity. The tests were performed employing two different footprint models, the analytical flux source area model FSAM (Schmid, 1994; 1997) and the forward LS trajectory model by Rannik et al. (2003). To determine flux source areas for scintillometers Göckede et al. (2005b) developed a special footprint software package for line measurements.

The first footprint evaluation approach using natural tracers compared results from two measurement positions in heterogeneous terrain without using additional reference measurements to define the exact source strength for each type of land use. This approach assumed that changing flux contributions of different types of land use in the source area of a sensor result in changes of the measured quantity, providing that the source strengths of the different land use types are significantly different. Thus, for the comparison study, the two sensor positions had to be chosen such that changing wind directions

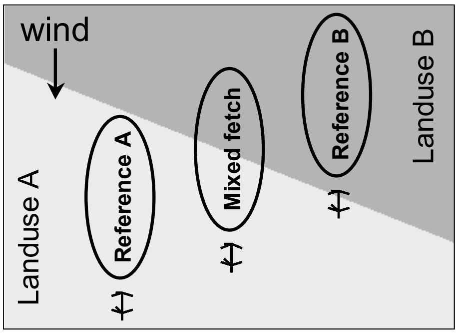


Figure 7: Sketch of the second footprint validation approach analyzing the correlation between measured fluxes at a mixed fetch position and modelled fluxes, which are composed of reference measurements using footprint model results. Figure taken from Göckede et al. (2005b).

and stability regimes induced a wide range of differences between the source area compositions (Figure 6). Göckede et al. (2005b) used this design to investigate a possible functional dependence between measured differences of the quantity and modelled flux contribution differences of the land use types, which could serve as a measure for the performance of the employed footprint model.

The first footprint evaluation approach using natural tracers, the comparison of measured flux differences and modelled land use differences for pairs of measurement positions, revealed correlations between measurement data and model results. Although the results scattered considerably for both footprint models, high differences in the measured fluxes corresponded generally with high differences in the computed flux contribution of the brownfield area, whereas for a similar source area composition the flux differences approached zero. However, a definite equation for a correlation analysis between flux measurements and source area composition could not be identified, and consequently, a quantitative evaluation of the results was not possible. The results indicated that both footprint models produced source areas that agreed with the characteristics of the measurement data, whereas no information could be obtained as to which of the footprint models produced the better results.

The second footprint comparison approach computed modelled values of a quantity for a measurement position with mixed source area using footprint-weighted reference values for each type of land use present in the surrounding terrain. These modelled values were subsequently compared with measurement data. In the simplest version at an experimental site consisting of two types of land use, this approach requires at least three measurement positions: two as reference measurements for each type of land use and one with a mixed fetch position. The approach required placing the first two sensors at positions with mostly homogeneous source areas for one type of land use. The third sensor was set up so that the source area was usually inhomogeneous, with the composition of land use types changing with varying atmospheric conditions (Figure 7).

To obtain a modelled value of the quantity to observe, as a first step the flux contributions of the different land use types had to be determined for the mixed fetch position. Subsequently, according to this ratio the measurement data of the two reference positions were mixed, yielding a weighted average value based on the actual source strengths within the source area. The coefficient of determination of a linear regression between measured and modelled quantities was used as a measure of the performance of the footprint model. The results for this footprint comparison approach (Figure 8) were obtained using sensible heat flux measurements of several eddy-covariance measurement complexes.

The principle advantage of this second footprint comparison approach was the clearly linear functional relationship between measured and modelled quantities. Assuming that additional distorting effects could be neglected, the data scatter could be attributed to imperfection of footprint modeling. Conse-

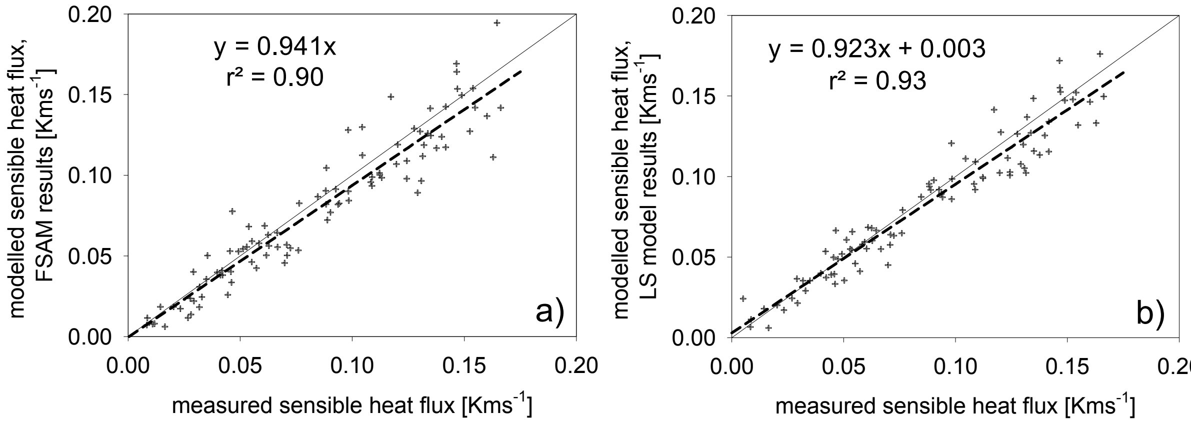
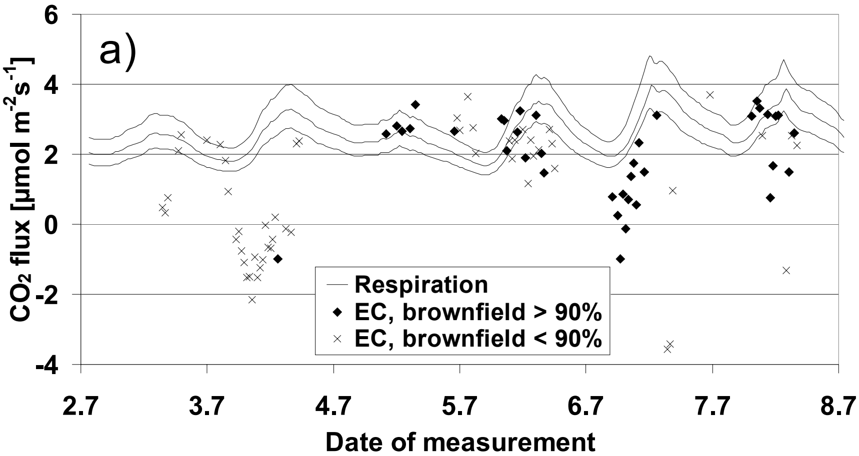


Figure 8: Test of the second footprint evaluation approach using natural tracers with sensible heat flux data measured by the eddy-covariance complexes during the STINHO-2 experiment. The correlation analysis between measured fluxes and modelled fluxes using reference data and footprint results was performed with a) the analytic FSAM model, and b) the LS model. Figure taken from Göckede et al. (2005b).

quently, the coefficient of determination r^2 makes an objective quantitative evaluation of the accuracy of the footprint model possible. Figure 8 demonstrates that for both the analytical and the LS footprint model, a close correlation between measured and modelled values of the sensible heat flux were obtained. The slightly higher r^2 value for the LS model suggested that this model provided better results than the analytic FSAM; however, the differences between the models are clearly not significant.

To simplify the data acquisition, the study by Göckede et al. (2005b) used an existing data set not especially designed for footprint validation purposes. Although they employed a high quality data set, experimental deficits reduced the significance of the findings. Several distorting factors introduced additional scatter to the data, so that the differences in the comparison between measured and modelled sensible heat fluxes could not be attributed only to incorrect footprint calculations. These uncertainties partly exceeded the deviations caused by the use of different footprint models, and thus a comparison between the two models on a quantitative basis proved no significant differences. Nevertheless, the findings demonstrated that natural tracer experiments can serve as a low-cost and practical alternative to artificial tracer experiments for footprint validation purposes as suggested by Foken and Leclerc (2004). Using an experimental design especially set up for footprint purposes, future studies should clearly prefer the second validation approach - the correlation analysis between measured and modelled quantities using reference measurements - because it allows for a direct and quantitative comparison of the performance of different models.

Göckede et al. (2005b) demonstrated that a uniform instrumental design is an important prerequisite to working out significant differences in a successful quantitative evaluation of a footprint validation experiments using natural tracers. This is especially the case in the use of eddy-covariance measurements, as the additional scatter introduced when comparing measurements from different types of sensors often exceeded the effect of the use of different footprint models. On the other hand, scintillometer measurements in combination with the software tool to determine source areas for line measurements developed by Göckede et al. (2005b) proved to be a highly suitable data source for this kind of experiment because of their small instrumental random errors. These findings are supported by the study by Reth et al. (2005, Appendix H), which, among other objectives, compared CO_2-fluxes derived by a closed soil chamber system and the soil-vegetation-atmosphere-transfer- (SVAT) model PROXEL (Tenhunen et al., 1995; Falge et al., 2003) with those measured by an eddy-covariance measurement complex.



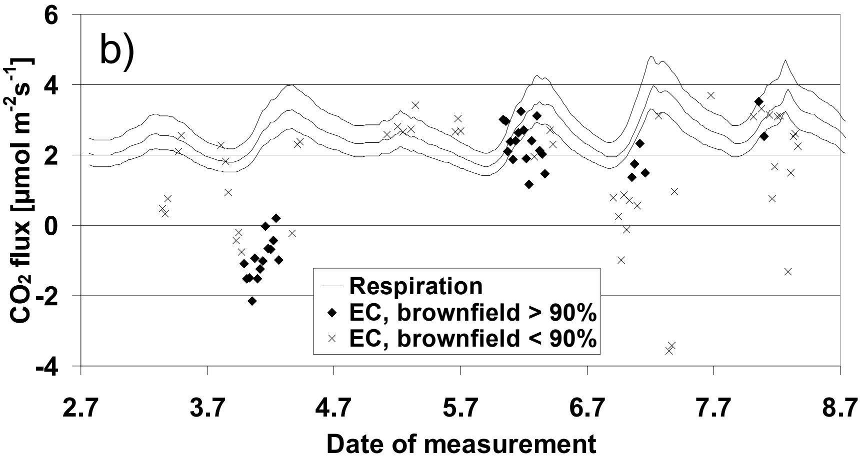


Figure 9: Comparison of respiration fluxes measured by soil chambers and eddy-covariance derived CO_2-fluxes. The thin lines bracket the results for the soil chamber data (thick line: mean values). Dots (crosses) represent the eddy-covariance measurements with a brownfield flux contribution of higher than (lower than) 90 %. Results were obtained with a) the analytic FSAM and b) the forward LS model.

Reth et al. (2005) performed their comparison experiment in an area consisting of a brownfield part and a short grass meadow. The closed soil chamber systems, which measured the respiration processes on both types of land use, were supplemented by SVAT-model results to include the respiration processes above the meadow, while the eddy-covariance system was set up at a mixed fetch position influenced by both brownfield and meadow. To use this design for footprint validation purposes, two different strategies were tested: the first approach used footprint modelling to identify eddy-covariance measurements dominated by the brownfield area, and compared those fluxes directly to the respiration results from the soil chambers. The performance of the footprint models should be evaluated by their ability to identify those eddy-covariance measurements that agreed well with the soil chamber data. The second strategy was similar to the second footprint validation approach presented in the manuscript by Göckede et al. (2005b). Again, a modelled value of the quantity to observe was computed, with the difference that a combination of soil chamber data and SVAT model results provided the reference measurements for different types of land use. However, experimental problems caused a high scatter in the results, making a footprint validation study impossible.

A test of the first footprint validation strategy, using the analytic FSAM (Schmid, 1994; 1997) and the forward LS model presented by Rannik et al. (2003), provided the results presented in Figure 9, which are not presented in this form in the manuscript by Reth et al. (2005). Both models computed the eddy-covariance measurements dominated by the brownfield area (flux contribution from brownfield higher than 90 %). Reth et al. (2005) assumed a high correlation between these data points and the respiration measurements of the soil chambers but, as shown in Figure 9, both models managed to identify only a part of the eddy-covariance measurements that fit into the corridor of the respiration measurements (including the possible range of uncertainty), while other data points labelled as brownfield-dominated did not correspond with the soil chamber data. Systemic differences between the measurement techniques in combination with internal boundary layer effects significantly scattered the results. While the former can be attributed to the scatter between both data sets in periods with general agreement, the latter are responsible for larger deviations as observed for example on July 3. The high scatter, which exceeded the effects of the use of different footprint models by a significant amount, did not allow any kind of statistical evaluation of the results.

Due to these problems, which also prevented reliable results for the second footprint validation approach, Reth et al. (2005) concentrated their study on the use of analytic footprint modelling for the improvement of comparison studies between soil chamber data and eddy-covariance measurement. They succeeded in developing a basic framework that allowed the comparison between up-scaled chamber estimates and eddy-covariance measurements of net ecosystem exchange. Using an analytical footprint model to analyse the source area for the eddy-covariance data, the modelled NEE derived from a combination of chamber measurements and SVAT-data for different land use types produced comparable results to the eddy-covariance measurements (r^2=0.69). Their study pointed to future adjustments that could further improve this already satisfying agreement between the employed measurement techniques, such as the determination of related biological and atmospheric sub-processes, or the detailed testing of the footprint model for patchy ground cover.

4 Conclusions

The successful realisation of an approach that allows including terrain characteristics into the interpretation of micrometeorological data sets (Göckede et al., 2004; 2005a) proved to be an important quality control tool for measurement sites situated in complex terrain. As shown by Rebmann et al. (2005) in their extensive study on 18 CARBOEUROFLUX sites, knowledge of the flux contribution of the land use type intended to observe, the horizontal structure of footprint regions with different average data quality, or the evaluation of the performance of a coordinate rotation procedure significantly improved the understanding of the processes affecting the quality of eddy-covariance measurements. In addition, the standardised approach made a comparative study on a large number of sites possible for the first time, providing a survey of the mean flux data quality and an evaluation of the effect of the local terrain on the measurements. For future studies, the software package presented by Göckede et al. (2005a), which is based on the original version of the evaluation approach for complex measurement sites by Göckede et al. (2004) and the experience of the studies by Rebmann et al. (2005) and Reithmaier et al. (2005), forms an optimum compromise between the accuracy of the modelling results and a practical applicability to various sites. The easy-to-provide input data set was especially adapted to allow for comparative studies of a large number of sites. As a consequence, the updated version of the site evaluation approach as presented by Göckede et al. (2005a) has been chosen for a comparative quality control study on the flux measurement sites organised in the 6th framework of the CarboEurope-IP project.

Still, this version of the approach is based on certain simplifications in order to provide a site evaluation tool that is practical and easy to use. However, improving conceptual weak characteristics such as the assumption of horizontally homogeneous flow conditions by the employed forward LS footprint model, or the use of uniform flow statistics for various types of forest ecosystems, would mean abandoning the concept of an easy applicability. As the input data required to describe e.g. a horizontally inhomogeneous modelling domain would be very extensive, detailed studies overcoming these weak points could only be performed on single selected study sites. To include these aspects into the site evaluation approach will be the principal focus of the author's future work on this subject.

As first steps towards the improved interpretation of footprint results for studies in complex terrain, the second quality control issue analysed in this thesis, the test of validation approaches for footprint models using natural tracer measurements, provided important experience in this field of research, and formed the basis for the design of future research projects. Based on field measurements of an existing data set, the studies by Göckede et al. (2005b) and Reth et al. (2005) provided successful but cost-efficient approaches to testing the suitability of using natural tracer experiments for footprint validation purposes as proposed by Foken and Leclerc (2004). Their results clearly demonstrated that simple field experiments with eddy-covariance or scintillometer instrumentation can provide valuable information for such evaluation, while a comparison of these techniques with soil chamber measurements should be avoided due to systemic differences. It could be shown that flux variations measured in an area composed of sources and sinks with different source strengths can largely be explained by the composition of land use types in the source area of the sensor computed by a footprint model. In case the experimental setup allows performing reference measurements of the temporal changes of the source strength of each land use type, natural tracer experiments make the objective comparison of footprint approaches on a quantitative basis possible. A continuation of experiments based on these natural tracer approaches could significantly increase the number of footprint validation studies, and therefore enhance the acceptance of footprint studies such as the site evaluation approach by Göckede et al. (2004; 2005a) by evaluating the models under conditions in which they are frequently being used.

The studies by Göckede et al. (2005b) and Reth et al. (2005) also demonstrate the significant influence of the instrumental setup and the arrangement of sources and sinks for the quantity to observe for the accuracy of a footprint validation experiment using natural tracers. In the case of the STINHO-2 data set that was employed by these two studies, experimental deficits prevented the determination of significant differences between the employed footprint models. However, this research provides a basis for the design of improved natural tracer experiments that are especially designed for a quantitative footprint evaluation. Such experiments, which for the next step of development should concentrate on rather undisturbed field experiments, are still cheaper and less complicated than artificial tracer studies. They should make use of a uniform experimental design that also monitors passive tracers such as the CO_2-flux. The individual land use classes in the experimental area should be homogeneous sources or sinks for the quantity observed. The measurements should be performed in a heterogeneous terrain with a clearly defined and simple structure, while aerodynamic step changes should be avoided as much as possible. Additional sensors monitoring the source strengths at several positions within one type of land use, or operating at several measurement heights at the mixed fetch position in order to allow for several simultaneous evaluations, could further improve the results.

References

Arnold, K, Ziemann, A, Raabe, A, Spindler, G (2004) Acoustic tomography and conventional meteorological measurements over heterogeneous surfaces. Meteorol Atmos Phys 85: 175-186

Aubinet, M, Grelle, A, Ibrom, A, Rannik, Ü, Moncrieff, J, Foken, T, Kowalski, AS, Martin, PH, Berbigier, P, Bernhofer, C, Clement, R, Elbers, J, Granier, A, Grünwald, T, Morgenstern, K, Pilegaard, K, Rebmann, C, Snijders, W, Valentini, R, Vesala, T (2000) Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Adv Ecol Res 30: 113-175

Aubinet, M, Heinesch, B, Longdoz, B (2002) Estimation of the carbon sequestration by a heterogeneous forest: night flux corrections, heterogeneity of the site and inter-annual variability. Global Change Biol 8: 1053-1071

Aurela, M, Laurila, T, Tuovinen, JP (2002) Annual CO2 balance of a subarctic fen in northern Europe: Importance of the wintertime efflux. J Geophys Res-Atmos 107: 4607

Baldocchi, DD (1997) Flux footprints within and over forest canopies. Boundary-Layer Meteorol 85: 273-292

Baldocchi, DD, Finnigan, JJ, Wilson, K, Paw U, KT, Falge, E (2000) On measuring net ecosystem carbon exchange over tall vegetation on complex terrain. Boundary-Layer Meteorol 96: 257-291

Baldocchi, DD, Falge, E, Gu, L, Olson, R, Hollinger, D, Running, S, Anthoni, P, Bernhofer, C, Davis, K, Fuentes, JD, Goldstein, A, Katul, G, Law, BE, Lee, X, Malhi, Y, Meyers, T, Munger, JW, Oechel, W, Pilegaard, K, Schmid, HP, Valentini, R, Verma, S, Vesala, T, Wilson, K, Wofsy, S (2001) FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapour and energy flux densities. Bull Amer Meteorol Soc 82: 2415-2435

Berbigier, P, Bonnefond, JM, Mellmann, P (2001) CO2 and water vapour fluxes for 2 years above Euroflux forest site. Agric For Meteorol 108: 183-197

Bernhofer, C, Aubinet, M, Clement, R, Grelle, A, Grünwald, T, Ibrom, A, Jarvis, P, Rebmann, C, Schulze, E-D, Tenhunen, JD (2003) Spruce forests (Norway and Sitka spruce, including Douglas fir): Carbon and water fluxes and Balances, ecological and ecophysiological determinants. In: Valentini, R (Ed), Fluxes of Carbon, Water and Energy of European Forests, Ecological Studies Series, Vol. 163. Springer, Berlin, Heidelberg, New York, pp. 99-123

Beyrich, F, Herzog, HJ, Neisser, J (2002) The LITFASS project of DWD and the LITFASS-98 experiment: The project strategy and the experimental setup. Theor Appl Climatol 73: 3-18

Carrara, A, Kowalski, AS, Neirynck, J, Janssens, IA, Yuste, JC, Ceulemans, R (2003) Net ecosystem CO2 exchange of mixed forest in Belgium over 5 years. Agric For Meteorol 119: 209-227

Claussen, M (1990) Area-averaging of surface fluxes in a neutrally stratified, horizontally inhomogeneous atmospheric boundary layer. Atmos Environ 24A: 1349-1360

Cooper, DI, Eichinger, WE, Archuleta, J, Hipps, L, Kao, J, Leclerc, MY, Neale, CM, Prueger, J (2003) Spatial source-area analysis of three-dimensional moisture fields from lidar, eddy covariance, and a footprint model. Agric For Meteorol 114: 213-234

Dolman, AJ, Moors, EJ, Elbers, JA (2002) The carbon uptake of a mid latitude pine forest growing on sandy soil. Agric For Meteorol 111: 157-170

Falge, E, Tenhunen, JD, Aubinet, M, Bernhofer, C, Clement, R, Granier, A, Kowalski, A, Moors, E, Pilegaard, K, Rannik, Ü, Rebmann, C (2003) A model-based study of carbon fluxes at ten European forest sites. In: Valentini, R (Ed), Fluxes of Carbon, Water and Energy of European Forests, Ecological Studies Series, Vol. 163. Springer, Berlin, Heidelberg, New York, pp 151-177

Finkelstein, PL, Sims, PF (2001) Sampling error in eddy correlation flux measurements. J Geophys Res D106: 3503-3509

Finn, D, Lamb, B, Leclerc, MY, Horst, TW (1996) Experimental evaluation of analytical and Lagrangian surface-layer flux footprint models. Boundary-Layer Meteorol 80: 283-308

Flesch, TK, Wilson, JD, Yee, E (1995) Backward-time Lagrangian stochastic dispersion models and their application to estimate gaseous emissions. J Appl Meteorol 34: 1320-1332

Flesch, TK (1996) The footprint for flux measurements, from backward Lagrangian stochastic models. Boundary-Layer Meteorol 78: 399-404

Foken, T, Wichura, B (1996) Tools for quality assessment of surface-based flux measurements. Agric For Meteorol 78: 83-105

Foken, T, Mangold, A, Hierteis, M, Wichura, B, Rebmann, C (1999) Characterization of the heterogeneity of the terrain by normalized turbulence characteristics. In: Proceedings of the 13th Symposium on Boundary Layer and Turbulence, Dallas, TX, American Meteorological Society, 26-27

Foken, T, Mangold, A, Rebmann, C, Wichura, B (2000) Characterization of a complex measuring site for flux measurements. In: Proceedings of the 14th Symposium on Boundary Layer and Turbulence, Aspen, CO, American Meteorological Society, 388-389

Foken, T (2003) Angewandte Meteorologie, Mikrometeorologische Methoden. Springer, Berlin, Heidelberg, New York, 289 pp

Foken, T, Göckede, M, Mauder, M, Mahrt, L, Amiro, BD, Munger, JW (2004) Post-field data quality control. In: Lee, X, Massman, WJ, Law, BE (Eds), Handbook of Micrometeorology: A guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp. 181-208

Foken, T, Leclerc, MY (2004) Methods and limitations in validation of footprint models. Agric For Meteorol 127: 223-234

Garratt, JR (1990) The internal boundary layer - a review. Boundary-Layer Meteorol 50: 171-203

Garratt, JR (1992) The atmospheric boundary layer. Cambridge University Press, Cambridge, 316 pp

Gash, JHC (1986) A note on estimating the effect of a limited fetch on micrometeorological evaporation measurements. Boundary-Layer Meteorol 35: 409-414

Göckede, M, Foken, T, Gerchau, J, Liebethal, C, Mauder, M (2002a) Dokumentation des Experiments STINHO-1. Universität Bayreuth, Abteilung Mikrometeorologie, Arbeitsergebnisse, Print ISSN 1614-8916, No. 18, 47 pp

Göckede, M, Foken, T, Liebethal, C, Mauder, M (2002b) Dokumentation des Experiments STINHO-2. Universität Bayreuth, Abteilung Mikrometeorologie, Arbeitsergebnisse, Print ISSN 1614-8916, No. 19, 34 pp

Göckede, M, Rebmann, C, Foken, T (2004) A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. Agric For Meteorol 127: 175-188

Göckede, M, Markkanen, T, Hasager, CB, Foken, T (2005a) Update of a footprint-based approach for the characterisation of complex measurement sites. Boundary-Layer Meteorol: doi 10.1007/s10546-005-6435-3

Göckede, M, Mauder, M, Markkanen, T, Arnold, K, Leps, J-P, Foken, T (2005b) Approaches to validate footprint models using natural tracer measurements from a field experiment. Agric For Meteorol (submitted)

Granier, A, Ceschia, E, Damesin, C, Dufrene, E, Epron, D, Gross, P, Lebaube, S, Le Dantec, V, Le Goff, N, Lemoine, D, Lucot, E, Ottorini, JM, Pontailler, JY, Saugier, B (2000) The carbon balance of a young Beech forest. Funct Ecol 14: 312-325

Grünzweig, JM, Lin, T, Rotenberg, E, Schwartz, A, Yakir, D (2003) Carbon sequestration in arid-land forest. Global Change Biol 9: 791-799

Haenel, HD, Grünhage, L (1999) Footprint analysis: A closed analytical solution based on height-dependent profiles of wind speed and eddy viscosity. Boundary-Layer Meteorol 93: 395-409

Hasager, CB, Jensen, NO (1999) Surface-flux aggregation in heterogeneous terrain. Quart J Roy Meteorol Soc 125: 2075-2102

Hasager, CB, Nielsen, NW, Jensen, NO, Boegh, E, Christensen, JH, Dellwik, E, Soegaard, H (2003) Effective roughness calculated from satellite-derived land cover maps and hedge-information used in a weather forecasting model. Boundary-Layer Meteorol 109: 227-254

Haugen, DA (1978) Effects of sampling rates and averaging periods on meteorological measurements. In: Proceedings of the 4th Symposium on Meteorological Observations and Instrumentation, American Meteorological Society, 15-18

Højstrup, J (1993) A statistical data screening procedure. Meas Sci Technol 4: 153-157

Horst, TW, Weil, JC (1992) Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary-Layer Meteorol 59: 279-296

Horst, TW, Weil, JC (1994) How far is far enough - the fetch requirements for micrometeorological measurement of surface fluxes. J Atmos Ocean Technol 11: 1018-1025

Horst, TW, Weil, JC (1995) Corrigenda: How far is far enough - the fetch requirements for micrometeorological measurements of surface fluxes. J Atmos Ocean Technol 12: 447

Horst, TW (1999) The footprint for estimation of atmosphere-surface exchange fluxes by profile techniques. Boundary-Layer Meteorol 90: 171-188

Houghton, JT, Ding, Y, Griggs, DJ, Noguer, M, van der Linden, PJ, Xiaosu, D (2001) IPCC Third Assessment Report: Climate Change 2001. The scientific basis. Cambridge University Press, Cambridge, 944 pp

Joffre, R, Ourcival, JM, Rambal, S, Rocheteau, A (2003) The key-role of topsoil moisture on CO_2 efflux from a Mediterranean Quercus ilex forest. Ann For Sci 60: 519-526

Kaimal, JC, Finnigan, JJ (1994) Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, New York, 289 pp

Kljun, N, Rotach, MW, Schmid, HP (2002) A three-dimensional backward Lagrangian footprint model for a wide range of boundary-layer stratifications. Boundary-Layer Meteorol 103: 205-226

Knohl, A, Schulze, ED, Kolle, O, Buchmann, N (2003) Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. Agric For Meteorol 118: 151-167

Kormann, R, Meixner, FX (2001) An analytical footprint model for non-neutral stratification. Boundary-Layer Meteorol 99: 207-224

Laurila, T, Thum, T, Aurela, M, Lohila, A (2003) Carbon dioxide fluxes between the scots pine forest and the atmosphere, meteorology and biomass data during SIFLEX-2002, Final report of SIFLEX-2002 project. European Space Agency (in preparation),

Leclerc, MY, Thurtell, GW (1990) Footprint prediction of scalar fluxes using a Markovian analysis. Boundary-Layer Meteorol 52: 247-258

Leclerc, MY, Shen, S, Lamb, B (1997) Observations and large-eddy simulation modeling of footprints in the lower convective boundary layer. J Geophys Res-Atmos 102: 9323-9334

Leclerc, MY, Karipot, A, Prabha, T, Allwine, G, Lamb, B, Gholz, HL (2003a) Impact of non-local advection on flux footprints over a tall forest canopy: a tracer flux experiment. Agric For Meteorol 115: 19-30

Leclerc, MY, Meskhidze, N, Finn, D (2003b) Comparison between measured tracer fluxes and footprint model predictions over a homogeneous canopy of intermediate roughness. Agric For Meteorol 117: 145-158

Mangold, A (1999) Untersuchung der lokalen Einflüsse auf Turbulenzmessungen der Station Weidenbrunnen. Diploma Thesis, University of Bayreuth, Bayreuth, 175 pp

Marcolla, B, Pitacco, A, Cescatti, A (2003) Canopy architecture and turbulence structure in a coniferous forest. Boundary-Layer Meteorol 108: 39-59

Pasquill, F (1972) Some aspects of boundary layer description. Quart J Roy Meteorol Soc 98: 469-494

Pasquill, F, Smith, FB (1983) Atmospheric Diffusion, 3rd edition. John Wiley and Sons, Inc., New York, 437 pp

Rannik, Ü, Aubinet, M, Kurbanmuradov, O, Sabelfeld, KK, Markkanen, T, Vesala, T (2000) Footprint analysis for measurements over a heterogeneous forest. Boundary-Layer Meteorol 97: 137-166

Rannik, Ü, Markkanen, T, Raittila, J, Hari, P, Vesala, T (2003) Turbulence statistics inside and over forest: Influence on footprint prediction. Boundary-Layer Meteorol 109: 163-189

Rebmann, C, Anthoni, P, Falge, E, Göckede, M, Mangold, A, Subke, J-A, Thomas, C, Wichura, B, Schulze, ED, Tenhunen, JD, Foken, T (2004) Carbon budget of a spruce forest ecosystem. In: Matzner, E (Ed), Biogeochemistry of forested catchments in a changing environment, Ecological Studies, Vol. 172. Springer, Berlin, Heidelberg, New York, pp. 143-160

Rebmann, C, Göckede, M, Foken, T, Aubinet, M, Aurela, M, Berbigier, P, Bernhofer, C, Buchmann, N, Carrara, A, Cescatti, A, Ceulemans, R, Clement, R, Elbers, JA, Granier, A, Grünwald, T, Guyon, D, Havránková, K, Heinesch, B, Knohl, A, Laurila, T, Longdoz, B, Marcolla, B, Markkanen, T, Miglietta, F, Moncrieff, JB, Montagnani, L, Moors, E, Nardino, M, Ourcival, J-M, Rambal, S, Rannik, Ü, Rotenberg, E, Sedlak, P, Unterhuber, G, Vesala, T, Yakir, D (2005) Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling. Theor Appl Climatol 80: 121-141

Reithmaier, L (2003) Application of remote sensing methods for micrometeorological site evaluation. Diploma Thesis, University of Bayreuth, Bayreuth, 150 pp

Reithmaier, L, Göckede, M, Markkanen, T, Knohl, A, Churkina, G, Rebmann, C, Buchmann, N, Foken, T (2005) Use of remotely sensed land use classification to improve an approach for the evaluation of complex micrometeorological flux measurement sites. Theor Appl Climatol (accepted)

Reth, S, Göckede, M, Falge, E (2005) CO_2 efflux from agricultural soils in Eastern Germany - comparison of a closed chamber system with eddy covariance measurements. Theor Appl Climatol 80: 105-120

Reynolds, AM (1998) A two-dimensional Lagrangian stochastic dispersion model for convective boundary layers with wind shear. Boundary-Layer Meteorol 86: 345-352

Rodean, H (1996) Stochastic Lagrangian models of turbulent diffusion. American Meteorological Society, Boston, 84 pp

Sawford, BL (1985) Lagrangian stochastic simulation of concentration mean and fluctuation fields. J Clim Appl Meteorol 24: 1152-1166

Schmid, HP, Oke, TR (1990) A model to estimate the source area contributing to turbulent exchange in the surface layer over patchy terrain. Quart J Roy Meteorol Soc 116: 965-988

Schmid, HP (1994) Source areas for scalars and scalar fluxes. Boundary-Layer Meteorol 67: 293-318

Schmid, HP (1997) Experimental design for flux measurements: matching scales of observations and fluxes. Agric For Meteorol 87: 179-200

Schmid, HP (2002) Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. Agric For Meteorol 113: 159-183

Schuepp, PH, Leclerc, MY, MacPherson, JI, Desjardins, RL (1990) Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation. Boundary-Layer Meteorol 50: 355-373

Spunda, V, Cajanek, M, Kalina, J, Lachetova, I, Sprtova, M, Marek, MV (1998) Mechanistic differences in utilization of absorbed excitation energy within photosynthetic apparatus of Norway spruce induced by the vertical distribution of photosynthetically active radiation through the tree crown. Plant Sci 133: 155-165

Tenhunen, JD, Siegwolf, RA, Oberbauer, SF (1995) Effects of phenology, physiology, and gradients in community composition, structure, and microclimate on tundra ecosystem CO_2 exchange. In: Schulze, E-D, Caldwell, MM (Eds), Ecophysiology of photosynthesis. Springer, Berlin, Heidelberg, New York, pp. 431-460

Thomas, C, Ruppert, J, Lüers, J, Schröter, J, Mayer, JC, Bertolini, T (2004) Documentation of the WALDATEM-2003 Experiment. Universität Bayreuth, Abteilung Mikrometeorologie, Arbeitsergebnisse, Print ISSN 1614-8916, No. 24, 59 pp

Thomson, DJ (1987) Criteria for the selection of stochastic models of particle trajectories in turbulent flows. J Fluid Mech 180: 529-556

Vesala, T, Haataja, J, Aalto, P, Altimir, N, Buzorius, G, Garam, E, Hameri, K, Ilvesniemi, H, Jokinen, V, Keronen, P, Lahti, T, Markkanen, T, Makela, JM, Nikinmaa, E, Palmroth, S, Palva, L, Pohja, T, Pumpanen, J, Rannik, U, Siivola, E, Ylitalo, H, Hari, P, Kulmala, M (1998) Long-term field measurements of atmosphere-surface interactions in boreal forest combining forest ecology, micrometeorology, aerosol physics and atmospheric chemistry. Tr Heat Mass Momen T 4: 17-35

Vickers, D, Mahrt, L (1997) Quality control and flux sampling problems for tower and aircraft data. J Atmos Ocean Technol 14: 512-526

Wilczak, JM, Oncley, SP, Stage, SA (2001) Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol 99: 127-150

Wilson, JD, Sawford, BL (1996) Review of Lagrangian stochastic models for trajectories in the turbulent atmosphere. Boundary-Layer Meteorol 78: 191-210

List of Appendices

Appendix A: Individual contributions to joint publications

The results presented in this cumulative thesis were obtained in the context of collaborative studies with other scientists. Thus, many authors have contributed to the publications listed in the appendices B to H. The following paragraphs specify my own contributions to these different manuscripts.

Appendix B

Göckede, M*, Rebmann, C, Foken, T (2004) A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. Agric For Meteorol 127: 175-188

I alone developed the evaluation approach for complex micrometeorological measurement sites presented in this manuscript, and implemented the algorithms in a software package. I also wrote the text of this manuscript.

C. Rebmann was responsible for the data processing of the sites involved in the appended CARBOEUROFLUX quality assessment study (see also appendix C). In this context, she helped to improve the applicability of the approach with several helpful suggestions, and also produced the figures to the examples of results included in this manuscript.

The work profited from frequent scientific discussions with my supervisor, Th. Foken.

Appendix C

Rebmann, C*, Göckede, M, Foken, T, Aubinet, M, Aurela, M, Berbigier, P, Bernhofer, C, Buchmann, N, Carrara, A, Cescatti, A, Ceulemans, R, Clement, R, Elbers, JA, Granier, A, Grünwald, T, Guyon, D, Havránková, K, Heinesch, B, Knohl, A, Laurila, T, Longdoz, B, Marcolla, B, Markkanen, T, Miglietta, F, Moncrieff, JB, Montagnani, L, Moors, E, Nardino, M, Ourcival, J-M, Rambal, S, Rannik, Ü, Rotenberg, E, Sedlak, P, Unterhuber, G, Vesala, T (2005) Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling. Theor Appl Climatol 80: 121-141.

My contribution to this manuscript consisted in providing the software package (see also appendix B) required to perform this comparative site evaluation study in the framework of the CarboEurope project. This task involved frequent adaptations of parts of the program, which improved the stability of the algorithms and the practicability of the overall site evaluation approach. I was also to a large extent involved in the interpretation and discussion of the results, and I wrote the text passages referring to the site evaluation approach.

C. Rebmann performed the extensive data processing necessary for this study, using the site evaluation approach described in appendix B. She was principally responsible for the evaluation of the results in a comparative survey, and also wrote the major part of the text of this manuscript.

Th. Foken was the principal investigator of this quality assessment programme in the framework of CarboEurope, supervising the ongoing studies in frequent discussions. The remaining authors contributed the data sets from the sites analysed in this study.

**corresponding author of the specific publication*

Appendix D

Foken, T*, Göckede, M, Mauder, M, Mahrt, L, Amiro, BD, Munger, JW (2004) Post-field data quality control. In: Lee, X, Massman, WJ, Law, BE (Eds), Handbook of Micrometeorology: A guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp 181-208

Although this book section is not a peer-reviewed text in the strict sense, the publication of the manuscript in the context of a textbook on micrometeorological measurements implied a thorough reviewing by the editors. My contribution to this manuscript concerned the parts treating the site dependent quality control. This section is a shorter version of the paper presented in appendix A.

Th. Foken was the principal author of this manuscript. Each of the other co-authors was responsible for a specific subject within this data quality control approach, the details of which I do not describe here.

Appendix E

Reithmaier, L, Göckede, M*, Markkanen, T, Knohl, A, Churkina, G, Rebmann, C, Buchmann, N, Foken, T (2005) Use of remotely sensed land use classification to improve an approach for the evaluation of complex micrometeorological flux measurement sites. Theor Appl Climatol, accepted

This paper presents the results of the diploma thesis of L. Reithmaier, which was principally supervised by Th. Foken and N. Buchmann. The parts of this study concerning the application of the site evaluation approach were performed by L. Reithmaier in close collaboration with me. L. Reithmaier was responsible for the processing of the remote sensing data sets, and she conducted the initial studies on matrix resolution and the influence of the roughness length averaging schemes. She also wrote the first version of the manuscript.

However, I had to re-work the paper substantially, as fundamental shortcomings emerged because the use of the analytic footprint model did not allow for a sound statistical evaluation. I replaced most of the initial results of the site evaluation approach by re-calculations obtained with a Lagrangian stochastic footprint model, and re-wrote related passages of the manuscript. In addition, I provided all of the software tools employed for the site evaluation process and area averaging procedures in the course of this study.

T. Markkanen provided the Lagrangian stochastic footprint model that is of principal importance for the site evaluation studies in the present version of the manuscript. A. Knohl, G. Churkina and C. Rebmann assisted in remote sensing issues and data provision for the study sites.

Appendix F

Göckede, M*, Markkanen, T, Hasager, CB, Foken, T (2005a) Use of footprint modelling for the characterisation of complex measurement sites. Boundary-Layer Meteorol: submitted

I developed all of the improved algorithms and approaches that were incorporated into this updated version of the evaluation approach for complex micrometeorological measurement sites. I also wrote the text of this manuscript.

**corresponding author of the specific publication*

T. Markkanen provided the Lagrangian stochastic footprint model that is used in this version of the site evaluation approach. The updated version of the flux aggregation procedure is based on a micro-scale flux aggregation model provided by C.B. Hasager.

The work profited from frequent scientific discussions with my supervisor, Th. Foken.

Appendix G

Göckede, M*, Mauder, M, Markkanen, T, Arnold, K, Leps, J-P, Foken, T (2005b) Approaches to validate footprint models using natural tracer measurements from a field experiment. Agric For Meteorol, submitted

I developed and tested all the footprint validation approaches presented in this manuscript, and I also derived all the results shown. I also wrote the complete text of this manuscript.

M. Mauder assisted me in the raw data processing of the eddy-covariance measurement complexes. T. Markkanen provided the Lagrangian stochastic footprint model that is used here. K. Arnold and J.-P. Leps were responsible for the scintillometer measurements by the University of Leipzig and the eddy covariance measurements by the German Meteorological Service, respectively, that were employed in the course of this study.

The work profited from frequent scientific discussions with my supervisor, Th. Foken.

Appendix H

Reth*, S, Göckede, M, Falge, E (2005) CO_2 efflux from agricultural soils in Eastern Germany - comparison of a closed chamber system with eddy covariance measurements. Theor Appl Climatol 80: 105-120

I was responsible for the eddy-covariance measurements and the subsequent processing of the high frequency raw data. I also conducted all footprint analyses performed in the course of this study. Concerning the comparison of soil chamber measurements and fluxes derived with the eddy-covariance technique, the analysis and interpretation of the results was conducted in close collaboration, with equal contributions from all three authors. I wrote the parts of the manuscript relating to eddy-covariance, footprint studies, and also the 'results and discussion' section referring to the comparison of the two measurement techniques.

S. Reth operated the soil chamber system during the field experiment, and was principally responsible for the writing of the manuscript. He performed the analysis and interpretation of the soil chamber derived fluxes in close collaboration with E. Falge, who supervised the PhD-thesis of S. Reth.

**corresponding author of the specific publication*

Appendix B:
A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites

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Abstract

The adoption of the eddy covariance technique to estimate surface exchange is based on the assumption that certain meteorological conditions are valid. The most important of these are horizontal homogeneity, steady-state, and non-advective conditions. Since such conditions 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 to permit a correct interpretation of the measurement results.

Quality assessment tools for eddy covariance measurements have been combined with footprint modelling. This makes it possible to define the spatial context of the fluxes, and to include land use features of the surrounding terrain in the analysis. The quality of the flux data for different wind sectors and varying meteorological conditions is also determined, so that the most suitable situations for the collection of high-quality data sets can be identified. Additionally, the flux contribution of the different land use types present in the footprint area is calculated. The results are presented as two-dimensional graphs, which show the spatial distribution of the quality of different fluxes. These graphs identify terrain influences affecting the flux data quality. The evaluation is especially useful for checking to what extent the measured fluxes at a site are representative of a specific type of land use.

Keywords: eddy covariance, quality assurance, quality control, footprint modelling, heterogeneity

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1 Introduction

Eddy covariance measurements are frequently used for the assessment of turbulent exchange processes between the atmosphere and the underlying surface (e.g. Aubinet et al., 2000; Baldocchi et al., 2000). In complex terrain such as heterogeneous forests, which are often found in monitoring networks like FLUXNET, operation of flux measurements using the eddy covariance technique poses special problems, which complicate the correct interpretation of the results. Neglecting these problems introduces uncertainties into the results, e.g. in the assessment of the net carbon balance (Foken et al., 2004).

One problematic aspect is that the reliability of the eddy covariance technique depends on certain theoretical assumptions (Kaimal and Finnigan, 1994). The most important of these are stationarity of the measured data, fully developed turbulent conditions, mean vertical wind speed equal to zero, and no horizontal advection during an averaging period. These requirements are often violated in complex terrain, and their non-fulfilment reduces the quality of the measurement results. Foken and Wichura (1996) address this problem by assigning quality flags to the fluxes in accordance with the deviations found between parameterisations under ideal conditions and those actually measured.

Secondly, in a heterogeneous environment the land use types contributing to the measurements change with the varying source area of the fluxes. This source area, which can be calculated by footprint models, defines the region upwind of the measurement point which influences the sensor's measurements and is dependant on measurement height, terrain roughness, and boundary layer characteristics, such as the atmospheric stability (e.g. Schmid, 1997; Rannik et al., 2000; Kljun et al., 2002; Schmid, 2002). As most sites in monitoring networks are set up to measure fluxes over a specific type of vegetation, the changing contribution of this type of land use under different meteorological conditions has to be considered in order to be able to assess how representative the measurements are.

The approach presented has been developed as a site evaluation concept, which addresses the problems mentioned above. It combines a modified version of the Foken and Wichura (1996) quality assessment scheme for eddy covariance measurements with the analytic flux source area model (FSAM) by Schmid (1994, 1997). For an observation period of several months, each 30 minute measurement is rated with an individual quality flag for four different measured fluxes, namely momentum flux, sensible heat flux, latent heat flux, and CO_2-flux. The FSAM model is used to identify the location of the source area for each measurement, and to analyse the contribution of each type of land use to the measured flux. The proportion of the flux from the land use type of interest is also rated with a quality flag. Combining the individual results for the whole period produces a spatial distribution of the flux contribution and mean data quality for different flagged features in a discrete horizontal grid. The results, which are presented as two-dimensional graphs, allow the identification of areas with unfavourable measurement conditions and help to reveal instrumental errors such as flow distortion or misalignment of the sensors. With this information, high-quality datasets can be distinguished from poorer quality measurements, allowing more accurate interpretation of the results. This paper presents the development of a combination of quality criteria and footprint approaches, with case studies for a single eddy covariance measurement site. Detailed examples of the application of the method, including case studies demonstrating detection of unfavourable measurement conditions, can be found in the study by Rebmann et al. (2005). It should also be noted that the method was not designed to be a stand-alone procedure for the determination of annual budgets of exchange fluxes.

Instead, it provides an additional tool for the testing of flux data quality under turbulent conditions, and is therefore a tool which cannot be applied in all cases of exchange conditions, especially as it is restricted to the footprint model and the eddy covariance method.

2 Input dataset and quality assessment of flux data

In the case study presented, the observation period chosen for analysis covered 4 months of measurements in order to have available a good sample of the local wind climatology and different atmospheric stability conditions. To produce a meaningful site evaluation, processing of at least two or three months of 30 minute means from a period of the year with high absolute values of the measured fluxes is required.

The meteorological input dataset necessary to run the flux footprint model FSAM by Schmid (1994, 1997) comprised friction velocity, wind direction, Obukhov-length, and the standard deviation of the crosswind component. For use in the site evaluation approach presented here, terrain information on roughness length and land use type had to be provided in the form of discrete matrices with regular grid spacing. This information was read out from topographical maps of the area.

The land use matrix employed simply distinguished between areas dominated by the land use type intended to be observed at the specific site and other forms of land use. Differentiation between various surface cover types can in principle be refined to an arbitrary degree, depending on the user-defined objectives of the specific study. The approach of deriving roughness information from topographical maps was taken from the European Wind Atlas (Troen and Petersen, 1989). Four general types of land use, each with a defined roughness length, are specified. These are water areas (z_0=0.0002 m), open areas with few windbreaks (z_0=0.03 m), farm land with windbreaks (z_0=0.1 m), and forests and urban districts (z_0=0.4 m). Each grid element of the matrix is subdivided into quarters, and one of the four possible land use types has to be assigned to each quarter. To obtain the final effective roughness length for a matrix cell, a weighted mean value derived from the four quarters can be read out from the provided table. This procedure of non-linear averaging is an attempt at a flux aggregation method.

The quality assessment of the flux measurements is based on the analysis of high-frequency raw data. The data used were vertical and longitudinal wind components *w* and *u*, air temperature *T*, and water- and CO_2-concentrations. If raw data is not available, the approach presented can be only partially performed with mean values and standard deviations of the parameters listed above, with the additional provision of the fluxes of momentum, sensible heat, latent heat, and CO_2.

The quality assessment of the measured fluxes of momentum, sensible and latent heat, and carbon dioxide was performed with a modified version of the method by Foken and Wichura (1996). Individual quality flags were used to rate the stationarity of the data and to test for development of the turbulent flow field with integral turbulence characteristics (normalised standard deviations). The combination of these two ratings yielded the overall quality of the measurement. The vertical wind component *w* was analysed in a separate procedure.

The stationarity of the flow has to be tested to exclude, for example, possible influences of the daily cycle or changing weather conditions on the measured fluxes. For the test, 30 minute covariances were compared with the mean covariance derived from six 5 minute covariances obtained for the same period (Foken and Wichura, 1996). According to the deviations found between the values, quality flags ranging from 1 (best) to 9 (worst) were assigned. For example, deviations lower than 15 percent were rated with flag 1 (Foken, 2003; Foken et al., 2004). Stationarity was computed for all

Table 1
Recommended parameterisations of the integral turbulence characteristics of the vertical and horizontal wind components and the temperature (Thomas and Foken, 2002).

Integral turbulence characteristic	Stability range			
	$-3 < \zeta < -0.2$		$-0.2 < \zeta < 0.4$	
σ_w/u_*	$1.3(1-2\zeta)^{1/3}$ by Panofsky et al. (1977)		$0.21\ln\left[\frac{z_+ f}{u_*}\right]+3.1$	
σ_u/u_*	$4.15(\lvert\zeta\rvert)^{1/8}$ by Foken et al. (1991, 1997)		$0.44\ln\left[\frac{z_+ f}{u_*}\right]+6.3$	
	Stability range			
	$\zeta < -1$	$-1 < \zeta < -0.0625$	$-0.0625 < \zeta < 0.02$	$0.02 < \zeta$
$\lvert\sigma_T/T_*\rvert$	$(\lvert\zeta\rvert)^{-1/3}$	$(\lvert\zeta\rvert)^{-1/4}$	$0.5(\lvert\zeta\rvert)^{-1/2}$	$1.4(\lvert\zeta\rvert)^{-1/4}$
	by Foken et al. (1991)			

σ_w: standard deviation of vertical wind component w, σ_u: standard deviation of horizontal wind component u, u_*: friction velocity, T_*: scaling factor for the temperature, ζ: stability parameter ($(z-d)/L$), z_+: normalising factor with a value of 1 m, f: Coriolis parameter.

four fluxes included in the site evaluation approach.

Integral turbulence characteristics are based on the flux-variance similarity (Obukhov, 1960; Wyngaard et al., 1971). In conditions of fully developed and unperturbed turbulence (Lumley and Panofsky, 1964; Stull, 1988; Kaimal and Finnigan, 1994; Arya, 2001) they are functions of the stability of stratification (Panofsky et al., 1977; Foken et al., 1991). To use them as a measure of flux data quality, values parameterised with standard functions were compared to the measurement results. Functions and coefficients employed using this approach have been proposed by Thomas and Foken (2002) and are listed in Table 1. Deviations found between measured and parameterised values indicate not fully developed turbulence, or disturbances in the turbulent flow field, e.g. obstacles in the fetch or flow distortion caused by the instrument setup (DeBruin et al., 1991; Foken and Leclerc, 2004). As the existing parameterisation for the integral turbulence characteristics were determined over flat terrain and low vegetation, they were tested intensively for the use with tall vegetation before using them in this approach (Foken et al., 1999, 2000; Foken and Leclerc, 2004), which showed that there was no significant difference in the case of no pronounced terrain effects.

As for stationarity, the deviations found between measured and modelled values of the integral turbulence characteristics were utilised to assign a quality flag ranging from 1 (best) to 9 (worst) to each 30 minute measurement (Foken and Wichura, 1996). This corresponded to a range of percentage deviations between lower than 15% (class 1) and to larger than 1000% (class 9), with a non-linear partition of the range in between. For purposes of the quality test, this range is large enough that statistical problems can be neglected for steady state conditions. In the approach presented, the integral turbulence characteristics of the wind components u and w and the temperature T were compared with parameterisations. No theoretical formulations exist for the integral turbulence characteristics of CO_2 and H_2O fluxes. As the parameterisation available for the temperature T is not valid for neutral conditions, investigations of the integral turbulence

Table 2
Combination of quality flags for stationarity and integral turbulence characteristics as used for the quality assessment.

Stationarity (deviation in %)	integral turbulence characteristic (deviation in %)	Final flag
0-30	0-30	1
0-30	31-75	2
31-75	31-75	3
31-75	76-250	4
>75	>250	5

characteristics were mainly restricted to the wind components *u* and *w*.

The final quality flag for the investigated fluxes was derived from the individual ratings of stationarity and integral turbulence characteristics. In addition to this first modification of the original approach by Foken and Wichura (1996), a second simplification reduced the range of the overall rating to an interval of 1 to 5 instead of 1 to 9. This reduction in resolution has been introduced for the sake of concise visualisation of the results. Table 2 presents the modified scheme for the computation of the final quality flag.

In a separate quality analysis, non-rotated data of the mean vertical wind component *w* were checked for mean values, which exceed the threshold value of $|\overline{w}| = 0.35$ m s^{-1}, as proposed by Foken and Wichura (1996). Measurements, which fall below this threshold, can be corrected with typical rotation procedures (Aubinet et al., 2000; Wilczak et al., 2001), while values exceeding this threshold indicated strong topographical effects, or an incorrect orientation of the sensor. In a separate analysis, this quality check was also performed after subtracting the mean value of the vertical wind speed for the respective period and site from the measured value.

Detailed results and examples for all methods described above are provided by Rebmann et al. (2005) for 18 European flux monitoring stations. All examples shown here-in were calculated for the Waldstein Weidenbrunnen site (Gerstberger et al., 2004), which is located in the western part of the Fichtelgebirge mountains in Germany. The flux measurement tower (50°08'31''N, 11°52'01''E, 775 m asl) 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. The most important surface heterogeneities affecting the measurements are a large clearing situated approximately 250 m west of the tower, and the summit of the 'Großer Waldstein' (877 m a.s.l.), which lies at a distance of about 1700 m in the south-westerly sector. For the footprint analysis of this area, 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 0.1 km. The meteorological dataset employed for this analysis covers the period 1st May to 31st August, 1998. The climatology as well as intensive studies on the fluxes at the Waldstein Weidenbrunnen site are presented by Rebmann et al. (2004).

3 Footprint analysis

The analysis of the spatial context of the measurements was performed with the Eulerian analytic flux source area model (FSAM) as presented by Schmid (1994, 1997). This algorithm is based on the analytic footprint model by Horst and Weil (1992), and employs an extended version of the surface-layer dispersion model by Gryning et al. (1987) for the determination of the crosswind and vertical concentration distribution functions. The Gryning model implies that footprint algorithms of FSAM can no longer be solved analytically, but it makes possible the inclusion of thermal stratifications and a realistic wind profile (Schmid, 1994). FSAM assumes a constant flux layer with sources located only at the ground. The model is restricted to surface layer scaling (Schmid, 2002), and flow conditions have to be horizontally homogeneous. The algorithms are based on the inverted plume assumption, where the mean wind is parallel but counter to the x-axis direction. Vertical flux divergences are not accounted for, while diffusion in the lateral direction is assumed to be Gaussian. FSAM neglects alongwind diffusion completely, and lateral crosswind diffusion and vertical diffusion can be treated independently.

Due to its mathematical simplicity, FSAM can be operated at reasonable computational expense. The model was chosen for the approach presented, because not only does it provide crosswind integrated footprints as usual for analytic approaches, but it also computes two-dimensional source weight functions. The calculated source weight function for each individual measurement can be stored and reproduced in the form of four characteristic dimensions, which define the area, and position of the 10 percent to 90 percent contributions to the total flux. The source weight function adopted for individual measurements accounts for 90 percent of the total flux. The output format allows for the assignment of weighting factors to distinct cells of the matrices surrounding the tower, while the ability to store and reproduce the source weight function enables the accumulation of several model runs.

The FSAM-model was integrated into a FORTRAN-routine (hereafter referred to as Model 1) to link the meteorological measurements with the terrain information as provided by the input matrices for roughness length and land use, a procedure comparable to the one proposed by Grimmond et al. (1998). In Model 1, for each 30 minute measurement the source weight function was calculated and projected onto the roughness length matrix according to the actual meteorological conditions. Weighting factors ranging from zero to one reproducing the source weight function were assigned to all matrix cells lying within the concentric 10 to 90% isopleths produced by the FSAM-model, while all matrix cells outside this area were labelled with a weighting factor of zero. Subsequently, for each matrix cell, the roughness length information read out from the matrix was multiplied by the assigned weighting factor, and the final roughness length for the specific measurement was determined as the linear average of these products. As the roughness length is also an input parameter for the footprint model, the whole process was repeated iteratively with the computed roughness lengths as the new input value, until the difference between input and output roughness length fell below a user defined threshold. The first model run for each 30 minute-measurement had to be performed with an approximate value for z_0. Usually not more than three iteration steps were necessary to reach the final roughness length. Because this roughness length was determined as a linear mean, the algorithms of Model 1 performed a parameter aggregation, while the roughness length values provided by the matrix had been prepared with a non-linear flux aggregation approach. Problems concerning the roughness length iteration process, as well as consequences affecting the site evaluation method presented, are discussed in more detail in Section 6.

After the roughness length had been determined, the final form of the discrete source weight function was applied to the land use matrix. The assigned weighting factors were summed up for each of the different land use classes, yielding their relative flux contribution to the total flux as a percentage after normalisation of the results. This simple aggregation process is based on the assumption of a uniform flux over all terrain parts that have been assigned to the same land use class. As turbulent exchange conditions change with horizontal position in a heterogeneous environment, e.g. for a flow across a roughness step, which implies an overshoot of turbulence and a subsequent adaptation to the modified local roughness conditions, this procedure oversimplifies the real conditions. However, as inhomogeneous turbulence cannot be resolved by analytic footprint models, this adaptation is necessary. In order to facilitate the visualisation of land use types to be observed, the percentage values are converted into quality flags as shown in Table 3. For each 30 minute measurement period, these results were stored in an output array, together with the final roughness length and the characteristic dimensions of the source weight function.

Both roughness length iteration and evaluation of the land use structure within the source area are also influenced by the topography of the surrounding terrain. The requirements of the analytic FSAM model for homogeneous flow conditions and sources located at only one level in relation to the measurement height cannot be fulfilled in complex topography. Under these conditions, the accuracy of the results obtained is clearly further compromised for the sake of mathematical simplicity. Also, advection effects related to non-flat terrain cannot be resolved by the approach presented. Such processes definitely have to be considered when evaluating data quality for complex measurement sites, but to account for such sites, additional measurements at several positions surrounding the main tower have to be available.

Table 3
Conversion of percentage values for the area intended to be observed into quality flags used for the accumulation and the visualisation of the results.

Percentage of the land use type intended to be observed	Assigned quality flag
99 - 100	1
95 - 99	2
90 - 95	3
80 - 90	4
70 - 80	5
50 - 70	6
< 50	7

The FSAM-model is only applicable to a certain range of conditions, as specified by the ratios of measurement height and roughness length, measurement height and Obukhov length, and standard deviation of the crosswind velocity and friction velocity. Measurements, when any of those ratios are outside the defined range, have to be discarded, so that not all 30 minute averages of the observation period can be included in the analysis. In addition, the performance of the FSAM-algorithms is very sensitive to the input of the roughness length, because the input parameters - roughness length, measurement height, and Obukhov length - are internally normalised by z_0. Breakdown of the program is frequent for aerodynamically rough surfaces, especially when the Obukhov length has low positive values during stable stratification. Due to these problems, a number of nighttime situations are also excluded from the analysis. The consequences of this characteristic of the algorithms on the interpretation of the results are discussed in more detail in Section 6.

4 Source weight synthesis

For the site evaluation concept presented, the quality assessment of the flux data as described in Section 2 and the footprint analyses had to be combined for the complete observation period. We termed this process 'source weight synthesis', because in principle all the individual source weight functions for the 30 minute measurements are accumulated to yield an overall picture of flux contributions and data quality. The software for this task is a FOR-

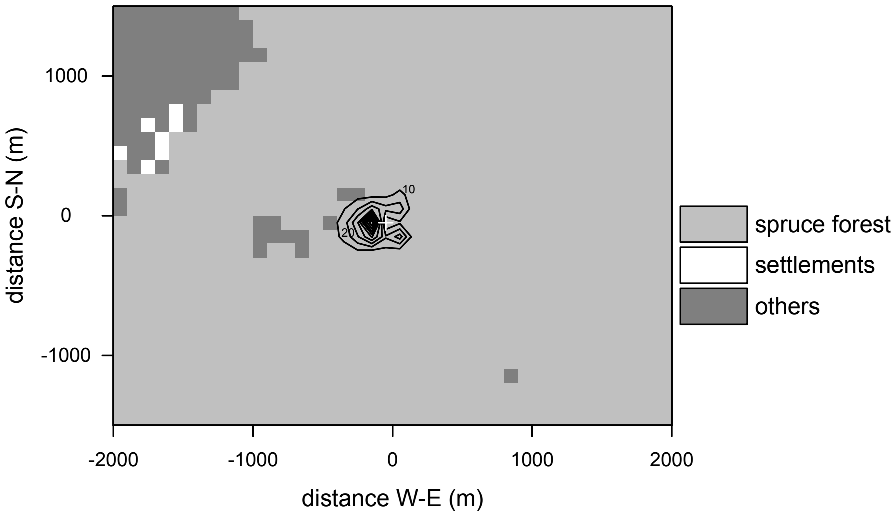

Fig. 1. Aerial view of the extent of the accumulated source weight function for the Waldstein Weidenbrunnen site for unstable atmospheric stratification for the period 1st May to 31st August 1998. The three-dimensional source weight function is indicated by the 9 black isopleths. The values represented by the isopleths are normalised with the highest value found within the entire matrix specified as percentages. The area within each isopleth represents the contribution to the total flux. The '10'-isopleth, for example, follows the ring of matrix cells with an accumulated flux contribution of 10 percent of the maximum flux contribution found within the entire matrix. The tower position is marked with the white cross. The greyscales show the land use distribution used as the input to the model.

TRAN routine termed Model 2 in the following text. A separation of the footprint analysis in Model 1 and the source weight synthesis in Model 2 was necessary because of the frequent breakdowns of the footprint routine due to input data restrictions, which require a manual post-processing of the results.

Model 2 operated a database, which collected, sorted, and analysed both flux data quality assessment and footprint results from the individual measurements of the observation period. By using the characteristic dimensions of the source weight function stored by Model 1, the assigned weighting factors were reproduced for each matrix cell. In the next step, the quality assessment results for the six different observed quantities were checked for the specific measurement. These were 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. For all cells with a non-zero weighting factor (all the cells which lie within the source area to be processed), entries specifying the individually assigned source weight and the quality flags were made in the database for each of the six different quantities observed.

After the complete observation period had been processed, the entries in the database were evaluated for each matrix cell in order to reveal the relative flux contribution to the total flux over the whole observation period, and the overall data quality for each of the six different quantities observed. To get the relative flux contribution, all entered weighting factors for each specific matrix cell were summed up, and the obtained values were normalised with the highest sum found in the entire matrix. To assess the overall data quality for each matrix cell, the weighting factors were sorted according to the quality flag for each observed quantity, and then summed up. The final quality flag was calculated as the median of the distribution of these sums. The derived results can be provided in a two-dimensional array, for presentation as two-dimensional graphs.

Model 2 offers further options to refine a site evaluation. Concerning the input data, a set of parameters can be set to a user defined

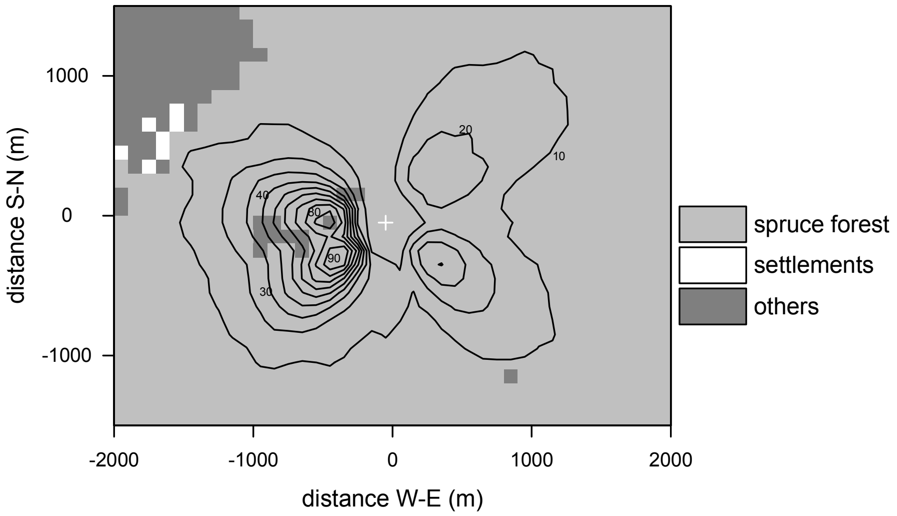

Fig. 2. Aerial view of the extent of the accumulated source weight function for the Waldstein Weidenbrunnen site for stable atmospheric stratification for the period 1st May to 31st August 1998. See Figure 1 for further details.

range, with all datasets not fulfilling these limits discarded from the analysis. Those parameters include, for example, time specifications, characteristics of the boundary layer such as friction velocity, atmospheric stability or sensible heat flux, or the quality flag ratings of the quantities to be investigated. The limit settings allow the user to restrict the analysis to well-defined situations, such as daytime measurements, high friction velocities with intense turbulence, or data sets with only the highest quality flag 1 for a specific flux. Combinations of limit restrictions for several parameters are possible. Parameter limits can also be altered automatically in a sequence.

5 Results

In Figures 1 and 2, the accumulation of the source weight functions for individual measurements taken over a four month period at the Waldstein Weidenbrunnen site is illustrated for unstable and stable stratification, respectively. In principle, this procedure resulted in a footprint climatology that indicates the relative influence of different parts of the surrounding terrain to a measurement. In both figures, the background shows the land use distribution which has been applied to determine the contributions of the different land use classes to the total measured flux. The black lines on both figures are isopleths, which reproduce the three-dimensional structure of the accumulated source weight function. The isopleths show the percentage contribution to the total flux, and should not be mixed up with the isopleths for fractional values provided by FSAM for individual measurements, as they are not encircling regions of integrated flux contributions. All matrix cells lying within the '90'-isopleths have accumulated flux contributions ranging between 90 and 100 percent of the maximum value within the entire matrix, while the integrated flux contribution within the ring may deviate from 10 percent of the total flux measured. Isopleths for cells with an accumulated flux contribution below the threshold of 10 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 this four month period the region close to and to the west of the mast was of principal importance for the measurement site, while the eastern sectors had only minor influence. For unstable stratification, the principal part of the fluxes measured was emitted within an area of about 600 m x 600 m (Fig. 1). In contrast to that, Figure 2 indicates a distinct gap of about 400 m between tower position and the peak of

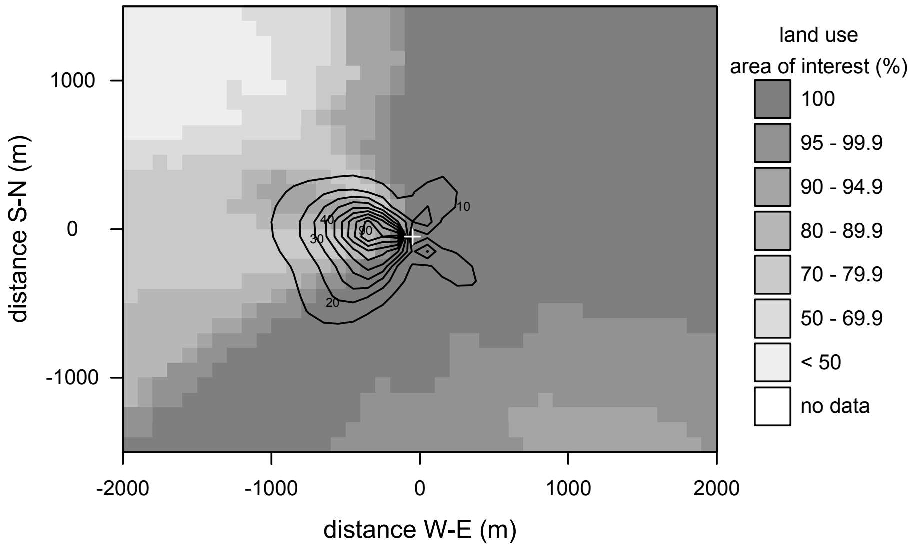

Fig. 3. Aerial view of the land use classification result in combination with the relative flux contribution (all stratification conditions) of each matrix cell for the Waldstein Weidenbrunnen site for the period 1st May to 31st August 1998. The normalised three-dimensional source weight function is indicated by the 9 black isopleths. The tower position is marked with the white cross. For each matrix cell, the greyscale indicates the percentage contribution of the land use type intended to be observed (spruce forest) to the total flux. See Figure 1 for further details.

the accumulated source weight functions for stable stratification. Under these conditions, the area with significant flux contributions extended to about 2500 m x 2500 m.

When comparing these figures it must be considered that the absolute values of the accumulated source weight functions are normalised by the highest values within the matrix, so that the maximum is equal to 100 percent. As the number of individual measurements accumulated for the stable case in Figure 2 is comparatively small in contrast to cases under unstable or neutral stratification, the peaks shown vanish almost completely when the results for all atmospheric conditions are displayed in the figures that follow.

In order to also include a visualisation of the overall quality of the results for the quantities observed, different greyscales can be used in the background of the figures to indicate the results of the data quality assessment. Figure 3 illustrates the classified contribution of the land use type to be observed, again for the Waldstein Weidenbrunnen site, in combination with the normalised relative flux contribution for all stratifications as indicated by the black isopleths. The pattern indicated by the shaded areas follows the distribution of the land use type intended to be observed, as provided by the land use matrix. However, the greyscales of each cell represent the integral flux contributions for its specific ‘footprint region’, thus all other cells that frequently form the source area of a flux also influence the result obtained. In this way, large scale transitions within the land use matrix used as input for the model are smeared, while small scale irregularities such as clearings in a forest might vanish if their overall influence on the footprint climatology is negligible. Dark shades show regions where source areas dominantly consisted of up to 100 percent of the land use type to be observed, in this case spruce forest, while lighter shades of grey indicate a growing influence of other land use classes, for example clearings or villages. In Figure 3, the light greyscales in the upper left corner indicate the declining influence of the spruce forest in the north western sector of the graph, indicating the proximity of the forest’s edge, which frequently influenced measurements within this sector under stable stratification.

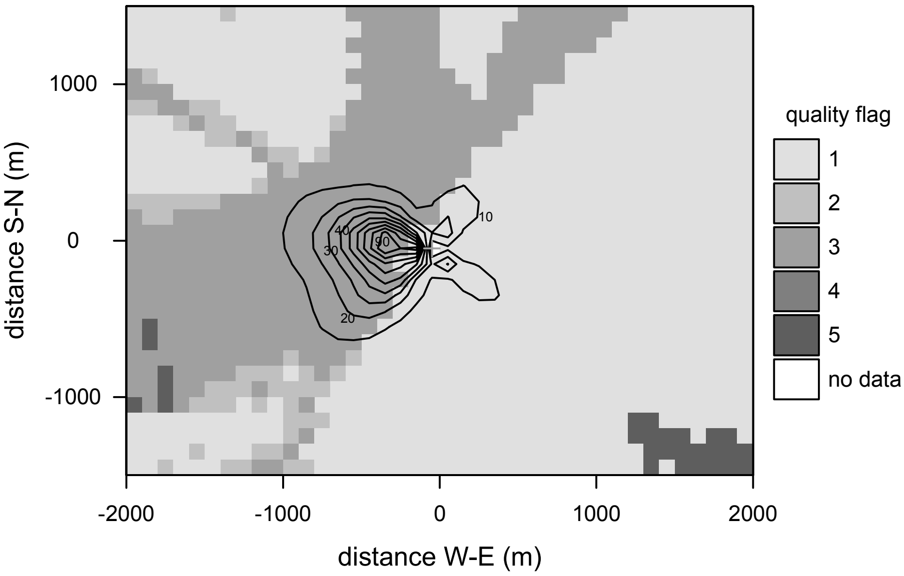

Fig. 4. Aerial view of the quality assessment result for the latent heat flux in combination with the relative flux contribution (all stratification conditions) of each matrix cell for the Waldstein Weidenbrunnen site for the period 1st May to 31st August 1998. The normalised three-dimensional source weight function is indicated by the 9 black isopleths. The tower position is marked with the grey cross. For each matrix cell, the greyscale indicates the dominant quality flag for the latent heat flux during the observed measurement period. See Figure 1 for further details.

In Figure 4, the greyscales show the dominant data quality flag for the latent heat flux, while the black isopleths again specify the relative flux contributions for the Waldstein Weidenbrunnen site. In this example, the light greyscales indicate the best flux data quality, while the flag rating is worse for the darker cells. For most parts of the measurement site, the overall quality of the latent heat flux was very high, but there were also regions to the west and to the north of the tower which were only of intermediate quality. The overall worse quality in these wind sectors can be attributed to fog events and air masses with high humidity or rain with winds blowing from these directions, which significantly influenced the analyser used for the measurement of the water concentrations necessary to determine the fluxes.

The concept of accumulating the results of a large number of footprint analyses, as shown in Figures 1 to 4, may be used as a tool to evaluate the performance of different footprint algorithms. Inhomogeneities in the land use or roughness structure of the terrain surrounding the tower, which affect both value and quality of the measurements, will also be visible when showing the data quality of a specific flux. Thus, the approach presented may be used as an alternative to the procedure of using a set of single footprint evaluations to show the influence of inhomogeneities, as presented by Foken and Leclerc (2004).

6 Limitations and outlook

While the approach presented has been designed to be practical and easy to use, in order to improve its results for research purposes, some of its features should still be refined. Modifications could be made concerning the footprint model adopted, the area averaging concept, and the preparation of terrain data.

The shortcomings of the FSAM model by Schmid (1994, 1997), which are listed in Section 3 of this paper, pose some problems that have to be considered when interpreting the results (see also Schmid, 2002). The restrictions concerning some of the input parameter ratios as well as the numerical instability of the algorithms, especially under stable stratification, lead to a discrimination against night time

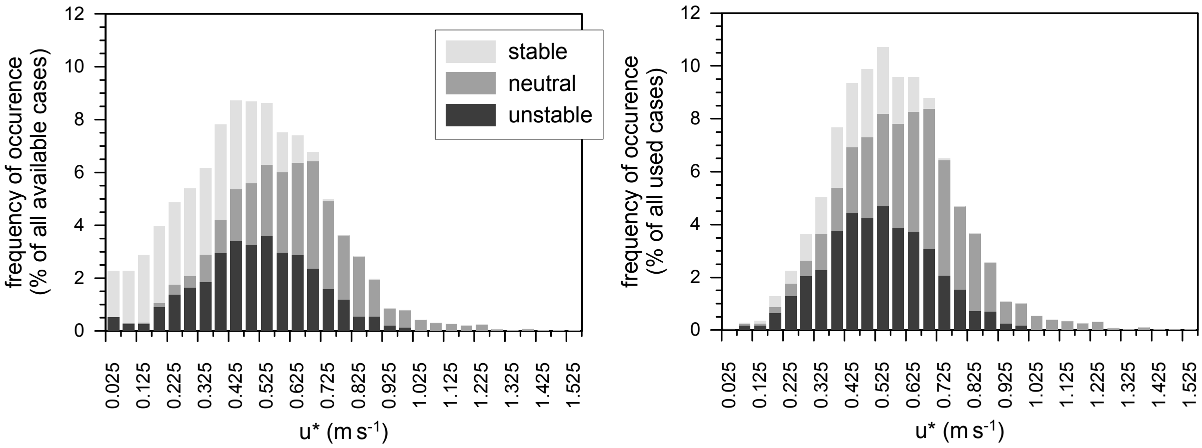

Fig. 5. Comparison of the frequency distributions of classified friction velocities for the complete dataset and the processed dataset for the measurement period 1st May to 31st August 1998.

situations, with a large percentage of the cases with low friction velocities being excluded from the analysis (Fig. 5). This reduces the relative flux contribution in the outer areas of the matrices, as many measurements made under stable conditions with source weight peaks kilometres away from the tower are discarded. On the other hand, the theoretical assumptions underlying the footprint calculations, such as the similarity theory, are not fulfilled under weak turbulence conditions, so that most of the discarded measurements would have had to be excluded from the site evaluation anyway. In the FLUXNET network, for example, through the use of the u_*-criteria (Goulden et al., 1996), all measurements with a friction velocity smaller than typically 0.3 m s^{-1} are excluded, and the data are replaced by values parameterised using plant ecological methods.

In principle, the assumptions for the use of FSAM were not fulfilled under the conditions presented. The analytic model requires horizontal homogeneity, while in this study it is adopted to assess the influence of terrain heterogeneity on the data quality of flux measurements. Therefore, it has to be considered that there is an increased level of uncertainty concerning the modelled source areas. In addition, due to the absence of alongwind diffusion in FSAM, additional errors are introduced during situations with strong turbulence intensities, with the effect that the matrix cell containing the tower should make a zero flux contribution. The peaks of the relative flux contributions are shifted away, and usually there are several peaks in different wind directions around the tower. However, a study by Soegaard et al. (2003) facing similar problems obtained results supporting the idea of also using analytic footprint models in heterogeneous terrain.

To account for the impact of some of these problems on the final quality assessment results, the same kind of analysis as described above was also carried out with a forward Lagrangian stochastic flux footprint model (Rannik et al., 2000; Markkanen et al., 2003). This approach considers transport processes within the canopy space as well as alongwind diffusion. The stochastic algorithm also relies on the inverted plume assumption, and thus only valid in horizontally homogeneous flow (Schmid, 2002). In addition, in the present context pre-calculated source weight functions for homogeneous conditions were used to replace the FSAM routine in Model 1. Primarily due to the consideration of alongwind diffusion, the source weight functions for individual measurements have peaks closer to the tower, and even stretch partly downwind of the tower. In comparison to the approach using the analytic FSAM model, when processing a large number of data sets, this method significantly enhances the accumulated flux contribution of the matrix cell containing the tower and the region nearby. As a consequence, especially sites with only short fetches over the land use to be observed received better quality ratings. This result suggests that the source areas as computed by the analytic FSAM model are too large, modifying significantly the evaluation of the flux contributions of the different land use types, particularly at heterogeneous sites. If these assumptions are confirmed by further studies, the site evaluation approach presented could be further improved by the integration of a Lagrangian stochastic footprint model. However, the intention of the approach presented here is to provide an easy-to-use site evaluation instrument. The stochastic models, which need several additional parameters to be fitted to specific site conditions, might be too complicated for practical purposes.

Regarding area averaging of the roughness length, the approach presented uses both non-linear flux aggregation for the preparation of the roughness length matrix (Troen and Petersen, 1989), and a subsequent linear parameter aggregation when computing a footprint dependent roughness length for individual measurements. To analyse the effect of this mixture on the final results, test runs have been performed for which parameter aggregation replaced the flux aggregation for the preparation of the roughness length matrices. Overall, this leads to larger roughness lengths in the individual matrix cells, and consequently slightly smaller source areas were computed by the FSAM-model. As the averaging scheme only affects matrix cells with mixed land use, tests carried out at a site with large uniform fetches revealed only a slight increase, of the order of a few millimetres, in the final roughness length for about 20 percent of the data sets from the complete observation period. For less than one percent of the cases, the location of the point of maximum influence of the source area was shifted more than 5 m. A modification of more than one percent of the flux contribution of the land use type intended to be observed occurred for only about 1.5 percent of the measurements. Thus, under homogeneous conditions, the choice of the averaging scheme has a negligible influence on the site evaluation. However, a significant effect might be found at sites with only small patches of uniform land use and a high variability of roughness lengths. A scheme to use only flux aggregation for the complete calculation of an individual roughness length for each measurement is under development. Also, simple logarithmic averaging of the roughness lengths (e.g. Mason, 1988; Claussen, 1990) could be applied, but according to Hasager and Jensen (1999), this technique yields effective roughness lengths that may be more than an order of magnitude too small.

Overall, it seems questionable whether a footprint based determination of the effective roughness length is capable of providing realistic results for all situations. In the first place, there are certain theoretical limitations that have to be noted. On the one hand, momentum is not a passive scalar independent of other sources as required for analytical and most forward Lagrangian stochastic footprint models, and on the other hand, the assumption of horizontal homogeneity of the flow is definitely not fulfilled in the context of the approach presented. While these restrictions should be of only minor importance for most cases, the problem of flow adjustment in inhomogeneous terrain may have significant consequences. Recent results obtained with the flow model proposed by Hasager and Jensen (1999) suggest that in heterogeneous terrain with large roughness length differences between the land use forms, the geometry of the roughness elements and the relative position of roughness length transitions to the sensor position is more important for the effective roughness length than the composition of roughness elements in the source area. As shown by Schmid and Bünzli (1995) and Klaassen et al. (2002), flow over a transition from a smooth to a rough surface, e.g. at a forest edge, leads to a significant flux enhancement over the rough part of the terrain. Simple footprint models cannot resolve this effect. Accordingly, the approach presented here delivers a high accuracy for the roughness length determination only in the absence of high turbulence overshoots or undershoots which might occur due to large roughness transitions.

The preparation of terrain data can also be performed using remote sensing methods. With satellite images such as those provided by Landsat ETM+ instead of topographical maps as the data source, land use matrices can in principle be produced in the same way as described in Section 2 of this paper. Tests revealed that this alternative does not reduce the accuracy of the results. The use of remote sensing methods facilitates an increased number of differentiated land use classes, and thus allows us to produce a more detailed analysis of the sources of the fluxes. In addition, both an enlargement of the sampled area and the preparation of maps with more detailed horizontal resolution are possible without a significant increase in effort. In general, the tests carried out with terrain information provided by remote sensing methods revealed that the more detailed information on roughness and land use characteristics did not significantly change the overall result of the currently presented site evaluation approach.

7 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 analytic flux source area model (FSAM) of Schmid (1994, 1997). Having specified for each cell surrounding the measurement tower the characteristics of the land surface, 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. Additionally, land use features of the surrounding area were included in the analysis, and the contribution of each land use type to the measured flux was calculated.

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 land use type intended to be observed 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. This holds true for both effects of surface heterogeneity and problems caused by the instrumentation itself, such as misalignment of the sensor or flow distortion by the tower. The method can also be used to test and evaluate different footprint algorithms.

The site evaluation approach presented has been developed as a robust tool for the characterisation of complex measurement sites using only basic input parameters. The requirements for processing time and data preparation should be kept low enough to allow the evaluation of several measurement sites in a comparative study, such as the one presented by Rebmann et al. (2005) for 18 European flux monitoring sites. Thus, the models and algorithms implemented in the approach constitute a compromise between the degree of detail analysed and the applicability of the algorithms chosen.

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References*

Arya, S.P., 2001. Introduction to Micrometeorology. Academic Press, San Diego, 415 pp.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. and Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Adv. Ecol. Res. 30, 113-175.

Baldocchi, D.D., Finnigan, J.J., Wilson, K., Paw U, K.T. and Falge, E., 2000. On measuring net ecosystem carbon exchange over tall vegetation on complex terrain. Boundary-Layer Meteorol. 96, 257-291.

Claussen, M., 1990. Area-averaging of surface fluxes in a neutrally stratified, horizontally inhomogeneous atmospheric boundary layer. Atmos. Environ. 24A, 1349-1360.

DeBruin, H.A.R., Bink, N.J. and Kroon, L.J., 1991. Fluxes in the surface layer under advective conditions. In: Schmugge, T.J. and André, J.C. (Eds.), Workshop on Land Surface Evaporation, Measurement and Parametrization. Springer, Berlin, Heidelberg, New York, pp. 157-169.

Foken, T., Skeib, G. and Richter, S.H., 1991. Dependence of the integral turbulence characteristics on the stability of stratification and their use for Doppler-Sodar measurements. Z. Meteorol. 41, 311-315.

Foken, T. and Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. Agric. For. Meteorol. 78, 83-105.

Foken, T., Jegede, O.O., Weisensee, U., Richter, S.H., Handorf, D., Görsdorf, U., Vogel, G., Schubert, U., Kirtzel, H.-J. and Thiermann, V., 1997. Results of the LINEX-96/2 Experiment, Deutscher Wetterdienst, Forschung und Entwicklung, Arbeitsergebnisse 48, pp. 75.

Foken, T., Mangold, A., Hierteis, M., Wichura, B. and Rebmann, C., 1999. Characterization of the heterogeneity of the terrain by normalized turbulence characteristics. In: Proceedings of the 13th Symposium on Boundary Layer and Turbulence, Dallas, TX, American Meteorological Society, pp. 26-27.

Foken, T., Mangold, A., Rebmann, C. and Wichura, B., 2000. Characterization of a complex measuring site for flux measurements. In: Proceedings of the 14th Symposium on Boundary Layer and Turbulence, Aspen, CO, American Meteorological Society, pp. 388-389.

Foken, T., 2003. Angewandte Meteorologie, Mikrometeorologische Methoden. Springer, Berlin, Heidelberg, New York, 289 pp.

Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B.D. and Munger, J.W., 2004.

* References ‚in print' were actualised in comparison to the original manuscript.

Post-field data quality control. In: Lee, X., Massman, W.J. and Law, B.E. (Eds.), Handbook of Micrometeorology: A guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp. 181-208.

Foken, T. and Leclerc, M.Y., 2004. Methods and limitations in validation of footprint models. Agric. For. Meteorol. 127, 223-234.

Gerstberger, P., Foken, T. and Kalbitz, K., 2004. The Lehstenbach and Steinkreuz catchments in NE Bavaria, Germany. In: Matzner, E. (Ed.), Biogeochemistry of Forested Catchments in a Changing Environment, Ecological Studies, Vol. 172. Springer, Berlin, Heidelberg, New York, pp. 15-44.

Goulden, M.L., Munger, J.W., Fan, F.-M., Daube, B.C. and Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: method and critical evaluation of accuracy. Global Change Biol. 2, 159-168.

Grimmond, C.S.B., King, T.S., Roth, M. and Oke, T.R., 1998. Aerodynamic roughness of urban areas derived from wind observations. Boundary-Layer Meteorol. 89, 1-24.

Gryning, S.-E., Holtslag, A.A.M., Irwin, J.S. and Sivertsen, B., 1987. Applied dispersion modelling based on meteorological scaling parameters. Atmos. Environ. 21, 79-89.

Hasager, C.B. and Jensen, N.O., 1999. Surface-flux aggregation in heterogeneous terrain. Quart. J. Roy. Meteorol. Soc. 125, 2075-2102.

Horst, T.W. and Weil, J.C., 1992. Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary-Layer Meteorol. 59, 279-296.

Kaimal, J.C. and Finnigan, J.J., 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, New York, 289 pp.

Klaassen, W., van Breugel, P.B., Moors, E.J. and Nieveen, J.P., 2002. Increased heat fluxes near a forest edge. Theor. Appl. Climatol. 72, 231-243.

Kljun, N., Rotach, M.W. and Schmid, H.P., 2002. A three-dimensional backward Lagrangian footprint model for a wide range of boundary-layer stratifications. Boundary-Layer Meteorol. 103, 205-226.

Lumley, J.L. and Panofsky, H.A., 1964. The structure of atmospheric turbulence. Interscience Publishers, New York, 239 pp.

Markkanen, T., Rannik, Ü., Marcolla, B., Cescatti, A. and Vesala, T., 2003. Footprints and fetches for fluxes over forest canopies with varying structure and density. Boundary-Layer Meteorol. 106, 437-459.

Mason, P.J., 1988. The formation of areally-averaged roughness lengths. Quart. J. Roy. Meteorol. Soc. 114, 399-420.

Obukhov, A.M., 1960. O strukture temperaturnogo polja i polja skorostej v uslovijach konvekcii. Izv. AN SSSR, ser. Geofiz., 1392-1396.

Panofsky, H.A., Tennekes, H., Lenschow, D.H. and Wyngaard, J.C., 1977. The characteristics of turbulent velocity components in the surface layer under convective conditions. Boundary-Layer Meteorol. 11, 355-361.

Rannik, Ü., Aubinet, M., Kurbanmuradov, O., Sabelfeld, K.K., Markkanen, T. and Vesala, T., 2000. Footprint analysis for measurements over a heterogeneous forest. Boundary-Layer Meteorol. 97, 137-166.

Rebmann, C., Anthoni, P., Falge, E., Göckede, M., Mangold, A., Subke, J.-A., Thomas, C., Wichura, B., Schulze, E.D., Tenhunen, J.D. and Foken, T., 2004. Carbon budget of a spruce forest ecosystem. In: Matzner, E. (Ed.), Biogeochemistry of forested catchments in a changing environment, Ecological Studies, Vol. 172. Springer, Berlin, Heidelberg, New York, pp. 143-160.

Rebmann, C., Göckede, M., Foken, T., Aubinet, M., Aurela, M., Berbigier, P., Bernhofer, C., Buchmann, N., Carrara, A., Cescatti, A., Ceulemans, R., Clement, R., Elbers, J.A., Granier, A., Grünwald, T., Guyon, D., Havránková, K., Heinesch, B., Knohl, A., Laurila, T., Longdoz, B., Marcolla, B., Markkanen, T., Miglietta, F., Moncrieff, J.B., Montagnani, L., Moors, E., Nardino, M., Ourcival, J.-M., Rambal, S., Rannik, Ü., Rotenberg, E., Sedlak, P., Unterhuber, G., Vesala, T. and Yakir, D., 2005. Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling. Theor. Appl. Climatol., doi: 10.1007/s00704-004-0095-y.

Schmid, H.P., 1994. Source areas for scalars and scalar fluxes. Boundary-Layer Meteorol. 67, 293-318.

Schmid, H.P. and Bünzli, D., 1995. The influence of surface texture on the effective roughness length. Quart. J. Roy. Meteorol. Soc. 121, 1-21.

Schmid, H.P., 1997. Experimental design for flux measurements: matching scales of observations and fluxes. Agric. For. Meteorol. 87, 179-200.

Schmid, H.P., 2002. Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. Agric. For. Meteorol. 113, 159-183.

Soegaard, H., Jensen, N.O., Boegh, E., Hasager, C.B., Schelde, K. and Thomsen, A., 2003. Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modelling. Agric. For. Meteorol. 114, 153-173.

Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dordrecht, Boston, London, 666 pp.

Thomas, C. and Foken, T., 2002. Re-evaluation of Integral Turbulence Characteristics and their Parameterisations. In: Proceedings of the 15th Symposium on Boundary Layers and Turbulence, Wageningen, The Netherlands, American Meteorological Society, pp. 129-132.

Troen, I. and Petersen, E.L., 1989. European Wind Atlas. Published for the Commission of the European Communities, Directorate General for Science, Research and Development (Brussels, Belgium), Risø National Laboratory, Roskilde, Denmark, 656 pp.

Wilczak, J.M., Oncley, S.P. and Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol. 99, 127-150.

Wyngaard, J.C., Coté, O.R. and Izumi, Y., 1971. Local free convection, similarity and the budgets of shear stress and heat flux. J. Atmos. Sci. 28, 1171-1182.

Appendix C:
Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling

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With 8 Figures

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Summary

Measuring turbulent fluxes with the eddy covariance method has become a widely accepted and powerful tool for the determination of long term data sets for the exchange of momentum, sensible and latent heat, and trace gases such as CO_2 between the atmosphere and the underlying surface. Several flux networks developed continuous measurements above complex terrain, e.g. AmeriFlux and EUROFLUX, with a strong focus on the net exchange of CO_2 between the atmosphere and the underlying surface. Under many conditions basic assumptions for the eddy covariance method in its simplified form, such as stationarity of the flow, homogeneity of the surface and fully developed turbulence of the flow field, are not fulfilled. To deal with non-ideal conditions which are common at many FLUXNET sites, quality tests have been developed to check if these basic theoretical assumptions are valid.

In the framework of the CARBOEUROFLUX project, we combined quality tests described by Foken and Wichura (1996) with the analytical footprint model of Schmid (1997). The aim was to identify suitable wind sectors and meteorological conditions for flux measurements. These tools were used on data of 18 participating sites. Quality tests were applied on the fluxes of momentum, sensible and latent heat, and on the CO_2-flux, respectively. The influence of the topography on the vertical wind component was also checked. At many sites the land use around the flux towers is not homogeneous or the fetch may not be large enough. So the relative contribution of the land use type intended to be measured was also investigated. Thus the developed tool allows comparative investigations of the measured turbulent fluxes at different sites if using the same technique and algorithms for the determination of the fluxes as well as analyses of potential problems caused by influences of the surrounding land use patterns.

1 Introduction

The EUROFLUX network (Valentini et al., 2000) was established in 1996 to improve knowledge about forest-atmosphere CO_2 exchange over the long term under various climatic and geographical conditions. The eddy covariance method was chosen for the flux measurements, as it is the most direct method to measure the net flux of carbon dioxide entering or leaving the ecosystem and has been proven to be efficient and reliable (Wofsy et al., 1993; Greco and Baldocchi, 1996; Valentini et al., 1996). The CARBOEUROFLUX programme continued the goal to improve our understanding on magnitude, location, temporal behaviour and causes of the carbon source/sink strengths of terrestrial ecosystems in the context of the Kyoto protocol. The project is based on 30 study sites where continuous long term carbon, energy and water exchanges are investigated together with ecological processes controlling the ecosystem biospheric exchanges. The study sites represent various forest ecosystems of the European continent, encompassing different species, community structures, management practices and distribution with respect to climatic change.

In order to reduce the uncertainty associated with site-to-site variation on flux measurement methods and calculations, the CARBO-EUROFLUX programme was designed with the same hardware and software specifications at all sites and with standard measurement protocols, data quality checks and storage systems (Aubinet et al., 2000, 2003). This part of the project aims to make the turbulent flux data which are determined according to standard measurement protocols comparable and wants to help in finding solutions if using the eddy covariance method in its simplified form at non-ideal sites.

The measurement accuracy of turbulent fluxes depends mainly on micrometeorological conditions. Required conditions for high-quality eddy covariance measurements are amongst others stationarity of the measured data, a fully developed turbulence, and no average vertical movement of the air. In this paper we focus on a few quality tests in combination with footprint modelling as a tool which can help to find sectors in the region surrounding the towers that have potential to violate basic assumptions made when using the eddy covariance method in its simplified form.

Non-stationarity of the measured components for example may be caused by the daily cycle and changing weather conditions. Obstacles such as trees, the supporting tower or the measuring devices themselves may disturb the turbulent wind field (Arya, 2001). The vertical wind component w was analysed for unrotated data by a simple procedure to identify strong influences of the topography, probably connected with advection, or missorientation of the sensor. All tests are applied on single 30-minute measurements, even if the averaging time may not be sufficient under some circumstances (Finnigan et al., 2003).

Any flux measurement performed at a single point is influenced by an effective upwind source area. The dimensions of this area depend on the observation height, the surface roughness, and the characteristics of the boundary layer as well as the atmospheric stability. Many efforts were made in the past to determine the source area or footprint for flux measurements (see Schmid, 2002). As many flux sites were established above heterogeneous or complex terrain, it is most important to know which part of the surrounding surface has the strongest contribution on the measurements. To analyse size and location of the source area, as well as the land use structure, a software package based on footprint modelling developed by Göckede et al. (2004) was adopted. The footprint routine used in the framework of the quality assessment software is the FSAM proposed by Schmid (1997).

The basic idea of the site characterisation concept is to combine existing quality assessment tools for flux measurements with footprint modelling. In this way it is possible to define the spatial context of the fluxes and to include topographical and land use features of the surrounding terrain in the analysis. The approach enables us to determine the flux data quality for different wind sectors and meteorological conditions and thus to identify the most suitable situations for the collection of high-quality data sets. Quality features also depend on the terrain structure of the surrounding landscape, such as the contribution of specific types of land use or the heterogeneity of roughness elements which can be incorporated into the site characterisation.

2 Methodology for site characterisation

For the site characterisation we used data-sets that covered at least two months and were chosen from those months of the year with the highest values of the fluxes. For the performance of the footprint operations, the minimum input data-set consisted of half-hourly means of friction velocity u_*, wind direction φ, Obukhov-length L, and the standard deviation of the cross wind component σ_v.

Two different matrices with regular grid spacing were needed to perform the calculations, with one single value representing information on land use type and roughness length z_0, respectively, for each quadratic grid element. The minimum requirement for the land use matrix was to distinguish between the land use type of interest and other areas. The land use type of interest is the vegetation type intended to be measured at the specific site, in this study mainly forest. Preparation of the roughness length matrix was partly derived from the land use information, assigning a fixed roughness length value to each of the land use classes. An alternative approach, proposed by Troen and Petersen (1989) in the European Wind Atlas, was to approximate the roughness length as a weighted mean from roughness elements taken from topographical maps. Details concerning the preparation of the matrices may be taken from Göckede et al. (2004).

2.1 Quality assessment

The quality assessment approach applied for the evaluation of the measured fluxes is a modified version of the method proposed by Foken and Wichura (1996). Here we concentrate on the two components stationarity and integral turbulence characteristics. Other possible sources of error in long-term flux measurements and their possibilities for corrections and solutions such as high pass filtering the covariance by coordinate rotation or the influence of the averaging length on the fluxes are discussed in detail by Finnigan et al. (2003) and others. Some groups operating flux sites are recently using the planar fit method (Paw U et al., 2000; Wilczak et al., 2001) by which one can avoid additional causes of errors. Additional mean flow contributions to the vertical transport have to be considered by measuring or modelling. For example, corrections which are necessary due to advection and density fluxes are described by Paw U et al. (2000) and Staebler and Fitzjarrald (2004).

The combination of the two features mentioned above yields the final quality flag for the specific measurement of our evaluations (Foken, 2003). The quality flag for the vertical wind component w is analysed in a separate appraisal.

The quality of flux data is based on the analysis of high-frequency raw data. Therefore the vertical (w) and longitudinal (u) wind components, sonic temperature (T), and H_2O- and CO_2-concentrations were used. In our study, mostly 20 Hz-data have been used to calculate stationarity and standard deviations for those variables.

For the stationarity tests, the 30-minute covariances of the measured signals i and j were compared with the mean covariance out of six 5-minute covariances from the same interval according to Foken and Wichura (1996). Under ideal conditions, the scalar concentrations and wind velocities in the atmosphere are steady with time $(\partial x/\partial t = 0)$. Turbulent fluxes are mainly determined as 30-minute means in the FLUXNET community. Thus we tested stationarity for these periods, even if longer time periods would be necessary as averaging time for the fluxes especially under stable atmospheric stratification (Oncley et al., 1990; Foken and Wichura, 1996; Finnigan et al., 2003). Quality flags for stationarity were then assigned to each half-hourly flux according to the deviations found between both values. These flags ranged from 1 (best) to 9 (worst). For example, a difference of less than 15 percent is rated with flag 1, flag 9 refers to a difference of more than 1000 percent (Foken, 2003; Foken et al., 2004).

Necessary input parameters for the tests of the integral turbulence characteristics are the standard deviations of the vertical and the longitudinal wind components w and u (σ_w and σ_u), as well as the standard deviation of the temperature T (σ_T). Integral turbulence characteristics are basic similarity characteristics of the atmospheric turbulence. They indicate whether or not the turbulent flow field is fully developed. These scaling factors of the normalised dispersions have been described by several authors (Panofsky et al., 1977; Foken et al., 1991; Arya, 2001). Even though the similarity characteristics for the turbulence relations were originally determined over flat terrain and short vegetation, it could be shown that there is no significant difference in the characteristics over tall vegetation (Foken et al., 1999, 2000; Villani et al., 2003; Foken and Leclerc, 2004). Therefore the development of the turbulence was investigated by comparing the integral turbulence characteristics (normalised standard deviations) of the wind components u and w and the temperature T with theoretical values according to the flux variance similarity (Obukhov, 1960; Wyngaard et al., 1971) by using the coefficients according to Thomas and Foken (2002). The recommended parameterisations by Thomas and Foken (2002) are listed in Table 1.

Table 1. Recommended parameterisations of the integral turbulence characteristics of the vertical and horizontal wind components and the temperature (Thomas and Foken, 2002). With: σ_w: standard deviation of vertical wind component w, σ_u: standard deviation of horizontal wind component u, u_*: friction velocity, T_*: scaling factor for the temperature, ζ: stability parameter $((z-d)/L)$, z_+: normalising factor with a value of 1 m, f: Coriolis parameter.

Integral turbulence characteristic	Stability range			
	$-3 < \zeta < -0.2$		$-0.2 < \zeta < 0.4$	
σ_w/u_*	$1.3(1-2\zeta)^{1/3}$ by Panofsky et al. (1977)		$0.21\ln\left[\frac{z_+ f}{u_*}\right]+3.1$	
σ_u/u_*	$4.15(\lvert\zeta\rvert)^{1/8}$ by Foken et al. (1991, 1997)		$0.44\ln\left[\frac{z_+ f}{u_*}\right]+6.3$	
	$\zeta < -1$	$-1 < \zeta < -0.0625$	$-0.0625 < \zeta < 0.02$	$0.02 < \zeta$
$\lvert\sigma_T/T_*\rvert$	$(\lvert\zeta\rvert)^{-1/3}$	$(\lvert\zeta\rvert)^{-1/4}$	$0.5(\lvert\zeta\rvert)^{-1/2}$	$1.4(\lvert\zeta\rvert)^{-1/4}$
	by Foken et al. (1991)			

Unfortunately, no formulations exist for the dispersions of CO_2 and H_2O. In addition, the parameterisations developed for the temperature T are not valid above forest for neutral conditions. Thus, investigations of integral turbulence characteristics are restricted to the wind components u and w. As with stationarity, flags were assigned according to the difference between measured and modelled values, ranging from 1 to 9. A difference of less than 15 percent was rated again with flag 1.

For the computation of the final quality flag for a specific flux, the following scheme has been used. Both, quality flags for stationarity and integral turbulence characteristics were taken into account, and their combination produces results in the range between 1 to 5 (Table 2).

Table 2. Combination of quality flags for stationarity and integral turbulence characteristics as used for the quality assessment.

Stationarity (deviation in %)	integral turbulence characteristic (deviation in %)	Final flag
0-30	0-30	1
0-30	31-75	2
31-75	31-75	3
31-75	76-250	4
>75	>250	5

For the following fluxes, the resulting quality flags are based on stationarity and the listed integral turbulence characteristics:

Momentum flux: stationarity tests for $\overline{w'u'}$ and comparison of σ_w/u_* and σ_u/u_* with modelled values.

Sensible heat flux: stationarity tests for $\overline{w'T'}$ and comparison of σ_w/u_* and σ_T/T_* with modelled values.

Latent heat flux: stationarity tests for $\overline{w'q'}$ and comparison of σ_w/u_* with modelled values.

CO_2-flux: stationarity tests for $\overline{w'CO_2'}$ and comparison of σ_w/u_* with modelled values.

Concerning the mean vertical wind component $\overline{w}$, flags were assigned according to the classification scheme in Foken and Wichura (1996). Values of $\left|\overline{w}\right|$ below a threshold of 0.35 m s^{-1} were assumed as acceptable, because these can be eliminated by typical rotation procedures (Aubinet et al., 2000, 2003; Wilczak et al., 2001). $\overline{w}$ was appraised before any coordinate rotation was applied on the wind components. The relatively large value as a threshold was chosen to differentiate between valid and rejected measurements, as cases above this value indicate severe problems. The procedure was also performed after subtracting the average $\overline{w}$ at each site for the periods investigated to account for slight missorientation of the anemometer. The percentage of rejected measurements is evaluated in a separate analysis, as described later.

2.2 Footprint modelling

The footprint routine used is the Eulerian analytic flux footprint model FSAM, as presented by Schmid (1997). This model is restricted to surface layer scaling and horizontally homogeneous flow conditions. It does not take into account turbulent diffusion along the mean wind and assumes Gaussian distribution in the crosswind direction. It allows the determination of the source area for a specific measurement with reasonable computational expense. Although the demand for horizontal homogeneity is often violated, the mathematical simplicity and the two-dimensional output of the footprint distribution makes FSAM a useful tool for the examination of complex measurement sites.

The footprint routine was integrated into a software tool which has been developed and upgraded within the course of the study presented. For each specific measurement, the calculated source weight function for a flux contribution of 90 % of the FSAM-algorithm is projected onto the matrices containing the terrain information, considering the actual wind direction. According to weighting factors assigned to the matrix cells, a weighted roughness length is computed and the land use matrix is analysed for the structure of the land use elements within the computed source area. As a main result, the contribution of the land use type of interest to the total flux is determined. Due to the necessary approximations implemented in all existing flux footprint models, also the results obtained by the procedure described using FSAM have to be regarded as an estimate of the real area of influence. The uncertainties induced are even enhanced by the operation of the model in inhomogeneous conditions. To discuss the consequences of these characteristics of the approach is beyond the scope of the paper presented. More details are given by Göckede et al. (2004).

Parameterisation and the storage of results as outlined above were performed for each 30-minute measurement of the data-sets provided. Due to some restrictions of the FSAM-model in respect of certain ratios of the input parameters, a portion of the input data set cannot be processed. The conditions of failure of the model are closely connected with the validity range of the Monin-Obukhov similarity theory, thus break-ups of FSAM usually indicate incorrect physics. Problems occur mostly during stable stratification, when the computed source area grows to an extent that destabilises the numerical algorithms. The effect leads to a certain bias in the input data set, because a considerable number of the night-time situations are excluded from the analysis. This poses some problems for the comparison of different measurement sites as performed in this study, because parameters of the general experimental set-up, such as measurement height or mean roughness length, also influence the numerical stability. However, most of the discarded measurements would have had to be excluded from the site evaluation anyway, because the theoretical assumptions (e.g. similarity theory) are not fulfilled.

2.3 Source weight synthesis

To produce the cumulative characterisation of the flux data quality for a specific site, the results of the footprint calculations were connected with the quality assessment of turbulent

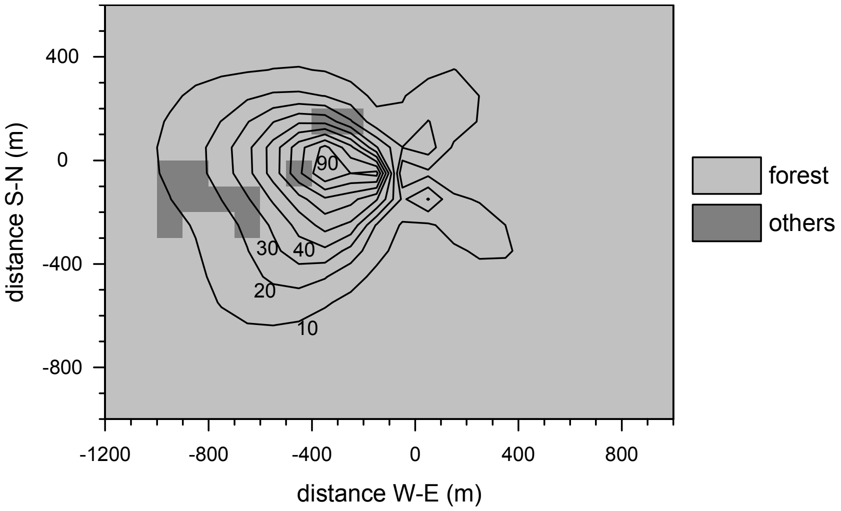

Fig. 1. The relative flux contribution determined with the analytic footprint model for DE-Wei (Waldstein Weidenbrunnen) for the period May 1st – Aug 31st, 1998, including all stratification regimes ($-2.0 \leq \zeta \leq 0.4$). Original size of grid cells for the calculations: 100 m. The grid cell with the highest flux contribution got the value 100 %, the flux contribution of the other grid cells is determined relative to the maximum. The tower is located at 0/0, north is on top. Different greyscales indicate different land use types as input for the model. Lines denote isopleths with the same flux contribution averaged over the investigated period (in %). The size of the area is zoomed, so that grid cells with a relative flux contribution of 5 % on average over all investigated cases are still within the area shown. Figs. 2 – 7 are scaled in a similar way if not mentioned otherwise.

flux data. The products of the procedure are two-dimensional matrices. These matrices show, for example, the dominating data quality class for each of the grid cells of the matrix surrounding the tower, and can be combined with its contribution to the total flux.

Fig. 1 shows an example of the cumulated flux contributions (isopleths) for the Waldstein Weidenbrunnen site in Germany (DE-Wei) over a 4-month period in summer 1998 (4155 half-hourly data-sets contributing to the graph) together with the different land use classes. Stable, neutral and unstable cases are taken into account, but only 17 % of the cases represent stable stratification ($\zeta > 0.0625$, $\zeta = (z_m - d)/L$, z_m: observation height, d: zero plane displacement). The peak (approximately in the centre of the isopleth marked with 90) about 350 m west of the tower represents the area with the highest flux contribution in the footprint. The area is zoomed so that grid elements with flux contributions of more than 5 % are still present on the graph although the calculations have been performed for an area of 5100 m x 7100 m. All other figures presented, constitute the flux contribution together with the investigated quality features and are reduced according to the same criteria.

The quality features investigated in combination with the source area synthesis are momentum flux, sensible heat flux, latent heat flux, CO_2-flux, vertical wind speed, and the contribution of the land use type of interest within the source area to the total flux measured. The results of the individual footprint analyses were collected for the complete input data set processed by the model, including the distributions of summed weighting factors for each matrix cell and the different quality features. The higher the sum of one specific quality class, the more often this cell was part of the source area for a measurement with the corresponding data quality flag. The final quality result for each cell and each quality feature is determined by the median of the distribution of summed weighting factors.

A more exact description of the concept of complex site evaluation, as well as detailed information on the programs used, are provided by Göckede et al. (2004).

3 Footprint modelling and quality checks applied on CARBOEUROFLUX data

18 groups from the CARBOEUROFLUX project contributed to the QA/QC program and provided the required data (half-hourly means as well as raw data) for the investigations. The standard deviation of the lateral wind component (σ_v), which is necessary as input for the footprint model, could not be provided by some groups, but could be calculated at least for the periods where high-frequency data were supplied, and was parameterised otherwise.

Most groups provided the land use maps according to the minimum requirements: roughness lengths and land use were determined for a grid size of 50 to 150 metres for an area with a size of about 4000 m x 4000 m. Some groups provided land use maps with a resolution of 25 m, and more detailed land use classifications derived from remote sensing data.

For 4 out of 18 investigated sites the footprint calculations were performed in two different ways: once with roughness length values (z_0) according to the wind atlas scheme (Troen and Petersen, 1989) as for all the other sites, and an additional model run with higher roughness length values according to the local vegetation characteristics. The latter was performed for the sites with land use data from remote sensing, and with z_0 values taken as 1/10 the canopy height h_c.

The equipment and software used in the CARBOEUROFLUX project is standardised according to Aubinet et al. (2000). For the investigations in the context of the quality analysis of flux data, the software used was developed during the EUROFLUX project according to the recommendations in the paper mentioned above. One main feature of importance affects the detrending of the raw data. Linear detrending was applied on each half-hour data series and also on the 5 minute segments. All sites but one were measuring H_2O- and CO_2-fluxes with closed path systems (LI6262, LI-COR Inc., Lincoln, NE, USA). For one site (IT-Ren, Renon) we had the chance to investigate H_2O- and CO_2-fluxes measured with both systems in parallel (closed path: LI7000, open path: LI7500, both LI-COR Inc., Lincoln, NE, USA).

For all sites but one the area intended to be measured is forest, varying from low to high density (200 – 8500 stems / ha), from very young to old forests and also covering different species (pine, spruce, beech, etc.). Canopy heights vary from 6.5 m (FR-Pue, Puechabon) to 33 m (DE-Hai, Hainich). Some of the sites have a completely flat topography; some have very steep slopes in the near surrounding (Table 3).

On average, the participating groups supplied half-hourly data for about 3 months and raw data for about 6 weeks. This is the reason why footprint calculations and land use classifications could be done for the complete period, whereas quality checks, especially the tests for stationarity, could only be performed for a part of the entire period (Table 3).

4 Results

On average, 4470 cases were available for the footprint modelling per site. For 63 % out of these, the footprint calculations could be performed. This percentage varied from 42 to 83 % between sites. In general, for all sites the highly convective and the very stable cases could not be calculated by the footprint model, mainly due to numerical instabilities. On average, 82 % of the unstable cases ($\zeta < -0.0625$), 99 % of the neutral cases, and only 24 % of the stable cases ($\zeta > 0.0625$) were calculated. Even though unstable and neutral cases are more prominent in the analysis, no weighting of the different stratification regimes was performed as very stable cases are rejected also if for example yearly sums of the net ecosystem ex-

Tab. 3. Characteristics of the participating flux measuring sites

Site code	Site name	Type of orography	elevation (m)	Measuring height (m)	Canopy height (m)	type ofland use intended to be observed (AOI)	period with data available for foot-print calculations	period for which quality tests were performed	Citation
BE-Vie	Vielsalm	gently sloping	450	40	27/35	Fagus sylvatica, Pseudotsuga menziesii	01.05.-31.08.2000	01.05.-31.08.2000	Aubinet et al. (2002)
BE-Bra	Brasschaat	flat	16	41	22	Pinus sylvestris, Quercus robur	31.05.-01.09.2000	31.05.-17.08., 23.08.-31.08.2000	Carrara et al. (2003)
CZ-BKr1	Bily Kriz	strong slope	900	12	8	Picea abies	01.07.-30.09.2000	01.07.-30.09.2000	Spunda et al. (1998)
FI-Hyy	Hyytiälä	gently sloping	181	23.3	14	Pinus sylvestris, Picea abies	01.05.-31.08.2001	07.05.-15.07.2001	Vesala et al. (1998)
FI-Sod	Sodankylä	flat	179	23.5	Okt 18	Pinus sylvestris	01.05.-30.09.2001	02.06.-18.07.2001	Laurila et al. (2003)
FI-Kaa	Kaamanen	flat	155	5	0.5	Wetland	01.05.-30.09.2000	07.06.-22.08.2000	Aurela et al. (2002)
FR-Hes	Hesse	flat/hilly	300	22	13	Fagus sylvatica	17.04.-31.12.2000	01.06.-28.08.2000	Granier et al. (2000)
FR-LBr	LeBray	flat	60	41.5	20	Pinus pinaster	07.05.-31.08.2000	01.07.-31.08.2000	Berbigier et al. (2001)
FR-Pue	Puechabon	flat	270	12.2	6.5	Quercus ilex	03.05.-31.07.2001	03.05.-03.06.2001	Joffre et al. (2003)
DE-Wei	Waldstein	hilly	780	32	19	Picea abies	01.05.-31.08.1998	01.05.-31.08.1998	Rebmann et al. (2004)
DE-Tha	Tharandt	flat/hilly	380	42	29	Picea abies	31.05.-30.08.2000	01.06.-30.06.2000	Bernhofer et al. (2003)
DE-Hai	Hainich	gently sloping	438	43.5	33	Fagus sylvatica	01.06.-31.08.2001	01.06.-31.08.2001	Knohl et al. (2003)
IL-Yat	Yatir	hilly	630	18.8	10	Pinus halepensis	01.01.-31.03.2001	01.01.-31.03.2001	Grünzweig et al. (2003)
IT-Ren	Renon	hilly, alpine	1730	40	28	Picea abies	05.10.-05.12.2001	04.10.-03.12.2001	Montagnani (1999)
IT-Non	Nonantola	flat	40	13	7	Quercus robur	01.04.-31.07.2001	01.06.-30.06.2001	Nardino et al. (2002)
IT-Lav	Lavarone	hilly, alpine	1370	33	28	Mixed: Abies alba, Picea abies, Fagus sylvatica	22.05.-30.09.2001	22.05.-30.09.2001	Marcolla et al. (2003)
NL-Loo	Loobos	flat	25	27	15.5	Pinus sylvestris	31.05.-30.08.2000	02.06.-14.07.2000	Dolman et al. (2002)
UK-Gri	Griffin	hilly	340	15.4	10	Picea sitchensis	09.01.-06.12.2000	18.06.-08.07.2000	

change of carbon dioxide (NEE) are determined from turbulent flux measurements (u_*-threshold).

For the sites for which we performed the additional model runs with z_0-values depending on canopy height, generally less stable and unstable cases could be calculated by the FSAM-routine. This resulted from restrictions of the model to certain intervals of the ratios of measurement height and roughness length, measurement height and Obukhov length, and standard deviation of the crosswind velocity and friction velocity, respectively (see Göckede et al., 2004). Consequences concerning the quality features are minor.

In the context of the synthesis we determined the contribution of the land use intended to be observed (Section 4.1), as well as the quality flags for each of the fluxes of momentum, sensible and latent heat, and for the carbon dioxide flux (Section 4.2).

The influence of topography was checked with the vertical wind component $\overline{w}$. A threshold of 0.35 m s^{-1} was taken for distinguishing acceptable and non-acceptable data after subtracting the respective mean value for each site (Section 4.3).

4.1 *Land use classification*

Only a few sites participating in the study are situated in homogeneous terrain and thus can be rated 'perfect' concerning the flux contribution of the land use type intended to be observed. On a half-hourly basis, the contribution of the land use intended to be observed (AOI) to the measured fluxes varied from 100 % to below 50 % over all investigated sites, depending on wind direction and stratification. This percentage contribution was separated into 7 classes for the final presentations: contribution from the land use intended to be observed: 100 %: class 1, 95 – 99.9 %: class 2, 90-94.9 %: class 3, 80-89.9 %: class 4, 70-79.9 %: class 5, 50-69.9 %: class 6, <50 %: class 7.

Four of the sites (CZ-BKr1, FR-Pue, IL-Yat, UK-Gri) are influenced in all investigated cases with more than 80 % from the land use intended to be observed (AOI classes 1 – 4). As an example of this category, the flux contribution together with the respective land use classification is shown for UK-Gri (Griffin) in Fig. 2a.

In the example shown in Fig. 2a, for the period from Jan 9th through Dec 6th, 2000, all investigated half-hourly fluxes (7062) origi-

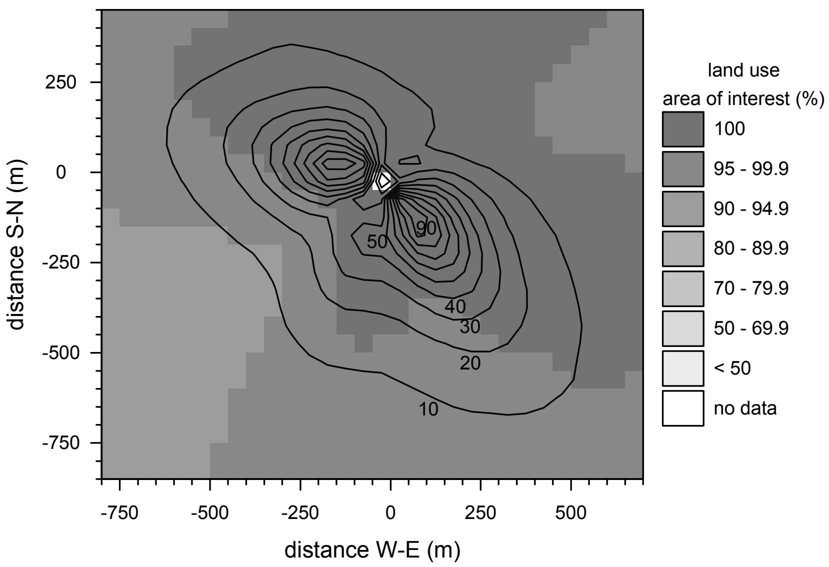

Fig. 2a. Representation of the land use classification with the relative flux contribution for UK-Gri (Griffin) for the period Jan 9th – Dec 6th, 2000, including all stratification regimes. Original size of grid cells for the calculations: 50 m. Dark greyscales indicate high contribution from the area of interest. Relative flux contribution, dimension of area and isopleths according to Fig. 1.

nated with more than 80 % from the land use intended to be observed. The two peaks with the highest flux contribution are almost totally influenced by the land use intended to be observed. Only small areas with flux contributions of less than 40 % are influenced by different land uses than forest.

For seven sites the land use intended to be observed contributes for more than 90 % of all cases with more than 80 % to the measured fluxes (FI-Kaa, FR-LBr, DE-Hai, IT-Ren, IT-Non, IT-Lav, NL-Loo, see Table 4). For the sites where the land use matrices were determined from remote sensing data (FI-Hyy, FI-Sod, FI-Kaa, FR-Hes and DE-Tha), the results generally look worse, because of the higher spatial resolution (20 – 25 m) and the enhanced differentiation of the land use classes compared to the sites where the matrices were determined from topographical maps. The exception is FI-Kaa, Kaamanen, where the land use intended to be observed is wetland and the measuring height is only 5 m. The low measuring height results in small footprints relatively close to the tower and hence, areas with different land use do not strongly influence the measurements. But also sites for which the land use matrices were provided with a resolution of 50, 100 or 150 m are partly strongly influenced by land use types different from the land use intended to be observed (BE-Vie, BE-Bra, DE-Wei). For BE-Vie, Vielsalm, two different forest types are intended to be observed: coniferous (Douglas fir, Silver fir, Norway spruce and Scots pine) and deciduous (beech) forest (Aubinet et al., 2002). If only the subplots conifers are taken as the species of interest, only 11 % of the measured fluxes originate with more than 80 % from the land use intended to be observed, and 20 % for the deciduous species, respectively. 'Mixed forest' (both forest types combined) as land use intended to be observed contributes in 79 % of all cases with more than 80 % to the measured fluxes. For the conifers (deciduous) 66 % (53 %) of all cases have flux contributions of less than 50 % from the area intended to be observed. These strong influences of land uses different from the forest type of interest is shown in Figs. 2b and 2c for the period May 1st until August 31st, 2000, with 2851 half-hourly values contributing to the graphs. The sector between 330 and 60° is favourable for the conifers, but has only small flux contribution. Westerly wind directions are more favourable for the deciduous forest, especially under unstable conditions.

4.2 Quality tests

Momentum flux τ: As explained earlier, the quality of the momentum flux is derived from a combination of stationarity of the covariance and the integral turbulence characteristics of the wind components *u* and *w*. Most sites (17 out of 18) show a high data quality in the momentum flux, with more than 72 % of all investigated cases flagged 1 and 2. Most of this classification is due to stationarity as the integral turbulence characteristics of the wind components agree mostly with the parameterisations. On average over all sites, 86 % of the data are of high quality concerning the momentum flux (86 % of the data are flagged 1 and 2 if integral turbulence characteristics are also taken into account, see Table 4). Cases with lower quality can mostly be attributed to distinct areas, often having a different land use than that intended to be measured, but also with lower flux contributions (BE-Bra, FR-Hes, FR-LBr, FR-Pue, DE-Tha, IT-Lav). Only one site has more cases with quality flags 3 to 5 (48 % of all data). But the supplied data for this site were from a period in autumn and winter with generally lower fluxes and more frequent stable conditions (IT-Ren). This results in more frequent cases with non-stationary conditions.

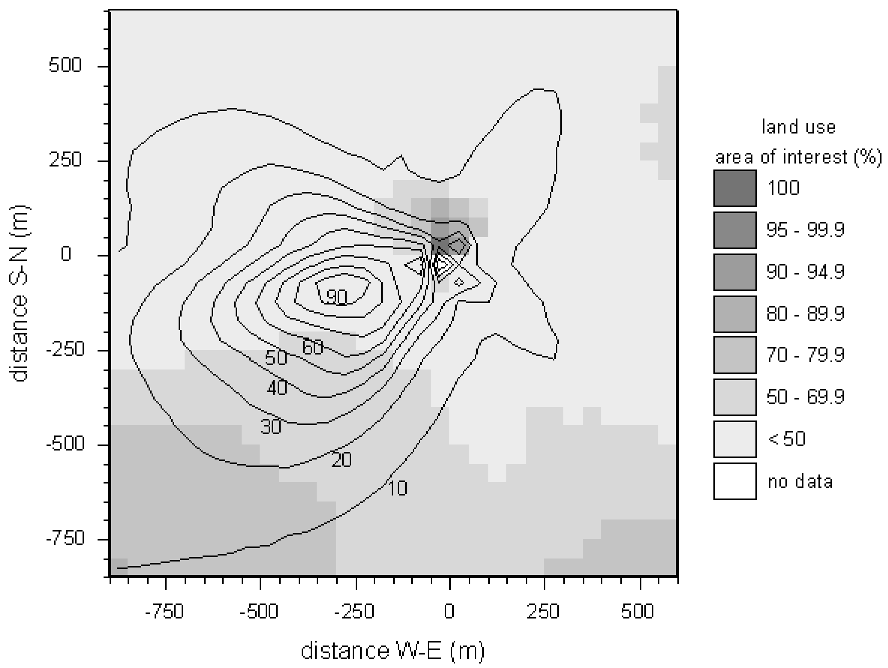

Fig. 2b. Representation of the land use classification with the relative flux contribution for BE-Vie (Vielsalm), with coniferous forest as area of interest for the period May 1st – Aug 31st, 2000, including all stratification regimes. Original size of grid cells for the calculations: 50 m. Dark greyscales indicate high contribution from the area of interest. Relative flux contribution and isopleths according to Fig. 1, dimension of area as provided and as used for calculations.

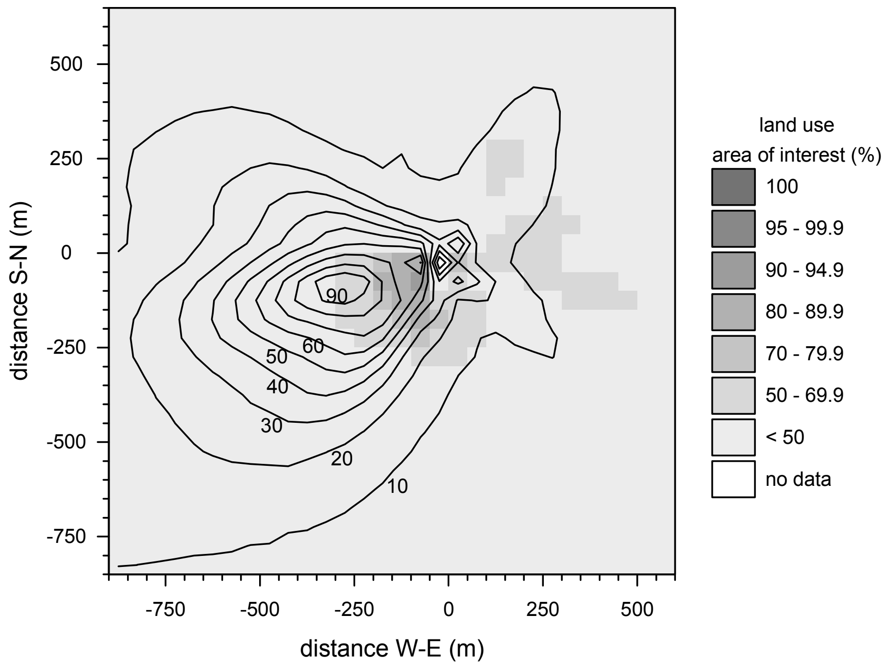

Fig. 2c. Representation of the land use classification with the relative flux contribution for BE-Vie (Vielsalm), with deciduous forest as area of interest for the period May 1st – Aug 31st, 2000, including all stratification regimes. Original size of grid cells for the calculations: 50 m. Dark greyscales indicate high contribution from the area of interest. Relative flux contribution and isopleths according to Fig. 1, dimension of area as provided and as used for calculations.

As an example, the aerial representation of quality flags for the momentum flux is shown for FR-Hes (Hesse) in Fig. 3 for the period June 1st – August 28th together with the relative flux contribution determined with the footprint model. 2032 half-hourly fluxes are contribut-

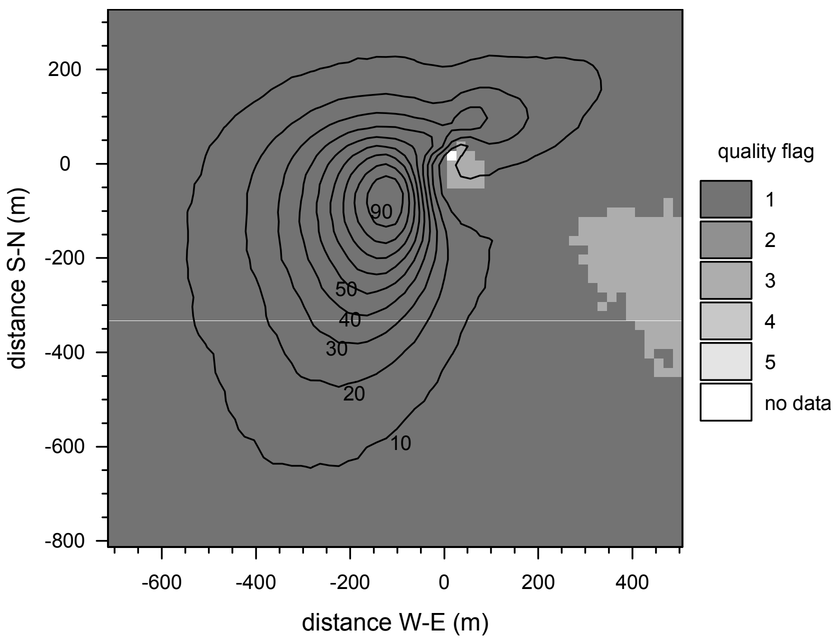

Fig. 3. Spatial distribution of stationarity flags for momentum fluxes τ with relative flux contribution for FR-Hes (Hesse) for the period Jun 1st – Aug 28th, 2000, including all stratification regimes. Original size of grid cells for the calculations: 20 m. The darkest grey indicates the highest quality class. Relative flux contribution, dimension of area and isopleths according to Fig. 1.

ing to this graph. Most of the grid cells are assigned to the highest quality class, except an area east of the tower of lower quality, which has only a small contribution to the fluxes (less than 10 %). Only a small area north-east of the tower shows some grid elements flagged more often 3 to 5, having slightly higher flux contribution.

Sensible heat flux H: The quality flags are derived from a combination of stationarity of the covariance and the integral turbulence characteristics of the wind component *w* and temperature *T*. As mentioned above, the integral turbulence characteristic of the temperature does not yet have a valid parameterisation for neutral and stable conditions. The investigations were performed anyhow, but they show almost the same characteristics for all sites: the measured values agree with the parameterisations only under unstable conditions. On an aerial basis this is reflected by grid cells flagged 1 closest to the tower (up to about 150 m) and all other areas flagged 2 to 5. Stationarity per se often shows a high data quality in all directions (CZ-BKr1, FI-Hyy, FI-Sod, FI-Kaa, DE-Wei, DE-Hai, NL-Loo), but instationarities generally occur more frequently with sensible heat than with momentum flux. For three sites, more than 90 % of the cases are flagged 1 (FI-Kaa, FR-Pue, DE-Hai, see Table 4). On average over all sites, 83 % of the data are of high quality concerning stationarity of the sensible heat flux, with only four sites having less than 80 % of the data in that quality class. Areas with lower quality than 1 are often very distinct and even congruent with those for the momentum fluxes (BE-Bra, FR-Hes, FR-LBr).

FR-Hes is shown as an example of the overlapping areas with frequently occurring instationarities for different fluxes in Fig. 4. Almost the same area as for the momentum flux is frequently influenced by instationarities of sensible heat fluxes (east of the tower), even though the area with lower measurement certainty is larger and more grid elements are flagged 3 to 5. This area is probably influenced by an area more far away, but with different land use than that intended to be observed, namely crops and grasslands. These latter areas have very different roughness lengths than forest and different properties concerning heat

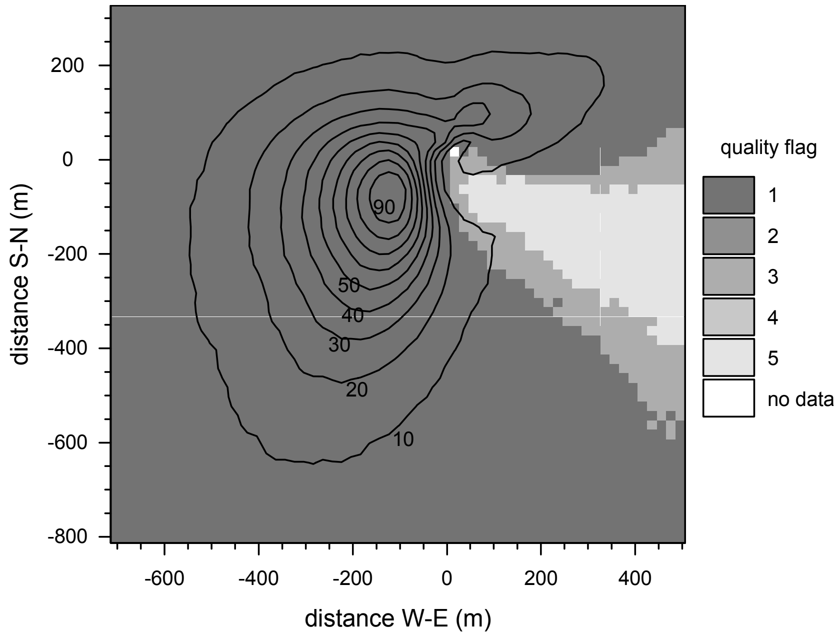

Fig. 4. Spatial distribution of stationarity flags for sensible heat fluxes *H* with relative flux contribution for FR-Hes (Hesse) for the period Jun 1st – Aug 28th, 2000, including all stratification regimes. Original size of grid cells for the calculations: 20 m. The darkest grey indicates the highest quality class. Relative flux contribution, dimension of area and isopleths according to Fig. 1.

exchange which are the reasons for instationarities of the covariances.

Latent heat flux λE: The quality flags are derived from a combination of stationarity of the covariance and the integral turbulence characteristic of the wind component *w*. We will focus here only on stationarity, as the integral turbulence characteristic of *w* is seldom negatively influenced and was already investigated with the momentum flux. On average over all sites, 68 % of all investigated cases are in the highest quality class. Only for two sites (NL-Loo, IT-Ren), less than 50 % of the measured H_2O-fluxes are flagged 1, and one site (FI-Kaa) has more than 95 % of the data in this quality class. Almost all grid cells are assigned to quality class 1 as well for FI-Sod, where 86 % of all measured latent heat fluxes got this quality flag. This means that at this site no wind direction or specific area causes instationarities per se. Lower quality in the latent heat flux may be attributed partly to the closed path system. Weather conditions with high air humidities or fog strongly influence the time lags between the vertical wind component and the water vapour concentration in the tubing (BE-Vie, CZ-BKr1, GE-Wei, IL-Yat). This also results in a more frequent occurrence of instationarities in the water vapour flux. This is demonstrated in Fig. 5 for CZ-BKr1, Bílý Kříž (1041 cases contributing to the graph). Higher uncertainty of the latent heat flux data is caused by the cases when the site is covered with clouds, sometimes accompanied by rain. Although southerly flow generally dominates at the site, more than 50 % of the cloud episodes are characterised by northerly wind directions. This explains why flags 3 and 5 in Fig. 5 are associated mostly with the northern sector.

Areas with lower quality assignment are generally often in western and southern directions from the towers, where low pressure events with moist conditions usually originate in Europe. Some sites also show distinct areas with higher frequencies of instationarities apart from the latter that may be attributed to the surrounding land use (BE-Bra, FI-Hyy, FR-Hes, FR-Pue, DE-Tha, DE-Hai, IT-Non, IT-Lav, NL-Loo). The results for the sites which have been measuring with open-path systems (IT-Ren, IT-Lav) show clearly that water va-

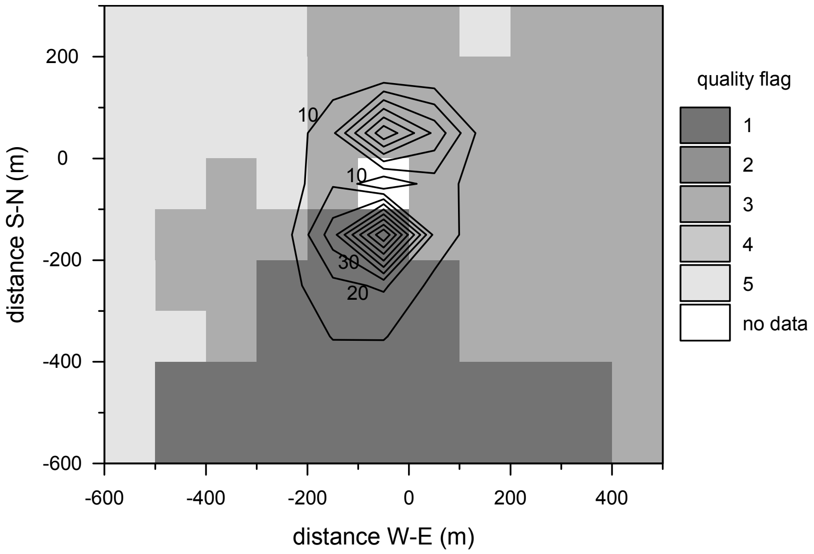

Fig. 5. Spatial distribution of stationarity flags for latent heat fluxes λE with relative flux contribution for CZ-BKr1 (Bílý Kříž) for the period Aug 17[th] – Sep 30[th], 2000, including all stratification regimes. Original size of grid cells for the calculations: 100 m. The darkest grey indicates the highest quality class. Relative flux contribution, dimension of area and isopleths according to Fig. 1.

pour fluxes are less often marked by instationarity if not influenced by the tubing. 6 % more data are assigned to the highest quality class for the open path-system compared to the closed-path system (IT-Ren).

Carbon dioxide flux F_{CO2}: The quality flags are derived from a combination of stationarity of the covariance and the integral turbulence characteristic of the wind component *w*. As for the latent heat flux, we will focus only on stationarity here. On average, 80 % of all data are flagged 1. CO_2-fluxes are less influenced by the closed-path system compared to the water vapour fluxes. Two flux sites (FI-Hyy, UK-Gri) had more than 90 % of the CO_2-fluxes assigned stationary (flag 1). For ten sites, more than 80 % of the fluxes were flagged 1 (BE-Vie, CZ-BKr1, DE-Wei, DE-Tha, DE-Hai, FI-Sod, FI-Kaa, FR-Pue, IL-Yat, NL-Loo), and only small areas, if any, generally having low flux contribution, show less measurement cer-

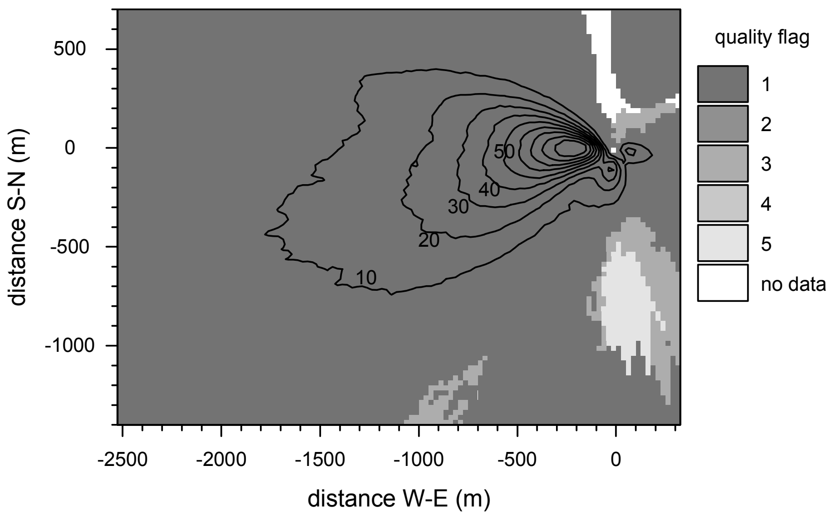

Fig. 6. Spatial distribution of stationarity flags for carbon dioxide fluxes F_{CO2} with relative flux contribution for DE-Tha (Tharandt) for the period Jun 1[st] – Jun 30[th], 2000, including all stratification regimes. Original size of grid cells for the calculations: 25 m. The darkest grey indicates the highest quality class. Relative flux contribution, dimension of area and isopleths according to Fig. 1.

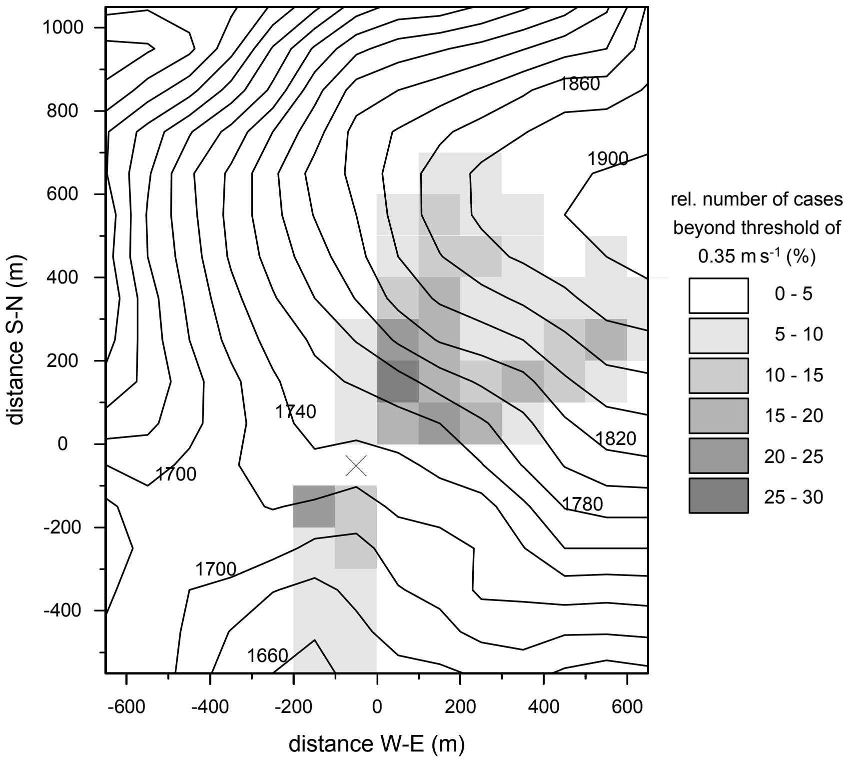

Fig. 7a. Spatial distribution of quality flags for the vertical wind component *w* with topography (isopleths: m asl) for IT-Ren (Renon) for the period Oct 4th – Dec 3rd, 2001, including all stratification regimes. Original size of grid cells for the calculations: 100 m. The tower grid is marked with a cross. Dark greyscales indicate a high relative number of cases exceeding the threshold of 0.35 m s^{-1}.

tainties. If not flagged 1, areas are usually flagged 3, which means the deviation is less than 50 % and, according to Foken and Wichura (1996), still acceptable for long-term measurements, which is the goal in the CARBOEUROFLUX project.

As an example, the aerial representation of the quality flags for the CO_2-fluxes is shown in Fig. 6 for DE-Tha, Tharandt (811 cases contributing to the graph). Distinct areas with lower measurement certainty, but also relative flux contributions of less than 10 %, can be seen south, south-west, and east of the tower. The easterly cases are restricted to a small sector close to the tower, the southerly cases are about 1 – 2 km upwind of the tower. The latter are associated with a very low flux contribution and few cases with lower quality result in a quality assignment like that presented in the graph. The vast majority of all cases (west and south-west of the tower) were flagged one. They form a very evenly footprint function with a peak about 200 m upwind of the tower.

The general high quality of carbon dioxide fluxes may also result from the fact that the turbulence structures are different for scalars compared to the wind components (Katul et al., 1996; Wichura et al., 2002). High frequency structures are not present and thus quality tests should be refined.

4.3 Vertical wind component w

The possible influence of advective processes was investigated with the help of the mean vertical wind component $\overline{w}$. A threshold of 0.35 m s^{-1} was chosen to differentiate between valid and rejected measurements. The investigations were performed for the $\overline{w}$ values after subtracting the mean value of $\overline{w}$ per site and respective period. This procedure has in most cases very little or no effect (< 0.5 %), but may

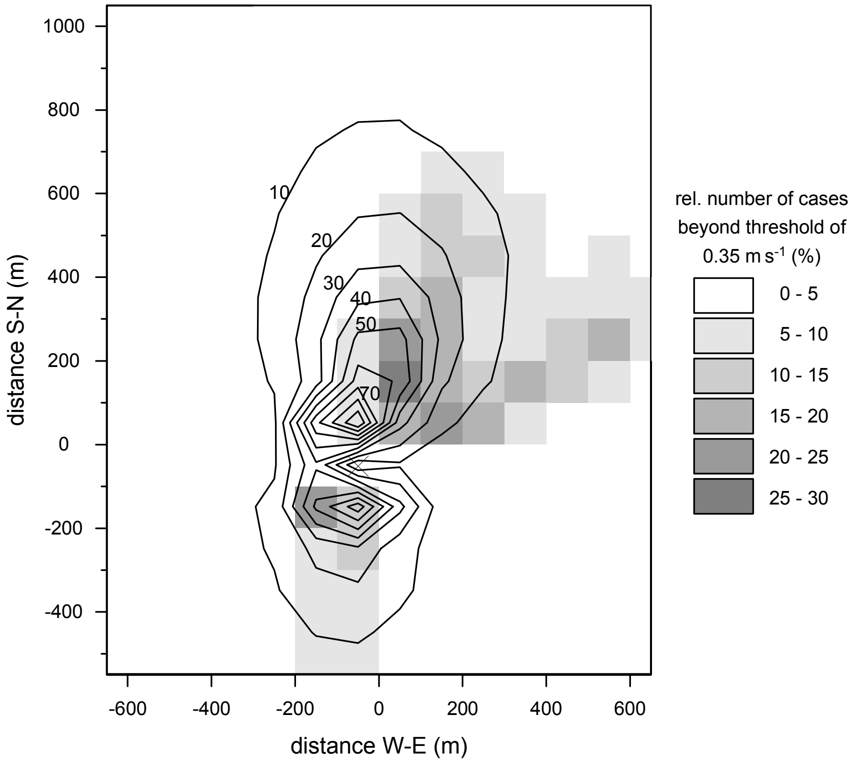

Fig. 7b. Spatial distribution of quality flags for the vertical wind component *w* with relative flux contribution (isopleths: flux contribution in %) for IT-Ren (Renon) for the period Oct 4th – Dec 3rd, 2001, including all stratification regimes. Size of the area and all other features as in Fig. 7a.

also change the results for some sites dramatically in both directions.

As some sites are completely flat or only slightly sloping, the threshold of 0.35 m s^{-1} was never (NL-Loo, BE-Bra, FR-Pue, IT-Non) or only occasionally exceeded (FI-Hyy, FI-Sod, FR-Hes, DE-Hai) and could then be attributed to the respective slopes. But at a few sites with flat terrain the threshold was exceeded for reasons that may be caused by a misalignment of the anemometer. For FR-LBr, another explanation could be possible: the storms of December 1999 ('Lothar') caused damaged areas south and west of the tower (50 % or more of the trees fell), the transition between damaged and (relatively) undamaged areas being precisely at tower level. So, for dominant (westerly) winds, the air was passing from a low density to a high density forest, this probably produced a positive vertical movement of the wind. At some sites with sloping terrain (BE-Vie, DE-Wei) the threshold was exceeded only in a few cases (less than 5 % of all data), which could then be attributed to higher horizontal wind speeds. The investigation is of course not independent of the mean horizontal wind speed. At three sites with steep slopes in the near surrounding, the limit of the vertical wind component was quite often exceeded (13 – 47 % of all cases, CZ-BKr1, IT-Ren, IT-Lav), but if the mean values of $\overline{w}$ are subtracted, the influence becomes less (2 % instead of 13 %) for IT-Lav, and is much more pronounced for CZ-BKr1 (60 % instead of 47 %). For CZ-BKr1, the effect can be explained by a pronounced dependence of $\overline{w}$ on the horizontal wind speed and direction at the site, which is situated on a steep but planar slope (inclined plane). Subtracting the mean $\overline{w}$ leads sometimes to lower but sometimes even to higher absolute values of the vertical velocity.

Figs. 7a and 7b demonstrate the aerial distribution of cases exceeding the threshold of 0.35 m s^{-1} for IT-Ren, Renon, which clearly depends on the topography (Fig. 7a). The threshold was exceeded mainly due to the steep slope to the north for 10 % of the investigated cases. Areas influenced by high vertical wind velocities also have high flux contributions as indicated by the peaks north and south from the tower in Fig. 7b.

4.4 Overall quality assessment

A general summary with numbers of cases in the highest quality classes for all investigated features relative to the total numbers of cases per site is listed in table 4.

Fig. 8 demonstrates the overall distribution of the relative numbers of quality flags for the fluxes of momentum τ, sensible and latent heat (H and λE), and the carbon dioxide flux F_{CO2}. Fig. 8a represents quality flags including integral turbulence characteristics and stationarity tests, whereas Fig. 8b shows only stationarity flags.

For the momentum flux, on average over all sites 70 % of the data are in the highest quality class. 27 % of the data are still flagged 2 and 3 and only 3 % of the data are flagged 4 and 5. Cases in classes 2 and 4 are attributed to the integral turbulence characteristics of w and u, whereas flags 1, 3 and 5 are due to stationarity, as can be seen by comparing the top left panels of Fig. 8a and 8b. The quality flags for the sensible heat flux are clearly influenced by the parameterisations of the integral turbulence characteristic of the temperature T, which are not valid for neutral and stable conditions and thus leading frequently to flag assignments of 2, 4 and 5. Stationarity per se shows most of the data flagged 1 (83 %). For the latent heat flux, 65 % of the fluxes are flagged 1 and only

Tab. 4. Land use classification (AOI is area of interest, meaning the land use type intended to be observed) and quality tests for the fluxes of momentum (including integral turbulence characteristics), sensible heat H, latent heat λE and carbon dioxide flux F_{CO2} (only stationarity) and vertical wind component $|\overline{w}|$. Numbers are relative to the total number of investigated cases for each site in %.

Site	AOI > 80%	τ flag 1-2	H stflag 1	λE stflag 1	F_{CO2} stflag 1	$\|\overline{w}\|$ < 0.35ms^{-1}
BE-Vie	79	90	84	54	83	100
BE-Bra	60	83	82	76	76	100
CZ-BKr1	100	84	82	53	85	53
FI-Hyy	70	92	86	73	93	100
FI-Sod	59	93	89	86	86	100
FI-Kaa	94	92	92	96	89	93
FR-Hes	32	86	80	64	72	99
FR-LBr	93	72	74	62	79	93
FR-Pue	100	87	91	82	84	10%
DE-Wei	86	91	87	51	80	98
DE-Tha	80	85	86	81	87	99
DE-Hai	97	93	90	71	87	100
IL-Yat	100	89	85	58	90	92
IT-Ren	98	51	60	40	52	90
IT-Non	90	81	74	85	78	100
IT-Lav	99	95	79	79	41	98
NL-Loo	96	94	87	49	87	100
UK-Gri	100	91	86	63	92	97
average	**85**	**86**	**83**	**68**	**80**	**95**

10 % are in classes 4 and 5. The average quality assessment for the carbon dioxide flux shows that 77 % of all data are flagged 1 and only 5 % of the data are assigned to stationarity class 5.

5 Discussion

Comparisons with Lagrangian footprint models have shown that results obtained with the analytical model of Schmid (1997) overestimate the longitudinal extension of the footprint areas, and thus provide a 'worst case' scenario concerning source area dimensions (Rannik et al., 2000; Kljun et al., 2002; Schmid, 2002).

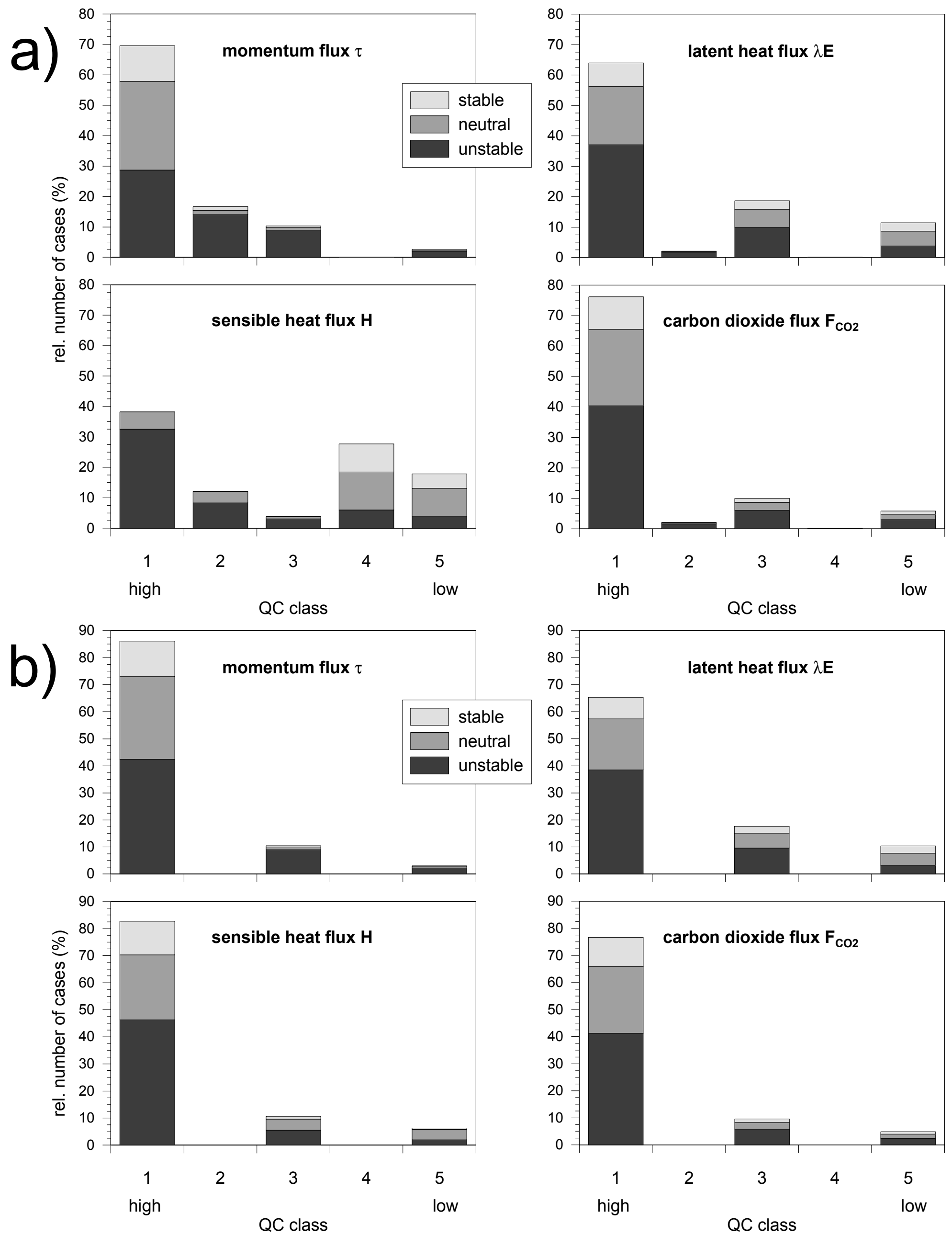

Fig. 8. Frequency distribution of quality flags relative to the number of cases per site for the fluxes of momentum τ, sensible heat H, latent heat λE and carbon dioxide F_{CO2} as averages over all sites. a) stationarity and integral turbulence characteristics, b) only stationarity.

Smaller footprints with peaks closer to the tower would result in fluxes more frequently originating from the area intended to be measured as was determined in this presentation.

One of the shortcomings of the analysis is that situations under strongly stable conditions ($\zeta > 0.4$) cannot by calculated by the footprint model, but these conditions are out of the range of the validity of the Monin-Obukhov similarity theory. Nevertheless, the results presented here include all meaningful stratification conditions, even though the picture is slightly biased concerning the frequency distribution of atmospheric stability. Both effects, the overestimation of the footprint dimensions and the relative low number of cases of stable conditions, probably cancel out each other if all stratification regimes are regarded together. Furthermore, the applied quality tests are not valid for very stable conditions anyhow, and fluxes occurring under low turbulence conditions are omitted when determining the net ecosystem exchange of carbon dioxide (NEE). Thus the bias in the analysis caused by less stable cases compared to neutral and unstable cases does not have a large influence on the results obtained with the footprint model. In general fluxes of low measurement certainty are more frequent under neutral and stable conditions, and if they originate from areas more far away from the tower. This is clear for example for the latent heat flux which is close to zero at night and the stationarity test is not reasonable under this condition.

The influence of roughness length values on the results of the footprint model was investigated by comparing the model output determined with z_0-values according to the wind atlas scheme (z_{0max} = 0.4 m, Troen and Petersen, 1989) and z_0-values relative to canopy height (z_0 = 1/10 h_c). Besides a smaller number of cases calculated by the footprint model for the runs with z_0 related to canopy height, the results do not differ significantly in this study.

The quality assessment revealed that on average over all sites, for the momentum flux 86 % of all half-hourly fluxes were assigned to the highest quality classes (1 and 2) concerning stationarity and integral turbulence characteristics. The parameterisations of the integral turbulence characteristics used for the sensible heat flux are not valid above forest under neutral and stable conditions and thus only stationarity was investigated in detail as quality feature. The development of parameterisations for the scalars is still an outstanding problem. On average 83 % of all cases were of highest quality for the sensible heat flux, whereas for the latent heat flux only 68 % could be assigned to the highest quality class. This generally lower measuring certainty can clearly be attributed to the type of measurements: at all sites besides two, closed path gas analysers have been used to measure the water vapour and carbon dioxide concentrations. Under weather conditions with high air humidity it becomes more and more difficult to determine the time lag between the vertical wind component and the water vapour signal probably due to adhesive effects in the sampling tube (Anthoni, personal commu-nication). This influences the stationarity test as can be seen by comparing the results for open- and closed path analysers for the site which was measuring with both systems in parallel. 45 % of the investigated half-hourly latent heat fluxes are assigned stationary for the open-path analyser compared to 39 % for the closed-path analyser. The latter numbers are relatively low compared to the average, as the data are from a period in autumn and winter with generally lower evaporative fluxes. Another reason for the lower quality observed for the H_2O-fluxes is due to the fact that these fluxes are generally close to zero under neutral and stable stratification conditions.

The investigations for the vertical wind component show that in some cases the anemometer was misaligned and has to be adjusted correctly. For topographically complex terrain it becomes obvious for which sectors drainage effects can be expected. Under those circumstances tilt correction procedures for eliminating systematically high values of the vertical wind component such as the planar fit method (Paw U et al., 2000; Wilczak et al., 2001) have to be applied.

6 Conclusions

The combination of the footprint model with quality assessment procedures provides a useful tool for the applicability on large data-sets as was done for 18 sites of the CARBOEUROFLUX project. The quality checks are valuable if the eddy covariance technique is used in its simplified form under non-ideal conditions and flux measurements become more comparable between sites. Despite the shortcomings of the footprint model, a comparison between 18 different sites distributed over Europe showed that this tool helps to find sectors in the footprint of a flux tower, which may be of lower measuring certainty under certain meteorological conditions. Flux measuring sites are often established in non-ideal terrain because of their ecological importance. If for example yearly sums of the carbon balance are to be determined, fluxes originating from sectors of minor quality should be rejected and be replaced by gap filling procedures, as is usually done for fluxes under low turbulence conditions. This may under some circumstances change yearly sums of the NEE.

Future investigations should take into account the limitations of the analytic footprint model employed here, as for example by using Lagrangian footprint models (Rannik et al., 2000; Kljun et al., 2002; Markkanen et al., 2003; Göckede et al., 2004). More realistic roughness length values compared to those recommended by the European Wind Atlas (Troen and Petersen, 1989) will also influence size and locations of the source areas and result in footprints closer to the tower. Thus, the analytical footprint model gives a conservative estimate especially for the land use classification. Higher resolution of the grid size for land use and roughness-length values could also enhance the accuracy of the results.

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References*

Arya SP (2001) Introduction to Micrometeorology. Academic Press, San Diego, 415 pp

Aubinet M, Grelle A, Ibrom A, Rannik Ü, Moncrieff J, Foken T, Kowalski AS, Martin PH, Berbigier P, Bernhofer C, Clement R, Elbers J, Granier A, Grünwald T, Morgenstern K, Pilegaard K, Rebmann C, Snijders W, Valentini R, Vesala T (2000) Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Adv Ecol Res 30: 113-175

Aubinet M, Heinesch B, Longdoz B (2002) Estimation of the carbon sequestration by a heterogeneous forest: night flux corrections, heterogeneity of the site and inter-annual variability. Global Change Biol 8: 1053-1071

Aubinet M, Clement R, Elbers J, Foken T, Grelle A, Ibrom A, Moncrieff H, Pilegaard K, Rannik U, Rebmann C (2003) Methodology for data acquisition, storage and

* References ‚in print' were actualised in comparison to the original manuscript.

treatment. In: Valentini, R (ed), Fluxes of carbon, water and energy of European forests. Ecological Studies, Vol. 163. Springer, Berlin, Heidelberg, New York, pp 9-35

Aurela M, Laurila T, Tuovinen JP (2002) Annual CO_2 balance of a subarctic fen in northern Europe: Importance of the wintertime efflux. J Geophys Res-Atmos 107: 4607

Berbigier P, Bonnefond JM, Mellmann P (2001) CO_2 and water vapour fluxes for 2 years above Euroflux forest site. Agric For Meteorol 108: 183-197

Bernhofer C, Aubinet M, Clement R, Grelle A, Grünwald T, Ibrom A, Jarvis P, Rebmann C, Schulze E-D, Tenhunen JD (2003) Spruce forests (Norway and Sitka spruce, including Douglas fir): Carbon and water fluxes and Balances, ecological and ecophysiological determinants. In: Valentini, R (ed), Fluxes of Carbon, Water and Energy of European Forests, Ecological Studies Series, Vol. 163. Springer, Berlin, Heidelberg, New York, pp 99-123

Carrara A, Kowalski AS, Neirynck J, Janssens IA, Yuste JC, Ceulemans R (2003) Net ecosystem CO_2 exchange of mixed forest in Belgium over 5 years. Agric For Meteorol 119: 209-227

Dolman AJ, Moors EJ, Elbers JA (2002) The carbon uptake of a mid latitude pine forest growing on sandy soil. Agric For Meteorol 111: 157-170

Finnigan JJ, Clement R, Malhi Y, Leuning R, Cleugh HA (2003) A re-evaluation of long-term flux measurement techniques - Part I: Averaging and coordinate rotation. Boundary-Layer Meteorol 107: 1-48

Foken T, Skeib G, Richter SH (1991) Dependence of the integral turbulence characteristics on the stability of stratification and their use for Doppler-Sodar measurements. Z Meteorol 41: 311-315

Foken T, Wichura B (1996) Tools for quality assessment of surface-based flux measurements. Agric For Meteorol 78: 83-105

Foken T, Jegede OO, Weisensee U, Richter SH, Handorf D, Görsdorf U, Vogel G, Schubert U, Kirtzel H-J, Thiermann V (1997) Results of the LINEX-96/2 Experiment. Deutscher Wetterdienst, Geschäftsbereich Forschung und Entwicklung, Arbeitsergebnisse 48, 75 pp

Foken T, Mangold A, Hierteis M, Wichura B, Rebmann C (1999) Characterization of the heterogeneity of the terrain by normalized turbulence characteristics. In: Proceedings of the 13th Symposium on Boundary Layer and Turbulence, Dallas, TX, American Meteorological Society, 26-27

Foken T, Mangold A, Rebmann C, Wichura B (2000) Characterization of a complex measuring site for flux measurements. In: Proceedings of the 14th Symposium on Boundary Layer and Turbulence, Aspen, CO, American Meteorological Society, 388-389

Foken T (2003) Angewandte Meteorologie, Mikrometeorologische Methoden. Springer, Berlin, Heidelberg, New York, 289 pp

Foken T, Göckede M, Mauder M, Mahrt L, Amiro BD, Munger JW (2004) Post-field data quality control. In: Lee, X, Massman, WJ, Law, BE (eds), Handbook of Micrometeorology: A guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp 181-208

Foken T, Leclerc MY (2004) Methods and limitations in validation of footprint models. Agric For Meteorol 127: 223-234

Göckede M, Rebmann C, Foken T (2004) A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. Agric For Meteorol 127: 175-188

Granier A, Ceschia E, Damesin C, Dufrene E, Epron D, Gross P, Lebaube S, Le Dantec V, Le Goff N, Lemoine D, Lucot E, Ottorini JM, Pontailler JY, Saugier B (2000) The carbon balance of a young Beech forest. Funct Ecol 14: 312-325

Greco S, Baldocchi DD (1996) Seasonal variations of CO_2 and water vapour exchange rates over a temperate deciduous forest. Global Change Biol 2: 183-197

Grünzweig JM, Lin T, Rotenberg E, Schwartz A, Yakir D (2003) Carbon sequestration in arid-land forest. Global Change Biol 9: 791-799

Joffre R, Ourcival JM, Rambal S, Rocheteau A (2003) The key-role of topsoil moisture on CO_2 efflux from a Mediterranean Quercus ilex forest. Ann For Sci 60: 519-526

Katul GG, Finkelstein PL, Clarke JF, Ellestad TG (1996) An investigation of the conditional sampling method used to estimate fluxes of active, reactive, and passive scalars. J Appl Meteorol 35: 1835-1845

Kljun N, Rotach MW, Schmid HP (2002) A three-dimensional backward Lagrangian footprint model for a wide range of boundary-layer stratifications. Boundary-Layer Meteorol 103: 205-226

Knohl A, Schulze ED, Kolle O, Buchmann N (2003) Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. Agric For Meteorol 118: 151-167

Laurila T, Thum T, Aurela M, Lohila A (2003) Carbon dioxide fluxes between the scots pine forest and the atmosphere, meteorology and biomass data during SIFLEX-2002, Final report of SIFLEX-2002 project. European Space Agency (in preparation)

Marcolla B, Pitacco A, Cescatti A (2003) Canopy architecture and turbulence structure in a coniferous forest. Boundary-Layer Meteorol 108: 39-59

Markkanen T, Rannik Ü, Marcolla B, Cescatti A, Vesala T (2003) Footprints and fetches for fluxes over forest canopies with varying structure and density. Boundary-Layer Meteorol 106: 437-459

Montagnani L (1999) Flussi di carbonio in un ecosistema alpina. PhD thesis. Italian, english summary. Italian National Library, Rome, Florence

Nardino M, Georgiadis T, Rossi F, Ponti F, Miglietta F, Magliulo V (2002) Primary productivity and evapotranspiration of a mixed forest. In: Congress CNR - I.S.A.Fo., Portici, 24.-25. September 2002, Istituto per i Sistemi Agricoli e Forestali del Mediterraneo

Obukhov AM (1960) O strukture temperaturnogo polja i polja skorostej v uslovijach konvekcii. Izv. AN SSSR, ser. Geofiz.: 1392-1396

Oncley SP, Businger JA, Itsweire EC, Friehe CA, LaRue JC, Chang SS (1990) Surface layer profiles and turbulence measurements over uniform land under near-neutral conditions. In: Proceedings of the 9th Symposium on Boundary Layer and Turbulence, Roskilde, Denmark, American Meteorological Society, 237-240

Panofsky HA, Tennekes H, Lenschow DH, Wyngaard JC (1977) The characteristics of turbulent velocity components in the surface layer under convective conditions. Boundary-Layer Meteorol 11: 355-361

Paw U KT, Baldocchi DD, Meyers TP, Wilson KB (2000) Correction of eddy-covariance measurements incorporating both advective effects and density fluxes. Boundary-Layer Meteorol 97: 487-511

Rannik Ü, Aubinet M, Kurbanmuradov O, Sabelfeld KK, Markkanen T, Vesala T (2000) Footprint analysis for measurements over a heterogeneous forest. Boundary-Layer Meteorol 97: 137-166

Rebmann C, Anthoni P, Falge E, Göckede M, Mangold A, Subke J-A, Thomas C, Wichura B, Schulze ED, Tenhunen JD, Foken T (2004) Carbon budget of a spruce forest ecosystem. In: Matzner, E (ed), Biogeochemistry of forested catchments in a changing environment, Ecological Studies, Vol. 172. Springer, Berlin, Heidelberg, New York, pp 143-160

Schmid HP (1997) Experimental design for flux measurements: matching scales of observations and fluxes. Agric For Meteorol 87: 179-200

Schmid HP (2002) Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. Agric For Meteorol 113: 159-183

Spunda V, Cajanek M, Kalina J, Lachetova I, Sprtova M, Marek MV (1998) Mechanistic differences in utilization of absorbed excitation energy within photosynthetic apparatus of Norway spruce induced by the vertical distribution of photosynthetically active radiation through the tree crown. Plant Sci 133: 155-165

Staebler RM, Fitzjarrald DR (2004) Observing subcanopy CO_2 advection. Agric For Meteorol 122: 139-156

Thomas C, Foken T (2002) Re-evaluation of Integral Turbulence Characteristics and their Parameterisations. In: Proceedings of the 15th Symposium on Boundary Layers and Turbulence, Wageningen, The Netherlands, American Meteorological Society, 129-132

Troen I, Petersen EL (1989) European Wind Atlas. Published for the Commission of the European Communities, Directorate General for Science, Research and Development (Brussels, Belgium). Risø National Laboratory, Roskilde, Denmark, 656 pp

Valentini R, De Angelis P, Matteucci G, Monaco R, Dore S, Scarascia-Mugnozza GE (1996) Seasonal net carbon dioxide exchange of a beech forest with the atmosphere. Global Change Biol 2: 199-207

Valentini R, Matteucci G, Dolman AJ, Schulze E-D, Rebmann C, Moors EJ, Granier A, Gross P, Jensen NO, Pilegaard K, Lindroth A, Grelle A, Bernhofer C, Grünwald T, Aubinet M, Ceulemans R, Kowalski AS, Vesala T, Rannik Ü, Berbigier P, Loustau D, Guomundsson J, Thorgeirsson H, Ibrom A, Morgenstern K, Clement R, Moncrieff J, Montagnani L, Minerbi S, Jarvis PG (2000) Respiration as the main determinant of carbon balance in European forests. Nature 404: 861-865

Vesala T, Haataja J, Aalto P, Altimir N, Buzorius G, Garam E, Hameri K, Ilvesniemi H, Jokinen V, Keronen P, Lahti T, Markkanen T, Makela JM, Nikinmaa E, Palmroth S, Palva L, Pohja T, Pumpanen J, Rannik U, Siivola E, Ylitalo H, Hari P, Kulmala M (1998) Long-term field measurements of atmosphere-surface interactions in boreal forest combining forest ecology, micrometeorology, aerosol physics and atmospheric chemistry. Tr Heat Mass Momen T 4, 17-35

Villani MG, Schmid HP, Su HB, Hutton JL, Vogel CS (2003) Turbulence statistics measurements in a northern hardwood forest. Boundary-Layer Meteorol 108: 343-364

Wichura B, Buchmann N, Foken T (2002) Carbon dioxide exchange characteristics above a spruce forest. In: Proceedings of the 25th Symposium on Agricultural and Forest Meteorology, Norfolk, VA, American Meteorological Society, 63-64

Wilczak JM, Oncley SP, Stage SA (2001) Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol 99: 127-150

Wofsy S, Goulden ML, Munger JW, Fan F-M, Bakwin PS, Daube BC, Bassow SL, Bazzaz FA (1993) Net exchange of CO_2 in a midlatitude forest. Science 260: 1314-1317

Wyngaard JC, Coté OR, Izumi Y (1971) Local free convection, similarity and the budgets of shear stress and heat flux. J Atmos Sci 28: 1171-1182

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Appendix D: Post-field data quality control

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Abstract This Chapter summarizes the steps of quality assurance and quality control of flux measurements with the eddy covariance method. An important part is the different steps of the control for electronic, meteorological and statistical problems. The fulfillment of the theoretical assumptions of the measuring method and the non-steady-state test and the integral turbulence test are extensively discussed as well as an overall flagging for data quality and a site specific quality analysis using footprint models. Finally, problems are discussed which are not included yet in the control program, mainly connected with the complicated turbulence structure at a forest site.

1 Introduction

A consistent procedure for quality control of meteorological data is essential for measurement networks and long-term measurement sites. This issue has been extensively addressed for standard meteorological networks. Reliable, automated procedures based on inspection of time series which can reduce quality control efforts and provide a consistent product across measurement networks, have been the focus of several studies. Smith et al. (1996) have constructed automated quality control procedures for slow response surface data that flag questionable data points for visual inspection. Hall et al. (1991) examined the quality assurance of observations from ships and buoys using output from a numerical weather prediction model as a constraint. Lorenc and Hammon (1988) constructed an automated procedure to flag errors from ship reports, buoys and synoptic reports. They concluded that their procedure does not give completely certain results, and that subjective analysis did better than the automated program during unusual conditions, such as developing depressions. Essenwanger (1969) presented an automated procedure for detecting erroneous or suspicious observational records based on obvious data errors, comparison of adjacent (in time or space) data, and by comparing to prescribed limits of a standard Weibull distribution. Essenwanger (1969) concluded that his automated technique could not unequivocally pinpoint differences between a rare event and an instrument problem. DeGaetano (1997) presents a scheme to quality control wind measurements. Methods to control radiation measurements were discussed by Gilgen et al. (1994), which can be implemented into continuously running systems.

In contrast to standard meteorological measurements there are only a few papers available that discuss quality control of eddy covariance measurements (Foken and Wichura 1996, Vickers and Mahrt 1997). Quality control of eddy covariances should include not only tests for instrument errors and problems with the sensors, but also evaluate how closely conditions fulfill the theoretical assumptions underlying the method. Because the latter depends on meteorological conditions, eddy covariance quality control tools must be a combination of a typical test for high resolution time series and examination of the turbulent conditions. A second problem is connected with the representativity of the

X. Lee et al. (eds.), Handbook of Micrometeorology, 181-208

measurements depending on the footprint of the measurement. The control of the percentage of the area of interest in the actual footprint is a further issue. It is the aim of the present Chapter to describe a set of possible tests and protocol for data flagging and give practical guidance for use in continuously running eddy covariance systems like the FLUXNET program.

2 Quality Assurance and Quality Control

Quality assurance is one of the most important issues for creation and management of a measuring program. Issues of quality assurance are widely known for routine meteorological measuring programs (Shearman 1992). The present network of carbon dioxide flux sites evolved from an assemblage of individual sites with varying objectives (biological or micrometeorological) and protocols, rather than being designed from the outset as a network. Therefore, the quality assurance of such measuring programs was written after starting the measurements (Aubinet et al. 2000, e.g. Moncrieff et al. 1997). And even now some of the topics are under discussion. A quality assurance (QA) scheme needs the following components:

- Specification of user requirements: The users of the flux data, which may be modelers or policy-makers, who need the information for example in the Kyoto process, need basic information of the measuring program such as accuracy, resolution in time and space (number of sites and surface types). An important task is the development of reliable and feasible measuring programs.
- Specification of the measuring system: A suitable measuring system must be developed according to the requirements and the personal, financial and scientific constraints. This was partly done (Moncrieff et al. 1997), but presently different types of systems are used because of changes and improvements in the measuring technique. This makes the comparability of the results of different sets of instruments difficult and comparison experiments are urgently required.
- Identification of suitable measuring locations: This is a most difficult problem, because several measuring stations were created where research facilities were already in place, rather than being selected according to micrometeorological criteria. Therefore, site characterization tools are needed to ensure data quality (see Section 3.3). Ideally, site selection would be made based on quality testing of data collected from a temporary tower prior to construction of an expensive tower station.
- Definition of necessary calibrations: Calibrations allow comparison of data among sites. The accuracy of any measurement is ultimately limited by the accuracy and frequency of calibration standards that are used. Most of the necessary calibrations and control issues are well described (Aubinet et al. 2000, Goulden et al. 1996, Moncrieff et al. 1997).
- Definition of quality control (QC): The most important part of quality assurance is quality control. Several tests are discussed in this Chapter. Quality control must be done in realtime or shortly after the measurements to minimize data loss by reducing the time to detect and fix instrument problems.
- Quality evaluation: This topic is similar to QC. The main difference is a description of the data quality to be able to compare data for different periods and sites. This is also a main goal of the present Chapter.
- Corrective actions: Corrective actions refers to corrections caused by calibrations, by the choice of the coordinate system, and the sensor size and separation, etc. Most of the corrections are dis-

cussed in the other Chapters of the book and the literature (Aubinet et al. 2000, Moncrieff et al. 1997, etc.).

- Feedback from the user of the data: The database is often the end product of a measuring program. However, the user needs some control of the data and the opportunity to provide feedback to the experimentalist to improve the data quality and to make necessary changes in the program.

3 Quality Control of Eddy Covariance Measurements

A uniform scheme does not exist for quality control of eddy covariance measurements. Only several aspects are discussed in the literature. For the producer of flux data there are a number of specific techniques but no instructions for practical handling of the data. In the following, an overview of different quality control steps is given:

- The first steps of data analysis are basic tests of the raw data (Vickers and Mahrt 1997) such as electrical tests of the amplitude, the resolution of the signal, the control of the electronic and meteorological range of the data and spikes (Højstrup 1993), which are discussed further in Section 3.1.
- Statistical tests must be applied to sampling errors of the time series (Finkelstein and Sims 2001, Haugen 1978, Vickers and Mahrt 1997) and are discussed in Section 3.2. Also abrupt steps in the time series, or reasons for non-stationarity must be identified (Mahrt 1991, Vickers and Mahrt 1997).
- A main issue for quality control are tests on fulfillment of the requirements for eddy covariance measurements. Steady state conditions and a developed turbulent regime are influenced not from the sensor configuration but from the meteorological conditions (Foken and Wichura 1996). The fulfillment of these conditions is discussed in Section 3.3.
- A system of general quality flagging of the data is discussed in Section 3.4 and a site specific evaluation of the data quality using footprint models is in Section 3.5.

3.1 Basic tests of the raw data

Vickers and Mahrt (1997) developed a framework of test criteria for quality control of fast response turbulence time series data with a focus on turbulent flux calculations. The tests are not framed in terms of similarity theory, nor do they assume that the fields necessarily follow any particular statistical distribution. Many types of instrument malfunctions can be readily identified with simple automated criteria. However, even after tuning the threshold values, the automated tests still occasionally identify behaviors that appears to be physical after visual inspection. Physically plausible behavior and instrument problems can overlap in parameter space. This underscores the importance of the visual inspection step in quality control to either confirm or deny flags raised by the automated set of tests. Data flagged but later deemed physical after graphical inspection are often found to be the most unusual and interesting situations, including intermittent turbulence, downward turbulence bursting, microfronts, gravity waves and other stable boundary layer phenomena. Some automated tests for quality control of turbulence time series are briefly summarized below.

Spikes are typically characterized as short duration, large amplitude fluctuations that can result from random noise in the electronics (Brock 1986). Quality control should include the identification and removal of spikes. For example, correlated spikes in the temperature and vertical velocity from a sonic anemometer can contaminate the calculated heat flux. Spikes that do not influence the fluxes still affect the variances. When the number of spikes becomes large, the entire data period should be considered suspect and discarded. The effect of water collecting on the transducers of some sonic anemometers often appears as spikes. Less than optimum electrical power supplies, which are sometimes necessary at remote measurement sites, can lead to frequent spiking. Unrealistic data values occur for a number of reasons. These data should be detected by comparing the minimum and maximum values to prescribed limits. For example, a vertical velocity in excess of 5 m s^{-1} close to the ground is probably not physical. However, visual inspection is sometimes required due to special circumstances, such as high turbulence levels associated with exceptionally strong surface heating. Højstrup (1993) tested a data screening procedure for application to Gaussian distributed turbulence data. Spikes are absolute quantities of measuring values which are larger than approximately four times of the standard deviation of the time series. This test should be repeated 2 or 3 times with each time series.

Some success identifying instrument problems has been achieved by comparing higher moment statistics to threshold values. Abnormally large skewness often indicates a problem, although care must be taken because, for example, the temperature near the ground during strong surface heating typically has large positive skewness. Unusually small or large kurtosis often indicates an instrument problem. Large kurtosis in the temperature field from a sonic anemometer is sometimes related to spiking associated with water on the transducers. Most despiking algorithms fail to remove this persistent type of spiking, in contrast to short duration high amplitude spikes associated with noise in the electronics. Histograms of values of a single turbulence channel are also useful. A non-typical distribution of the measuring data can indicate averaging errors connected with the digitalization. Such errors were found for the Solent sonic anemometers R2 and R3 (Chr. Thomas, University of Bayreuth, 2002, personal communication, problem solved partly by Gill in 2003). In this case for example the R2 measured no vertical wind of -0.01 m s^{-1} but the number of measuring points for 0.00 m s^{-1} was twice as high as the other data. This indicates a small shift to positive vertical wind velocities.

Unusually large discontinuities in the mean can be detected using the Haar transform. The transform is simply the difference between the mean calculated between two adjacent windows. Large values of the transform identify changes in the mean that are coherent on the time scale of the window width. The goal here is to detect semi-permanent changes as opposed to smaller scale fluctuations. A sudden change of offset is one example of an instrument related jump in mean variables. The window size and the threshold values that identify suspect periods may need adjustment for particular datasets. For example, for aircraft data in the convective boundary layer, the mean vertical wind may change significantly as the aircraft enters and exits large scale coherent thermals. However, for tower measurements close to the ground, coherent changes in the mean vertical wind are typically much smaller. Care must be taken with aircraft data over heterogeneous surfaces, where coherent changes in the mean fields are common due to the formation of local internal boundary layers. For example, a sharp change in mean temperature will be found where the aircraft intersects the top of a warm internal boundary layer. In less clear cases, data from other levels and other instruments should be consulted for verification.

Instrument problems can also be detected by comparing the variance to prescribed thresholds. A sequence of variances should be calculated for a sequence of sliding, overlapping windows to detect isolated problems. For example, a brief period with near zero temperature fluctuations could be due to a temporarily non-responding instrument. Visual inspection is sometimes necessary in stable conditions where the true physical variances can become very small, usually due to a combination of strong temperature stratification and weak mean wind shear. Unusually large variance often indicates an instrument malfunction.

In recent years many closed path carbon dioxide analyzers (LiCor 6262) were replaced by open path sensors (LiCor 7500). These sensors are more sensitive to rain and frost. The development of a site-specific test using precipitation, radiation wind and temperature data can help to indicate these situations. This can be done with statistical methods like multiple regressions. Such tests can be important, because interference is not always clearly indicated in the time series.

3.2 Statistical tests

The calculation of means, variances and covariances in geophysical turbulence is inherently ambiguous, partly due to nonturbulent motions on scales which are not large compared to the largest turbulent eddies. As a result of these motions, geophysical time series are normally nonstationary to some degree (Foken and Wichura 1996, Vickers and Mahrt 1997). The physical interpretation of the flux computed from nonstationary time series is ambiguous in that it simultaneously represents different conditions and the computed perturbations for calculation of the flux are contaminated by nonstationarity, which can only be partially removed by detrending or filtering. Nonturbulent motions contaminate the flux calculation in that the flux due to nonturbulent motions may be primarily random error, as found in Sun et al. (1996). Attempts to remove nonstationarity by trend removal or filtering violates Reynolds averaging, although often the errors are small. Attempts to reduce the nonstationarity by reducing the record length increases the random flux error. Techniques for approximately separating random variations and nonstationarity are presented in Mahrt (1998) and Trevino and Andreas (2000). Tests on non-steady state conditions are given in Section 3.3.1.

Systematic errors (flux bias) result from failure to capture all of the turbulent transporting scales (Foken and Wichura 1996, Lenschow et al. 1994, Oncley et al. 1996, Vickers and Mahrt 1997). Such systematic errors occur at either the large scale end where the largest transporting eddies may be excluded from the flux calculation, or at the small scale end where transport by small eddies can be eliminated by instrument response time, pathlength averaging, instrument separation and post-process filtering. With weak winds and substantial surface heating, many flux calculation procedures may exclude larger-scale turbulent flux due to slowly moving boundary-layer scale eddies (Sakai et al. 2001). Increasing the averaging time also captures nonturbulent, mesoscale motions (nonstationarity). With very stable conditions, turbulence quantities may be confined to very short time scales, sometime less than one minute (Vickers and Mahrt 2003). Use of traditional averaging periods of five minutes or more leads to perturbation quantities, which are strongly contaminated by gravity waves, meandering motions and other mesoscale motions (see Mahrt et al. 2001a and references therein). Some of these problems can be identified with the tests given in Section 3.3.2.

The random flux error is the uncertainty due to inadequate record length and the random nature of turbulence (Finkelstein and Sims 2001, Lenschow et al. 1994, Lumley and Panofsky 1964, Mann and Lenschow 1994, Vickers and Mahrt 1997). Once perturbation quantities are computed and products are taken to compute variances, fluxes and other turbulence moments, the turbulence quantities can be averaged over a longer time period to reduce random sampling errors. The latter is sometimes referred to as the “flux-averaging time scale” to distinguish it from the shorter averaging time scale used to define the perturbations. The time scale for averaging the flux normally should be longer than that used to compute the perturbations themselves. Reynolds averaging can still be satisfied as long as the averaging is unweighted (no filtering or detrending) (Mahrt et al. 2001b). For example, one might choose an averaging time of 2 minutes for very stable conditions but wish to average the 2-minute fluxes over 30 minutes or one hour to reduce random flux errors.

With very stable conditions where the turbulence is intermittent, reduction of the random error to acceptable levels may require a prohibitively long averaging time (e.g. Haugen 1973). The flux for a one-hour period can be dominated by one or two events and therefore a much longer averaging time is required. Howell and Sun (1999) choose the record length by attempting to objectively maximize the flux and minimize the random flux error.

The above results also apply to analysis of turbulence quantities from moving platforms such as aircraft, except that one must determine the averaging length from which to compute perturbations (often chosen to be 1 km) and choose the flux averaging length, sometimes chosen as the flight path length. In convective conditions with deep boundary layers, such an averaging length may exclude significant flux (Betts et al. 1990, Desjardins et al. 1992). The nonstationarity problem above becomes the heterogeneity problem for moving platforms (e.g. Desjardins et al. 1997). Reduction of random flux errors is facilitated by long flight paths for homogeneous surfaces or many repeated passes over heterogeneous surfaces (Mahrt et al. 2002).

The autocovariance analysis is widely used to determine the time lag for closed-path gas analyzers (Leuning and Judd 1996), because the concentration signal is measured some seconds later than the wind signal. Even data from open-path gas analyzer may have a small time offset between the measuring time and the position of the value in the data file because of electronic delays in recording and storing the data and finite signal processing times. If this is not known and not corrected in the logger program, it must be included in calculation of the fluxes. It is important to check the whole measuring system with an autocovariance analysis to identify time shifts between the signals.

3.3 Test on fulfillment of theoretical requirements

The widely used direct measuring method for turbulent fluxes is the eddy covariance method, which involves a simplification of turbulent conservation equations for momentum and scalar fluxes, e.g., the flux of a scalar, c

$$F_c = \overline{w'c'} = \frac{1}{N-1}\sum_{k=0}^{N-1}\left[\left(w_k - \overline{w}\right)\left(c_k - \overline{c}\right)\right] \tag{9.1}$$

where w is the vertical wind component. This equation implies steadystate conditions. The choice of averaging length depends on the cospectra of the turbulence and steady state conditions. With an ogive test (Oncley et al. 1990)

$$Og_{w,c}\left(f_0\right) = \int_{-\infty}^{f_0} Co_{w,c}\left(f\right)df \tag{9.2}$$

where Co is the cospectra of the vertical wind velocity and the concentration. The convergence of Og at low frequencies indicates that all relevant eddies are collected. On the other hand an excessive measuring length may include nonsteady-state conditions (see Chapters 2 and 5). Therefore, these conditions should be tested for each time series, because they can influence the data quality significantly (see Section 3.3.1). However, in most cases, convergence occurs within a 30-minute period.

The integral turbulence characteristics in the surface layer may depend on the latitude (Johansson et al. 2001); this may be relevant for tests on eddy covariance measurements. The influence of density fluctuations can be corrected (see Chapters 6 and 7). Conditions of horizontal homogeneity must also be fulfilled in order to avoid significant advection, which can be influenced by the choice of the coordinate rotation (see Chapters 3 and 10).

Of greater importance is whether developed turbulent conditions exist, with very weak turbulence the measuring method and methods based on surface layer similarities may not be valid. Examination of normalized standard deviations (integral turbulence characteristics, see Section 3.3.2) provides an effective test for adequately developed turbulence. These tests are also sensitive to other influences on the data quality like limitations of the surface layer height, gravity waves, internal boundary layers, flow distortion, high frequency flux loss (see Chapter 4). For example, internal boundary layers and flow distortion problems of the sensors and towers can indicate higher standard deviations of turbulence parameters. For situations with gravity waves the correlation coefficient between the vertical wind velocity and scalars can be high, resulting in unusually large fluxes. Such situations, often during the night and under stable conditions, must be indicated and the wave and the turbulent signal must be separated (Handorf and Foken 1997).

Foken and Wichura (1996) applied criteria to fast-response turbulence data to test for non-stationarity and substantial deviations from flux-variance similarity theory, whether due to instrumental or physical causes. These are described below.

3.3.1 Steady state tests

Steady state conditions means that all statistical parameters do not vary in time (e.g. Panofsky and Dutton 1984). Typical non-stationarity is driven by the change of meteorological variables with the time of the day, changes of weather patterns, significant mesoscale variability, or changes of the measuring point relative to the measuring events such as the phase of a gravity wave. The latter may occur because of changing footprint areas, changing internal boundary layers (especially internal thermal boundary layers in the afternoon), or by gravity waves. Presently there are two main tests used to identify non-steady state conditions. The first is based on the trend of a meteorological parameter over the averaging interval of the time series (Vickers and Mahrt 1997) and the second method indicates non-steady state conditions within the averaging interval (Foken and Wichura 1996).

Vickers and Mahrt (1997) regressed the meteorological element x over the averaging interval of a time series and determined the difference of x between the beginning and the end of the time series according to this regression, δx. With this calculation they determined the parameter of relative non-stationarity, mainly for wind components

$$RN_x = \frac{\delta x}{\overline{x}} \tag{9.3}$$

Measurements made over the ocean exceeded the threshold ($RN_x > 0.50$) 15 % of the time and measurements over forest exceeded the threshold 55 % of the time. A more rigorous measure of stationarity can found in Mahrt (1998).

The steady state test used by Foken and Wichura (1996) is based on developments of Russian scientists (Gurjanov et al. 1984). It compares the statistical parameters determined for the averaging period and for short intervals within this period. For instance, the time series for the determination of the covariance of the measured signals w (vertical wind) and x (horizontal wind component or scalar) of about 30 minutes duration will be divided into $M = 6$ intervals of about 5 minutes. N is the number of measuring points of the short interval ($N = 6{,}000$ for 20 Hz scanning frequency and a 5 minute interval):

$$\left(\overline{x'w'}\right)_i = \frac{1}{N-1}\left[\sum_j x_j w_j - \frac{1}{N}\sum_j x_j \sum_j w_j\right]$$

$$\overline{x'w'} = \frac{1}{M}\sum_i \left(\overline{x'w'}\right)_i \tag{9.4}$$

This value will be compared with the covariance determined for the whole interval:

$$\left(\overline{x'w'}\right)_o = \frac{1}{M(N-1)}\left[\sum_i \left(\sum_j x_j w_j\right)_i - \frac{1}{MN}\sum_i \left(\sum_j x_j \sum_j w_j\right)_i\right] \tag{9.5}$$

The authors proposed that the time series is steady state if the difference between both covariances

$$RN_{COV} = \left|\frac{\left(\overline{x'w'}\right) - \left(\overline{x'w'}\right)_o}{\left(\overline{x'w'}\right)_o}\right| \tag{9.6}$$

is less than 30%. This value is found by long experience and is in a good agreement with other test parameters also of other authors (Foken and Wichura 1996).

3.3.2 Test on developed turbulent conditions

Flux-variance similarity is a good measure to test the development of turbulent conditions. This similarity means that the ratio of the standard deviation of a turbulent parameter and its turbulent flux is nearly constant or a function of stability. These so-called integral turbulence characteristics are basic similarity characteristics of the atmospheric turbulence (Obukhov 1960, Wyngaard et al. 1971) and are routinely discussed in boundary layer and micrometeorology textbooks (Arya 2001, Foken 2003, Kaimal and Finnigan 1994, Stull 1988). Foken and Wichura (1996) used functions determined by Foken et al. (1991). These functions depend on stability and have the general form for standard deviations of wind components

$$\frac{\sigma_{u,v,w}}{u_*} = c_1\left(\frac{z}{L}\right)^{c_2} \tag{9.7}$$

where u is the horizontal or longitudinal wind component, v the lateral wind component, u_* the friction velocity and L the Obukhov length. For scalar fluxes the standard deviations are normalized by their dynamical parameters (e.g., the dynamical temperature T_*)

$$\frac{\sigma_x}{X_*} = c_1\left(\frac{z}{L}\right)^{c_2} \tag{9.8}$$

The constant values in Equations 9.7 and 9.8 are given in Table 9.1. For the neutral range the external forcing assumed by Johansson et al. (2001) and analyzed for the integral turbulence characteristics by Thomas and Foken (2002) was considered in Table 9.2 with the latitude (Coriolis parameter f). The parameters given for the temperature can be assumed for most of the scalar fluxes. It must be mentioned that under nearly neutral conditions the integral turbulence characteristics of the scalars have extremely high values (Table 9.1) and the test fails.

Table 9.1. Coefficients of the integral turbulence characteristics (Foken et al. 1997, 1991, Thomas and Foken 2002).

Parameter	z/L	c_1	c_2
σ_w/u_*	0 > z/L > -0.032	1.3	0
	-0.032 > z/L	2.0	1/8
σ_u/u_*	0 > z/L > -0.032	2.7	0
	-0.032 > z/L	4.15	1/8
σ_T/T_*	0.02 < z/L < 1	1.4	-1/4
	0.02 >z/L >-0.062	0.5	-1/2
	-0.062 > z/L > -1	1.0	-1/4
	-1 > z/L	1.0	-1/3

Table 9.2. Coefficients of the integral turbulence characteristics for wind components under neutral conditions (Thomas and Foken 2002).

Parameter	-0.2 < z/L < 0.4
σ_w/u_*	$0.21\ln\left(\frac{z_+ \times f}{u_*}\right)+3.1,\ z_+ = 1\ m$
σ_u/u_*	$0.44\ln\left(\frac{z_+ \times f}{u_*}\right)+6.3,\ z_+ = 1\ m$

The test can be done for the integral turbulence characteristics of both parameters used to determine the covariance. The measured and the modeled parameters according to Equations 9.7 or 9.8 will be compared according to

$$ITC_\sigma = \left|\frac{(\sigma_x/X_*)_{\text{model}} - (\sigma_x/X_*)_{\text{measurement}}}{(\sigma_x/X_*)_{\text{model}}}\right| \quad (9.9)$$

If the test parameter ITC_σ is < 30 %, a well developed turbulence can be assumed.

A similar parameter is the correlation coefficient between the time series of two turbulent parameters. If this correlation coefficient is within the usual range (Table 9.3) a well-developed turbulence can be assumed (Kaimal and Finnigan 1994).

3.4 Overall quality flag system

To be useful, the results of data quality checking must be made available in the final data archive. Measurements are normally flagged according to their status such as uncontrolled, controlled, corrected, etc. The quality tests given above open the possibility to flag also the quality of a single measurement. Foken and Wichura (1996) proposed to classify the tests according to Equations 9.6 and 9.9 into different steps and to combine different tests. An important parameter, which must be included in the classification scheme, is the orientation of the sonic anemometer, if the anemometer is not an omnidirectional probe and the measuring site has not have an unlimited fetch in all directions. For these

Table 9.3. Typical values for the correlation coefficient of the momentum and sensible heat flux.

Author	r_{uw}	r_{wT}
Hicks (1981)	-0.32	0.35 (z/L $\rightarrow$-0.0)
		0.6 (z/L $\rightarrow$-2.0)
Kaimal et al. (1990)	-0.3	0.5 (z/L < 0.0)
Kaimal and Finnigan (1994)	-0.35	0.5 (-2 < z/L < 0)
		-0.4 (0 < z/L < 1)
Arya (2001)	-0.15	0.6 (z/L < 0.0)

Table 9.4. Classification of the data quality by the steady state test according to Equation 9.6 and the integral turbulence characteristics according to Equation 9.9 and the horizontal orientation of a sonic anemometer of the type CSAT3 (Foken 2003)

a		b		c	
class	range	class	range	class	range
1	0–15%	1	0–15%	1	± 0–30°
2	16–30%	2	16–30%	2	± 31–60°
3	31–50%	3	31–50%	3	± 61–100°
4	51–75%	4	51–75%	4	± 101–150°
5	76–100%	5	76–100%	5	± 101–150!
6	101–250%	6	101–250%	6	± 151–170°
7	251–500%	7	251–500%	7	± 151–170°
8	501–1000%	8	501–1000%	8	± 151–170°
9	> 1000%	9	> 1000%	9	> ± 171 °

a: Steady state test according to Equation 9.6

b: Integral turbulence characteristics according to Equation 9.9

c: Horizontal orientation of the sonic anemometer

three tests the definition of the flags is given in Table 9.4. Further tests, like an acceptable range of the mean vertical wind velocity, can be included into this scheme.

The most important part of a flag system is the combination of all flags into a general flag for easy use. This is done in Table 9.5 for the flags given in Table 9.4. The user of such a scheme must know the appropriate use of the flagged data. The presented scheme was classified (by micrometeorological experiences) so classes 1 to 3 can be used for fundamental research, such as the development of parameterizations.

The classes 4-6 are available for general use like for continuously running systems of the FLUX-NET program. Classes 7 and 8 are only for orientation. Sometimes it is better to use such data instead of a gap filling procedure, but then these data should not differ significantly from the data before and after these data in the time series. Data of class 9 should be excluded under all circumstances. Such a scheme gives the user a good opportunity to use eddy covariance data. Finally the data can be presented together with the quality flag like in Figure 9.1. Most of the unusual values can be explained by the data quality flag. At night, other reasons can influence the measurements. For analysis of integrated fluxes rejected data will need to be filled in. Obviously, investigations to infer process relationships should exclude both flagged data and the gap-filled values.

Table 5. Proposal for the combination of the single quality flags into a flag of the general data quality (Foken 2003).

a	b	c	d
1	1	1–2	1–5
2	2	1–2	1–5
3	1–2	3–4	1–5
4	3–4	1–2	1–5
5	1–4	3–5	1–5
6	5	≤ 5	1–5
7	≤ 6	≤ 6	≤ 8
8	≤ 8	≤ 8	≤ 8
9	*	*	*

a: Flag of the general data quality

b: Steady state test according Equation 9.6

c: Integral turbulence characteristics according Equation 9.9

d: Horizontal orientation of the sonic anemometer

*: One or more of flags b, c and d equals 9

3.5 Site dependent quality control

Besides the quality classification of a single measuring series, classification of the site-specific data quality is needed to compare different sites within a network like FLUXNET for a better interpretation of experimental and modeled data. The data quality differs because of topography and this must be taken into account by comparison of the data quality. This quality check was developed to include footprint information (Foken et al. 2000). There are two different points of interest: The first point is

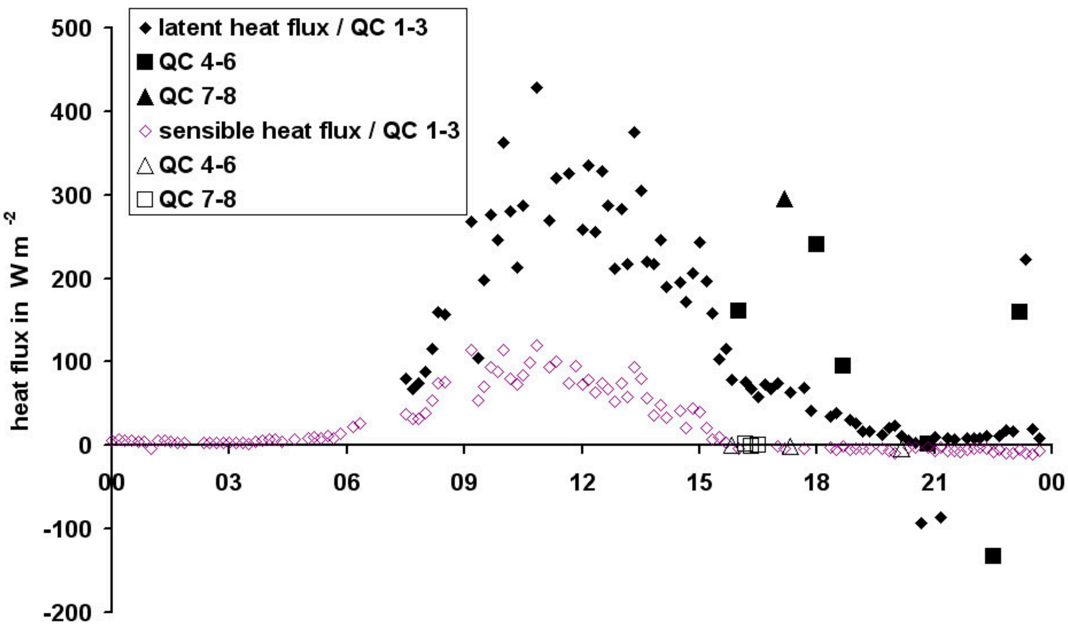

Figure 9.1. Daily cycle of the sensible and latent heat flux with quality classes measured by the University of Bayreuth during the LITFASS-1998 experiment (Beyrich et al. 2002) on June 02, 1998 in Lindenberg/Germany over grassland.

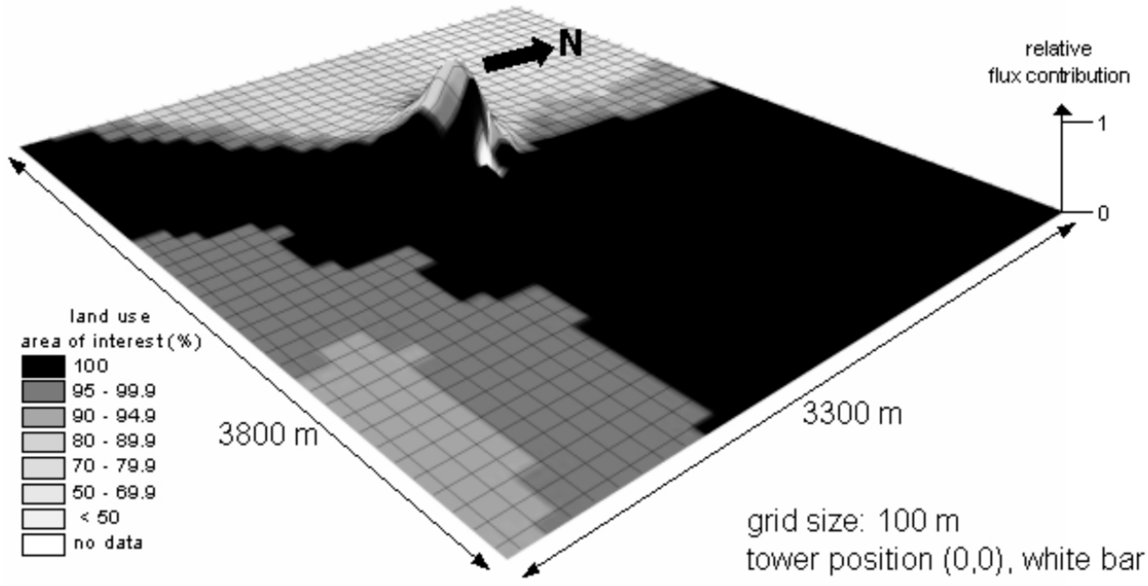

Figure 9.2. Quality analysis for the land use evaluation with flux contribution. Results were obtained with data from the Weidenbrunnen/Waldstein site for the period 01.05. – 31.08.1998 (Göckede et al. 2002).

the area of interest (e. g. a spruce forest) in the footprint of the measurements. The second point concerns the question: for which footprint areas can good data quality be assumed?

A program package has been developed (Göckede et al. 2004) and used for 18 CarboEurope eddy covariance measuring sites. The land use information of the surrounding is given by input matrices. Together with necessary meteorological input parameters, the main iteration loop of the program starts with a footprint calculation employing a user-defined start value for the roughness length z_0. The integrated Schmid (1997) model produces characteristic dimensions defining the two-dimensional horizontal extension of each so-called effect-level ring. Using these dimensions, which sketch a discrete version of the source weight function, it is possible to assign a weighting factor to each of the cells of the roughness matrix. A new roughness length z_0-final is calculated as the mean value of all the cells within the source area under consideration of the weighting factors. The iteration loop starts again with the improved value of z_0-final as the input value for the footprint routine. In the next step, the land use structure within the computed source area is analyzed. The weighting factors of the last source weighting function results are used to calculate the contribution of each type of land use (which can be up to 20, as defined by the user) to the total flux. Due to certain restrictions of the footprint model concerning the necessary input parameters, a portion of the input data set cannot be processed. Most of the time, these problems occur during stable stratification, when the computed source area grows to an extent that makes the numerical algorithms unstable. Finally figures like Figure 9.2 for the Weidenbrunnen/Waldstein site near Bayreuth/Germany (50°08'N, 11°52'E, 775 m a.s.l.), can be constructed that give a flux distribution over a four month measuring period that depends on the footprint. The color of the grid elements characterize the part of the area of interest to the flux. Such pictures can help find the best wind directions and the best positions of the tower to link the fluxes with the underlying surface.

To produce the overall performance of the flux data quality for a specific site, the results of all the footprint calculations are combined with the data quality assessment. The products of the procedure are two-dimensional matrices and graphs that form a combination of all the footprint analyses for the specific site. These matrices show, for example, the dominating data quality class for each of the grid

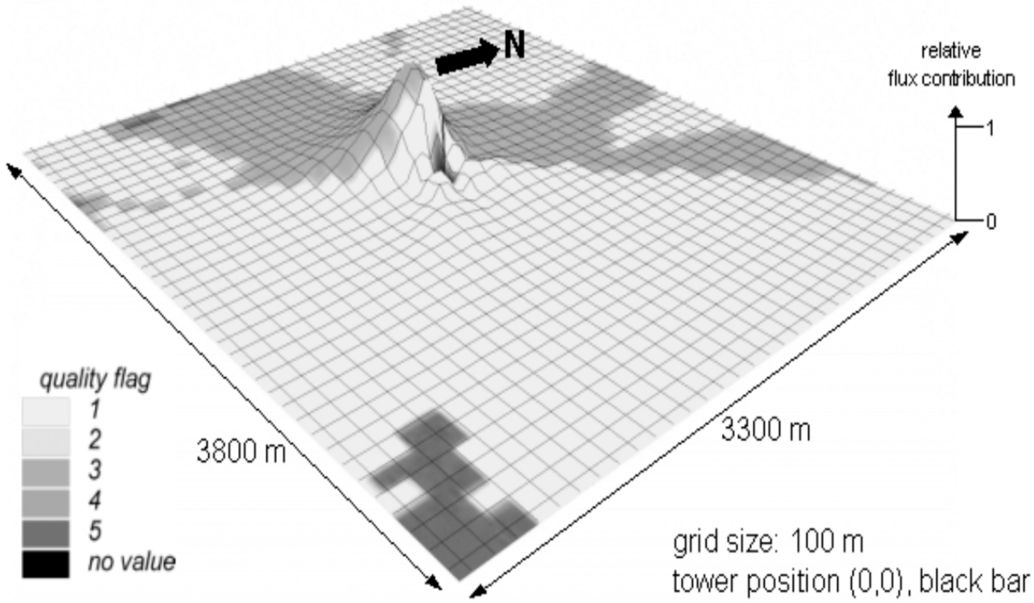

Figure 9.3. Quality flags for special distribution of the contribution to the latent heat flux. Results were obtained with data from the Weidenbrunnen/Waldstein site for the period 01.05.–31.08.1998 (Göckede et al. 2002).

cells (mean value) of the matrix surrounding the tower, in combination with its contribution to the total flux. This can be done for all types of fluxes. Only for scalar fluxes the quality flag of internal turbulence characteristics must be excluded in the near neutral case. As an example, the data quality distribution for the latent heat flux of Weidenbrunnen/Waldstein site is given in Figure 9.3. The lower data quality in western wind directions is caused by a clearing, which can also be indicated from the land use distribution (Figure 9.2). The low data quality in SWS direction (for stable stratification) is caused by the Waldstein mountain at a distance of 1.5 km. The possibility to bring data quality and possible influencing factors together is an application of the footprint model. Using the limit settings, the user of the program package can restrict the analysis to certain quality classes or a range of values for specific meteorological parameters, allowing a more detailed analysis under special conditions. The variation of these input parameters can also be performed automatically in a sequence mode with user defined upper and lower limits at specific increments.

4 Further problems of quality control

Energy balance closure has often been used to identify the quality of eddy covariance measurements (Aubinet et al. 2000). For most of the sites a closure of the energy balance equation

$$R_n - H - \lambda E - G \pm \Delta S = Res \qquad (9.10)$$

with R_n net radiation, H sensible heat flux, λE latent heat flux, G ground heat flux, ΔS heat storage, is not zero but has a residual Res of approximately 10-20%. In some investigations of the energy balance closure problem (Culf et al. 2004, Foken and Oncley 1995, Oncley et al. 2002), the main reasons for this problem are errors of the sensors. For example the influence of net radiometers is significant because of the large part of net radiation in the energy balance. Measuring problems also exist of heat storage especially in the soil layer above the heat flux plates. Another reason is that mesoscale fluxes are not measured (Chapter 5). These reasons for the residual of the energy balance closure does not allow an energy balance closure with a correction factor for all turbulent fluxes or the use of energy balance closure as a measure of the data quality. However, there are many other studies where energy balance closure is consistently underestimated, without an identifiable cause. This has created some disparity among the methods employed by different groups. Some researchers use the energy balance closure as a further check, and adjust the CO_2 flux in the same proportion as the loss in the other turbulent fluxes (e.g. Amiro 2001, Barr et al. 2002). Some other researchers do not account for this turbulent loss, and consensus has not been reached in the research community. As an additional problem different instruments have different footprints.

The method of coordinate rotation also influences the data. Such rotations are necessary to align the x-axis with the mean wind (first rotation), to define a z axis so that the mean vertical wind component is zero (second rotation) and to rotate the system on the third axis so that the lateral momentum flux is zero (third rotation). This method was discussed by McMillen (1988) with a running mean as the reference coordinate system. Presently a rotation for each averaging interval (30 minutes) without the third rotation is proposed (Aubinet et al. 2000). This method is widely criticized because single events like convection, gusts, coherent structures etc., which have nothing to do with the coordinate system, are the reason for a significant rotation for a particular averaging interval. Even over low vegetation and flat terrain, rotation angles of 20-40° can be detected in the night and early morning hours. Therefore the planar-fit method (Wilczak et al. 2001) has been suggested (see Chapter 3) which rotates according the mean streamlines (Paw U et al. 2000). This streamline dependent coordinate system must be determined for one site and changes only with changes in the mounting of the sensor, with the time of the year (deciduous forest), with the wind speed (two classes) and the wind direction in heterogeneous and hilly terrain. The rotation angles are small and on the order of 2-5° and can be more with significant slope. After the rotation the data quality analysis as described in Sections 3.3 and 3.4 produces significant differences in the data quality especially for low wind velocities. As shown in Figure 9.4, the data quality is significantly lower for double rotation in comparison to planar fit in the classes of low friction velocity. The first method has low quality data typically for $u_* < 0.3$ m s^{-1} whereas the planar fit corresponds to approximately $u_* < 0.2$ m s^{-1}. This influence must be recognized, because it can influence the so-called u_*-criteria to correct nighttime carbon dioxide fluxes (Goulden et al. 1996).

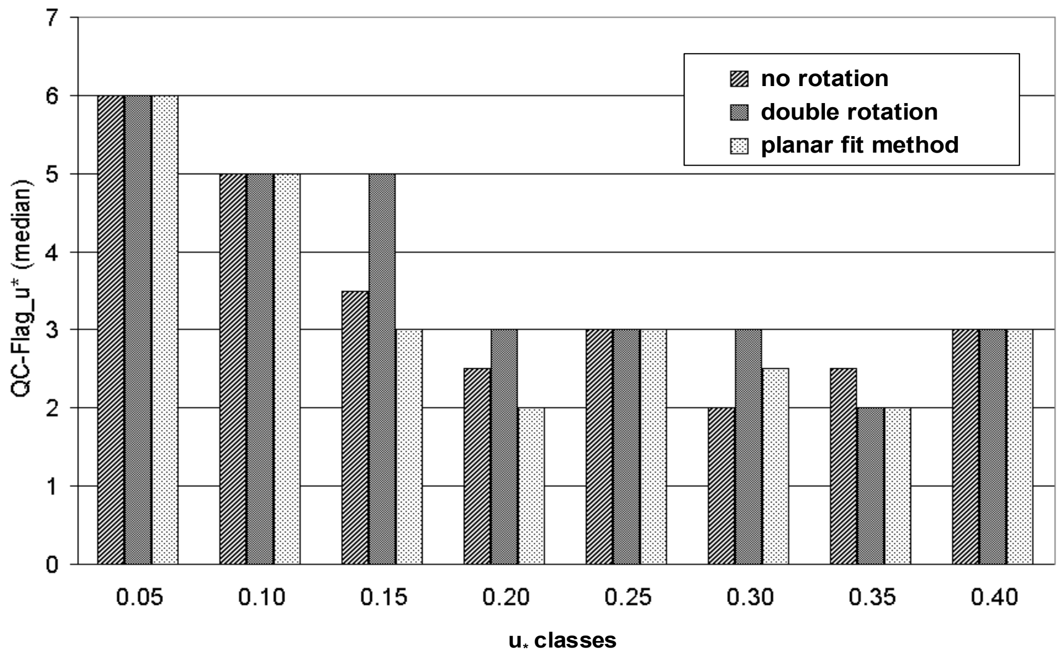

Figure 9.4. Data quality analysis for double rotation (Aubinet et al. 2000) and planar fit rotation (Wilczak et al. 2001) for measurements over an irrigated cotton field during EBEX-2000 (Oncley et al. 2002).

Quality control procedures identify periods of unsuitable data, leaving non-random gaps in the dataset. The quality control procedures, instrument malfunctions, maintenance and calibration periods often remove 20 to 40% of the data. These gaps need to be filled for applications where long-term integrations are needed, though gaps should not be filled for process studies. Gap-filling creates additional uncertainty in the data, and there will always be a compromise between the use of possibly questionable flux data and replacement with values generated from a gap-filling algorithm. Confidence in gap-filling increases with knowledge and experience at any given flux site.

Falge et al. (2001a, 2001b) provide reviews of gap-filling strategies for energy flux and net ecosystem exchange (NEE) measurements. A variety of methods need to be applied, depending on the reasons for the gap creation. Nighttime gaps in NEE are best filled by either using soil respiration chambers or through developing a site-specific relationship between the respiration flux (mostly soil) and environmental variables such as soil temperature and moisture. Missing daytime NEE data can be estimated using physiological relationships that typically incorporate air temperature and light measurements. Short (e. g., a single half-hour period) gaps are usually filled through interpolation, whereas longer gaps may be estimated using the average of some period of good data for the same time of day. Gap-filling by averaging also needs to consider that gaps are often created by environmental conditions differing from the average, such as instrument malfunctions during heavy precipitation. The implications of gap-filling can be substantial, and in the case of NEE, can change the conclusions on the magnitude of annual carbon sequestration. Falge et al. (2001a) compared some gap-filling methods for NEE for 18 sites, illustrating that different methods could alter the annual sum of NEE by -45 to +200 g C m^{-2}, a significant portion of the total flux for some ecosystems. The conclusion is that quality-procedures need to focus on truly incorrect data since there is still a large uncertainty in filling gaps, and that the estimation of long-term fluxes can best be improved with good knowledge of the site processes.

Over a forest site the turbulence structure is very complicated (Amiro 1990) sometimes with ramp structures mainly at daytime and wave structures (gravity waves) at nighttime (Chapter 8). The contribution of coherent structures to the whole flux is generally unknown. Well-organized ramp structures may be measured with the eddy covariance method. The determination of the flux due to ramp structures with the surface renewal method (Snyder et al. 1996) compares well with eddy covariance measurements (Rummel et al. 2002). In contrast, single coherent structures can indicate non-stationary conditions and be identified falsely as low quality data. We need continuously running procedures to calculate and control fluxes under these circumstances.

The decoupling of the atmosphere from the forest also needs to be considered. This is a typical situation during stable stratification at night. One must also consider the possibility of a mixing layer immediately above the forest canopy (Finnigan 2000, Raupach et al. 1996), caused by the high wind shear above the forest. The similarity analysis of the length scales of the shear layer and the coherent structures show that the forest and the atmosphere are often only coupled at daytime, often with strong coherent structures (Wichura et al. 2002).

One must also consider the mean transport at upper boundary of a control volume (Chapter 10). Also the horizontal and vertical advective transport must be taken into account to interpret the vertical flux. An adequate choice of the coordinate system, for instance by planar fit rotation can help to interpret the vertical advection. Nevertheless, these site specific phenomena are difficult to check through automatic quality control procedures.

Plant physiological tests and ecosystem level measurements of carbon or water budgets can also be very useful in verifying the quality of the flux data. For example, soil chambers can give nighttime estimates of respiration during periods of weak turbulence when micrometeorological conditions fail. Plant leaf chambers can confirm the response of plants to certain conditions when turbulent flux measurements are questioned. Biomass inventories (Curtis et al. 2002) provide additional checks on annual integrals of flux data. The best possible estimate of net ecosystem exchange should combine a consistent set of independently determined quantities.

5 Conclusion

The quality assurance and quality control are outstanding problems that are incompletely fulfilled in most of the FLUXNET networks. For new stations a complete quality assurance plan can help provide a measuring system that can run within a short time on a high quality level. The quality control is always a combination of different levels of control and some very site-specific tests. Although an absolute uniform tool is impossible, a set of minimum standards is essential to ensure data comparability between sites in a network and over time for long-term measurements. Nevertheless some tools for electrical, meteorological and statistical tests are available. Not only the tests but the correction of the data are necessary to produce high quality data. Very important are tests on the fulfillment of the theoretical basis of the eddy covariance method as in the non-stationarity tests and the integral turbulence characteristic test. Important is the combination of all test results in an overall quality flag for the user of the data. A proposal is given in this Chapter, but only standardization makes flux measurements comparable. This Chapter included a footprint dependent quality analysis in the CarboEurope flux program. Such analysis helps to assess the data quality of different stations. Nevertheless, the data quality is only one part of the problem. Ecological reasons make stations with a lower quality important, if the investigated ecosystem does not allow better data qualities due to hilly terrain etc. The presented quality control tools work under most of the meteorological conditions especially over low vegetation. The measurement of nighttime fluxes, when the theoretical basis of the eddy covariance method fails, is not yet included in this procedure and the complicated turbulence structure over forests needs more investigation to find adequate algorithms to check the data.

Quality control and quality assurance tests are a fundamental part of the protocols used to arrive at good estimates of turbulent fluxes and NEE. Many of the methods have been derived through experience by an ensemble of researchers. Although there is often a good reason for site-specific procedures, most of the scientific community has similar issues to address. Hence, networks are developing prescriptive procedures to achieve a basic level of data quality. Objective methods of removing spikes and identifying appropriate turbulent conditions, instrument malfunctions, non-stationary conditions, and appropriate fetch are common to all measurement sites. Decisions regarding coordinate rotation schemes, averaging periods, energy balance closure and gap-filling are less straightforward, and need to be further investigated to arrive at standard techniques. With the wide experience being gained through international FLUXNET collaborations, consensus on all of these procedures may be reached in the near future.

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7 References*

Amiro, B.D.: 1990, 'Comparison of turbulence statistics within three boreal forest canopies', *Boundary-Layer Meteorol.* **51**, 99-121.

Amiro, B.D.: 2001, 'Paired-tower measurements of carbon and energy fluxes following disturbance in the boreal forest', *Global Change Biol.* **7**, 253-268.

Arya, S.P.: 2001, *Introduction to Micrometeorology*, Academic Press, San Diego, 415 pp.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T.: 2000, 'Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology', *Adv. Ecol. Res.* **30**, 113-175.

Barr, A.G., Griffis, T.J., Black, T.A., Lee, X., Staebler, R.M., Fuentes, J.D., Chen, Z., Morgenstern, K.: 2002, 'Comparing the carbon budgets of boreal and temperate deciduous forest stands', *Can. J. For. Res.* **32**, 813-822.

Betts, A.K., Desjardins, R.L., MacPherson, J.I., Kelly, R.D.: 1990, 'Boundary-layer heat and moisture budgets from FIFE', *Boundary-Layer Meteorol.* **50**, 109-138.

Beyrich, F., Herzog, H.J., Neisser, J.: 2002, 'The LITFASS project of DWD and the LITFASS-98 experiment: The project strategy and the experimental setup', *Theor. Appl. Climatol.* **73**, 3-18.

Brock, F.V.: 1986, 'A nonlinear filter to remove impulse noise from meteorological data', *J. Atmos. Ocean. Technol.* **3**, 51-58.

Culf, A.D., Foken, T., Gash, J.H.C.: 2004, The energy balance closure problem. In: Kabat, P. et al. (Eds.), *Vegetation, water, humans and the climate. A new perspective on an interactive system*, Springer, Berlin, Heidelberg, pp. 159-166.

Curtis, P.J., Hanson, P.J., Bolstad, P., Barford, C., Randolph, J.C., Schmid, H.P., Wilson, K.B.: 2002, 'Biometric and eddy-covariance based estimates of annual carbon storage in five eastern North American deciduous forests', *Agric. For. Meteorol.* **113**, 3-19.

DeGaetano, A.T.: 1997, 'A quality-control routine for hourly wind observations', *J. Atmos. Ocean. Technol.* **14**, 308-317.

Desjardins, R.L., Hart, R.L., MacPherson, J.I., Schuepp, P.H., Verma, S.B.: 1992, 'Aircraft- and tower-based fluxes of carbon dioxide, latent, and sensible heat', *J. Geophys. Res.* **97**, 18477-18485.

Desjardins, R.L., MacPherson, J.I., Mahrt, L., Schuepp, P., Pattey, E., Neumann, H., Baldocchi, D., Wofsy, S., Fitzjarrald, D., McCaughey, H., Joiner, D.W.: 1997, 'Scaling up flux measurements for the boreal forest using aircraft-tower combination', *J. Geophys. Res.* **102D**, 29125-29133.

Essenwanger, O.M.: 1969, 'Analytical procedures for the quality control of meteorological data. *Proc.*

*References ‚in print' were actualised in comparison to the original manuscript

of the Amer. Meteor. Soc. Symposium on Meteorological Observations and Instrumentation, Meteorol. Monogr. **11**, 141-147.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H.: 2001a, 'Gap filling strategies for defensible annual sums of net ecosystem exchange', *Agric. For. Meteorol.* **107**, 43-69.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H.: 2001b, 'Gap filling strategies for long term energy flux data sets', *Agric. For. Meteorol.* **107**, 71-77.

Finkelstein, P.L., Sims, P.F.: 2001, 'Sampling error in eddy correlation flux measurements', *J. Geophys. Res.* **106D**, 3503-3509.

Finnigan, J.J.: 2000, 'Turbulence in Plant Canopies', *Annu. Rev. Fluid Mech.* **32**, 519-571.

Foken, T.: 2003, *Angewandte Meteorologie, Mikrometeorologische Methoden*, Springer, Berlin, Heidelberg, New York, 289 pp.

Foken, T., Jegede, O.O., Weisensee, U., Richter, S.H., Handorf, D., Görsdorf, U., Vogel, G., Schubert, U., Kirtzel, H.-J., Thiermann, V.: 1997, Results of the LINEX-96/2 Experiment, *Deutscher Wetterdienst, Forschung und Entwicklung, Arbeitsergebnisse* **48**, 75 pp.

Foken, T., Mangold, A., Rebmann, C., Wichura, B.: 2000, 'Characterization of a complex measuring site for flux measurements', *14th Symposium on Boundary Layer and Turbulence*, Aspen, CO, American Meteorological Society, 388-389.

Foken, T., Oncley, S.P.: 1995, 'Results of the workshop 'Instrumental and methodical problems of land surface flux measurements'', *Bull. Amer. Meteorol. Soc.* **76**, 1191-1193.

Foken, T., Skeib, G., Richter, S.H.: 1991, 'Dependence of the integral turbulence characteristics on the stability of stratification and their use for Doppler-Sodar measurements', *Z. Meteorol.* **41**, 311-315.

Foken, T., Wichura, B.: 1996, 'Tools for quality assessment of surface-based flux measurements', *Agric. For. Meteorol.* **78**, 83-105.

Gilgen, H., Whitlock, C.H., Koch, F., Müller, G., Ohmura, A., Steiger, D., Wheeler, R.: 1994, 'Technical plan for BSRN data management', *World Radiation Monitoring Centre (WRMC), Technical Report* **1**, 56 pp.

Göckede, M., Rebmann, C., Foken, T.: 2002, *Characterization of a complex measuring site for flux measurements*, Universität Bayreuth, Abteilung Mikrometeorologie, Arbeitsergebnisse, Print ISSN 1614-8916, No. **20**, 20 pp.

Göckede, M., Rebmann, C., Foken, T.: 2004, 'A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites', *Agric. For. Meteorol.* **127**, 175-188.

Goulden, M.L., Munger, J.W., Fan, F.-M., Daube, B.C., Wofsy, S.C.: 1996, 'Measurements of carbon sequestration by long-term eddy covariance: method and critical evaluation of accuracy', *Global Change Biol.* **2**, 159-168.

Gurjanov, A.E., Zubkovskij, S.L., Fedorov, M.M.: 1984, 'Mnogokanalnaja avtomatizirovannaja sistema obrabotki signalov na baze', *EVM. Geod. Geophys. Veröff., R. II* **26**, 17-20.

Hall, C.D., Ashcroft, J., Wright, J.D.: 1991, 'The use of output from a numerical model to monitor the quality of marine surface observation', *Meteorol. Mag.* **120**, 137-149.

Handorf, D., Foken, T.: 1997, 'Analysis of turbulent structure over an Antarctic ice shelf by means of wavelet transformation', *12th Symosium on Boundary Layer and Turbulence*, Vancouver BC, Canada, American Meteorological Society, 245-246.

Haugen, D.A. (Ed.), 1973, *Workshop on micrometeorology*, American Meteorological Society, Boston, 392 pp.

Haugen, D.A.: 1978, 'Effects of sampling rates and averaging periods on meteorological measurements', *4th Symposium on Meteorological Observations and Instrumentation*, American Meteorological Society Boston, 15-18.

Hicks, B.B.: 1981, 'An examination of the turbulence statistics in the surface boundary layer', *Boundary-Layer Meteorol.* **21**, 389-402.

Højstrup, J.: 1993, 'A statistical data screening procedure', *Meas. Sci. Technol.* **4**, 153-157.

Howell, J.F., Sun, J.: 1999, 'Surface layer fluxes in stable conditions', *Boundary-Layer Meteorol.* **90**, 495-520.

Johansson, C., Smedman, A., Högström, U., Brasseur, J.G., Khanna, S.: 2001, 'Critical test of Monin-Obukhov similarity during convective conditions', *J. Atmos. Sci.* **58**, 1549-1566.

Kaimal, J.C., Finnigan, J.J.: 1994, *Atmospheric Boundary Layer Flows: Their Structure and Measurement*, Oxford University Press, New York, 289 pp.

Kaimal, J.C., Gaynor, J.E., Zimmerman, H.A., Zimmerman, G.A.: 1990, 'Minimizing flow distortion errrors in a sonic anemometer', *Boundary-Layer Meteorol.* **53**, 103-115.

Lenschow, D.H., Mann, J., Kristensen, L.: 1994, 'How long is long enough when measuring fluxes and other turbulence statistics?', *J. Atmos. Ocean. Technol.* **11**, 661-673.

Leuning, R., Judd, M.J.: 1996, 'The relative merits of open- and closed path analysers for measurements of eddy fluxes', *Global Change Biol.* **2**, 241-254.

Lorenc, A.C., Hammon, O.: 1988, 'Objective quality control of observations using Bayesian methods. Theory, and a practical implementation', *Quart. J. Roy. Meteorol. Soc.* **114**, 515-544.

Lumley, J.L., Panofsky, H.A.: 1964, *The structure of atmospheric turbulence*, Interscience Publishers, New York, 239 pp.

Mahrt, L.: 1991, 'Eddy asymmetry in the sheared heated boundary layer', *J. Atmos. Sci.* **48**, 472-492.

Mahrt, L.: 1998, 'Flux sampling errors for aircraft and towers', *J. Atmos. Ocean. Technol.* **15**, 416-429.

Mahrt, L., Moore, E., Vickers, D., Jensen, N.O.: 2001a, 'Dependence of turbulent and mesoscale velocity variances on scale and stability', *J. Appl. Meteorol.* **40**, 628-641.

Mahrt, L., Vickers, D., Sun, J.: 2002, 'Spatial variations of surface moisture flux from aircraft data', *Adv. Water Res.* **24**, 1133-1142.

Mahrt, L., Vickers, D., Sun, J., Jensen, N.O., Jørgensen, H.: 2001b, 'Determination of the surface drag coefficient', *Boundary-Layer Meteorol.* **99**, 249-276.

Mann, J., Lenschow, D.H.: 1994, 'Errors in airborne flux measurements', *J. Geophys. Res.* **99**, 14519-14526.

McMillen, R.T.: 1988, 'An Eddy Correlation Technique with Extended Applicability to Non-Simple Terrain', *Boundary-Layer Meteorol.* **43**, 231-245.

Moncrieff, J.B., Massheder, J.M., DeBruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Søgaard, H., Verhoef, A.: 1997, 'A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide', *J. Hydrol.* **188-189**, 589-611.

Obukhov, A.M.: 1960, 'O strukture temperaturnogo polja i polja skorostej v uslovijach konvekcii', *Izv. AN SSSR*, ser. Geofiz., 1392-1396.

Oncley, S.P., Businger, J.A., Itsweire, E.C., Friehe, C.A., LaRue, J.C., Chang, S.S.: 1990, 'Surface layer profiles and turbulence measurements over uniform land under near-neutral conditions', *9th Symposium on Boundary Layer and Turbulence*, Roskilde, Denmark, American Meteorological Society, 237-240.

Oncley, S.P., Foken, T., Vogt, R., Bernhofer, C., Kohsiek, W., Liu, H., Pitacco, A., Grantz, D., Ribeiro, L., Weidinger, T.: 2002, 'The energy balance experiment EBEX-2000', *15th Symposium on Boundary Layer and Turbulence*, Wageningen, NL, American Meteorological Society, 1-4.

Oncley, S.P., Friehe, C.A., Larue, J.C., Businger, J.A., Itsweire, E.C., Chang, S.S.: 1996, 'Surface-layer fluxes, profiles, and turbulence measurements over uniform terrain under near-neutral conditions', *J. Atmos. Sci.* **53**, 1029-1054.

Panofsky, H.A., Dutton, J.A.: 1984, *Atmospheric Turbulence - Models and methods for engineering applications*, John Wiley and Sons, Inc., New York, 397 pp.

Paw U, K.T., Baldocchi, D.D., Meyers, T.P., Wilson, K.B.: 2000, 'Correction of eddy-covariance measurements incorporating both advective effects and density fluxes', *Boundary-Layer Meteorol.* **97**, 487-511.

Raupach, M.R., Finnigan, J.J., Brunet, Y.: 1996, 'Coherent eddies and turbulence in vegetation canopies: the mixing-layer analogy', *Boundary-Layer Meteorol.* **78**, 351-382.

Rummel, U., Ammann, C., Meixner, F.X.: 2002, 'Characterizing turbulent trace gas exchange above a dense tropical rain forest using wavelet and surface renewal analysis', *15th Symposium on Boundary Layer and Turbulence*, Wageningen, The Netherlands, American Meteorological Society, 602-605.

Sakai, R., Fitzjarrald, D., Moore, K.E.: 2001, 'Importance of low-frequency contributions to eddy fluxes observed over rough surfaces.' *J. Appl. Meteorol.* **40**, 2178-2192.

Schmid, H.P.: 1997, 'Experimental design for flux measurements: matching scales of observations and fluxes', *Agric. For. Meteorol.* **87**, 179-200.

Shearman, R.J.: 1992, 'Quality assurance in the observation area of the Meteorological Office', *Meteorol. Mag.* **121**, 212-216.

Smith, S.R., Camp, J.P., Legler, D.M.: 1996, '*Handbook of Quality Control, Procedures and Methods for Surface Meteorology Data*', Center for Ocean Atmospheric Prediction Studies,TOGA/COARE, Technical Report 96-3, 60 pp. [Available from Florida State University, Tallahassee, FL, 32306-3041.].

Snyder, R.L., Spano, D., Paw U, K.T.: 1996, 'Surface renewal analysis for sensible and latent heat flux density', *Boundary-Layer Meteorol.* **77**, 249-266.

Stull, R.B.: 1988, *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, Dordrecht, Boston, London, 666 pp.

Sun, J., Howell, Esbensen, S.K., Mahrt, L., Greb, C.M., Grossman, R., LeMone, M.A.: 1996, 'Scale dependence of air-sea fluxes over the Western Equatorial Pacific', *J. Atmos. Sci.* **53**, 2997-3012.

Thomas, C., Foken, T.: 2002, 'Re-evaluation of Integral Turbulence Characteristics and their Parameterisations', *15th Symposium on Boundary Layers and Turbulence*, Wageningen, The Netherlands, American Meteorological Society, 129-132.

Trevino, G., Andreas, E.L.: 2000, 'Averaging intervals for spectral analysis of nonstationary turbulence', *Boundary-Layer Meteorol.* **95**, 231-247.

Vickers, D., Mahrt, L.: 1997, 'Quality control and flux sampling problems for tower and aircraft data', *J. Atmos. Ocean. Technol.* **14**, 512-526.

Vickers, D., Mahrt, L.: 2003, 'The cospectral gap and turbulent flux calculations', *J. Atmos. Ocean. Technol.***20**, 660-672.

Wichura, B., Buchmann, N., Foken, T.: 2002, 'Carbon dioxide exchange characteristics above a spruce forest', *25th Symposium on Agricultural and Forest Meteorology*, Norfolk, VA, American Meteorological Society, 63-64.

Wilczak, J.M., Oncley, S.P., Stage, S.A.: 2001, 'Sonic anemometer tilt correction algorithms', *Boundary-Layer Meteorol.* **99**, 127-150.

Wyngaard, J.C., Coté, O.R., Izumi, Y.: 1971, 'Local free convection, similarity and the budgets of shear stress and heat flux', *J. Atmos. Sci.* **28**, 1171-1182.

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Appendix E: Use of remotely sensed land use classification to improve an approach for the evaluation of complex micrometeorological flux measurement sites

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Summary

Long-term flux measurement sites are often characterized by a heterogeneous terrain, which disagrees with the fundamental theoretical assumptions for eddy-covariance measurements. An evaluation procedure to assess the influence of terrain heterogeneity on the data quality has been developed by Göckede et al. (2004), which combines existing quality assessment tools for flux measurements with analytic footprint modeling. In addition to micrometeorological input data, this approach requires information defining the land use structure and the roughness of the surrounding terrain.

The aim of this study was to improve the footprint based site evaluation approach by using high-resolution land use maps derived by Landsat ETM+ and ASTER satellite data. The influence of the grid resolution of the maps on the results was examined, and four different roughness length classification schemes were tested. Due to numerical instabilities of the analytic footprint routine, as an additional footprint model a Lagrangian stochastic footprint routine (Rannik et al., 2003) was employed. Application of the approach on two German FLUXNET sites revealed only weak influence of the characteristics of the land use data when the land use structure was homogeneous. For a more heterogeneous site, use of the more detailed land use maps derived by remote sensing methods resulted in distinct differences indicating the potential of remote sensing for improving the flux measurement site evaluation.

1 Introduction

Long-term measurement programs to study the exchange and the feedback mechanisms of carbon dioxide for a wide range of ecosystems (Valentini et al., 2000; Baldocchi et al., 2001) are an important instrument for the establishment of the global carbon budget (Houghton et al., 2001). The eddy-covariance technique is the common tool for the assessment of the exchange fluxes (e.g. Aubinet et al., 2000; Baldocchi et al., 2000). However, this tech-

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nique requires certain basic assumptions such as horizontal homogeneity, steady-state, and non-advective conditions (e.g. Kaimal and Finnigan, 1994; Foken, 2003). These requirements are often not fulfilled, since many measurement sites are selected according to ecological relevance and not according to terrain homogeneity. Therefore, a site dependent quality control is needed to allow for a realistic interpretation of the flux measurements (Foken et al., 2004).

A quality check addressing the problem of horizontal heterogeneity at flux monitoring sites was first developed by Foken et al. (2000) by integrating a footprint approach with parameters characterizing the turbulent flow regime. This concept was improved by Göckede et al. (2004), who developed an approach for the evaluation of complex flux measurement sites situated in heterogeneous terrain. Their procedure combines footprint modeling based on the analytic flux source area model (FSAM) by Schmid (1994, 1997) with a modified version of the Foken and Wichura (1996) quality assessment scheme for eddy-covariance measurements. Rebmann et al. (2005) successfully applied this approach for a comparison study of 18 CARBOEUROFLUX eddy-covariance measurement sites. As input data, in addition to micrometeorological flux data the software requires a land use map and roughness length information of the terrain surrounding the flux tower site. For existing evaluation procedures (Rebmann et al., 2005), topographical maps were used as a basis for the required land use information. However, this method was time-consuming and resulted in maps of fairly low resolution and only few differentiated land use classes. In addition, the maps used to read out the land use information were often several years old and did not necessarily represent the exact situation during the time of measurement.

This study aimed at the evaluation of the influence of the land use information on the accuracy of the site evaluation approach. Satellite imagery was applied for a supervised land use classification as a standard remote sensing method (Lillesand and Kiefer, 2000) in order to process land use maps with different spatial resolutions of the area surrounding the measurement sites. In contrast to the use of topographical maps, remote sensing has the potential to allow for a more realistic and objective description of the terrain and therefore permits a more advanced parameterization in regional micrometeo-rological models (Hasager et al., 2003). This property of satellite land use classification has already been used in combining flux assignment and climate models in several studies (e.g. Scherer et al., 1996; Hasager and Jensen, 1999; Oechel et al., 2000; Hasager et al., 2003; Soegaard et al., 2003). To allow for a routine application of the site evaluation procedure, e.g. in the context of the CarboEurope project, the employed remote sensing data had to be low-cost and commercially available, and a basic and rather time-saving data processing procedure had to be chosen to make sure that the overall procedure remains practical and easy-to-use.

In order to test the applicability of remotely sensed land use classification to improve the site evaluation approach by Göckede et al. (2004), as study areas for this analysis we employed the two German FLUXNET sites Hainich, as an example of a site with a homogeneous land use structure, and the more heterogeneous Waldstein Weidenbrunnen site. Special attention was paid to the effect of grid resolution of the maps on the site evaluation approach. Additionally, the use of different roughness length classification schemes on the site evaluation output was analyzed. As the analytic footprint model usually employed in the site evaluation approach (Göckede et al., 2004) has some shortcomings when operated with high roughness lengths, an additional Lagrangian stochastic footprint model by Rannik et al. (2003) was used for the analysis of grid resolution and roughness length classification.

2 Site description

The first flux measurement site used for this study, Hainich, is located in the hilly region of the Central Upland Range of Germany, which forms the southwestern edge of several ranges of elevation between 400 and 500 m a.s.l. The flux measurement tower with a height of 43.5 m is part of the CarboEurope network (site DE-Hai), and is placed on a gentle north-facing slope (2-3° inclination) (Knohl et al., 2003) within the "Hainich National Park" (51°04'45'' N, 10°27'07'' E, 440 m a.s.l.). The forest surrounding the tower is dominated by beech (*Fagus sylvatica*), which is the land use type intended to be observed, as well as other interspersed deciduous species. Maximum tree height varies between 30 and 35 m. For the Hainich site, the time period from June 1st to August 31st, 2001 was used as the observation period.

The second flux measurement site, Waldstein Weidenbrunnen (Gerstberger et al., 2004), is located in the western part of the Fichtelgebirge mountains. The flux measurement tower (50°08'32" N, 11°52'03" E, 775 m a.s.l.) with the sensors employed here mounted at 33 m is also part of the CarboEurope network (DE-Wei). The surrounding terrain is hilly with moderate slopes, and the most important land use heterogeneities affecting the measurements are the large clearing situated approximately 250 m west of the tower and the summit of the 'Großer Waldstein' (877 m a.s.l.) that lies at a distance of about 1700 m in the south-westerly sector. Spruce (*Picea abies*) represents the dominant tree species of the forest, while the maximum tree height is around 19 m in the immediate vicinity surrounding of the tower. The dataset for the Waldstein Weidenbrunnen site covered the period May 1st to August 31st, 1998.

3 Remote sensing application

3.1 Land use classification procedure

To keep the overall site evaluation approach practical and widely applicable, the remote sensing method adopted must be based on a simple land use classification approach with sufficient accuracy. It should be applicable to standard image processing software, while the data sources had to be commercial available and low-cost, and must provide suitable spatial and spectral characteristics. For this reason, a standard supervised land use classification of commercially available multi-spectral satellite data of intermediate spatial resolution (Landsat ETM+, Enhanced Thematic Mapper plus, 30 m resolution, and ASTER, Advanced Spaceborne Thermal Emission and Reflectance, 15 m resolution) was used.

For the Hainich site, two Landsat ETM+ scenes with different phenological stages (April and July 2001) were chosen to perform a multi-temporal approach (e.g. Grignetti et al., 1997; Xiao et al., 2002). Because of frequent cloud cover in the year 2003 it was not possible to acquire several cloud-free images for the Waldstein Weidenbrunnen site, thus only one ASTER scene (April 2003) was available for the classification. In order to assure the precise geographic location, the scenes were georeferenced using topographical maps (scale 1:10000 and 1:50000).

An atmospheric correction was performed for the Landsat scenes using the ENVI stand alone program ACORN (Atmospheric CORrection Now) since here a multi-temporal approach was applied in contrast to the only one ASTER scene where a classification does not necessarily require atmospheric correction (Song et al., 2001). Within the classification process, the selection of training areas for all discernable classes was mainly based on a priori knowledge, and on the visual interpretation of color composites of Normalized Difference Vegetation Index (NDVI) images as well

Table 1. Description of land use classes existing at the two different sites (HA: Hainich site, WA: Waldstein Weidenbrunnen site).

Class	HA	WA	Description
conifer	x	x	conifer trees of several age classes, mainly composed of spruce
deciduous	x		mixed deciduous trees, mainly composed of beech
clearings	x	x	clearings, small open areas with sparsely scattered bushes or trees
shrubs	x		pioneer woodland with small trees, dense shrubs
grassland	x	x	permanent grassland, pasture land
summer crops		x	crops with peak in development in late summer, bare soil in spring
winter crops	x	x	crops their peak in development in early summer, harvested in July
winter crops2	x		like winter crops, but of short growth height, harvested before July
bare soil	x		non-vegetated area, partly sparsely covered with grassy patches
settlement	x	x	rural settlements, buildings, sealed areas
quarry		x	area of mining activities

as ratio images of Band 7 and Band 5. In order to obtain a representative set and to avoid illumination effects of the topography, the training areas were equally distributed over the entire scenes and were located on different sun expositions. Additionally, information from ancillary data such as topographic maps 1:10000, orthophotos, and a panchromatic Band of IKONOS (only for the Hainich site) was used due to its high spatial resolution for the validation of the identified training areas. To assess the quality of the selected training areas, the Jeffries-Matusita and Transformed Divergence Measures (Richards, 1993) were calculated. Their values (up to 2.0) indicate the separability of the training areas. Therefore, those training areas with values smaller than 1.9 were excluded from further processing, as were bands with high redundancy in the correlation matrix.

The actual classification was performed using the standard classifier, i.e. the maximum likelihood classifier (Richards, 1993) which has been proven to perform well (e.g. Smits et al., 1999). The probability threshold was defined as 0.95. The accuracy of the classification was verified using different statistical tests, including the calculation of the confusion matrix (contingency) (e.g. Congalton, 1991; Stehmann, 1997; Smits et al., 1999), the overall accuracy, and the kappa coefficient provided by ENVI. These statistics were performed using selected training areas as ground truth classes.

3.2 Land use classification results

Compared with the original method using topographical maps which in its basic version classified only two land use classes, i.e. the land use type intended to be observed (thereafter referred to as area of interest, AOI) and others, the remote sensing method allowed differentiation of the area into nine land use classes for the Hainich site and seven for the Waldstein Weidenbrunnen site (Table 1). The results obtained in the classification of the satellite images, for both Landsat ETM+ and ASTER, are illustrated in Fig. 1. The dominant land use class of the Hainich scene is deciduous forest (Table 2). It covers more than half (57.0%) of the total area (45 km²). Together with the land use classes shrubs (18.6%) and clearings (9.9%), it delineates roughly the same borders as the Hainich National Park. The dominant land use class of the Waldstein Weidenbrunnen site is the land use class conifer, covering more than 60% of the total classi-

Table 2. Class summary of different resolution maps as percentage of both the Hainich and the Waldstein Weidenbrunnen sites. Note the different resolution maps of the Hainich site, which start at only 30 m due to the lower resolution of Landsat ETM+ as compared to ASTER which starts at 15 m.

Resolution	**15m**	**30m**	**50m**	**75m**	**100m**	**30m**	**50m**	**75m**	**100m**	**150m**
[%]	*Waldstein Weidenbrunnen*					*Hainich*				
conifer	**61.1**	**61.1**	**61.0**	**61.2**	**61.1**	0.9	0.9	1.0	0.8	0.8
deciduous	-	-	-	-	-	**57.0**	**57.0**	**57.0**	**57.3**	**57.5**
clearings	12.3	12.2	12.1	12.0	11.9	9.9	9.9	9.8	10.0	10.6
shrubs	-	-	-	-	-	18.6	18.5	18.6	18.3	18.3
grassland	5.6	5.6	5.5	5.7	5.6	6.1	6.2	6.2	6.0	5.6
summer crops	6.5	6.5	6.6	6.6	6.7	-	-	-	-	-
winter crops	6.2	6.2	6.4	6.3	6.6	0.9	0.9	0.9	0.8	0.9
winter crops2	-	-	-	-	-	3.3	3.3	3.3	3.4	3.5
bare soil	-	-	-	-	-	0.3	0.3	0.2	0.3	0.3
settlement	4.8	4.9	4.9	5.0	5.0	0.8	0.8	0.7	0.7	0.6
quarry	0.3	0.3	0.3	0.4	0.4	-	-	-	-	-
unclassified	3.2	3.2	3.1	3.0	2.7	2.3	2.2	2.3	2.3	1.8
total area [km²]	Waldstein:		**36.18**							
	Hainich:		**45.00**							

fied area of about 36 km². This large forested area is only intercepted by the land use classes clearings (12.3%) and quarry (0.3%).

In general, both land use classifications reach high overall accuracy of above 92% (Hainich site: 92.3%, Waldstein Weidenbrunnen site: 98.6%). However, low accuracy is achieved by the land use class clearings, due to the heterogeneity within this class and shading error, especially in the case of the Hainich site (Reithmaier, 2003). As for the Waldstein Weidenbrunnen site, the accuracy of the land use class clearings has to be treated with caution due to the early acquisition time of available satellite data. Parts of this class could belong to the land use class conifer, because in both patches with more open canopies and windthrow areas, understory vegetation can be detected by the satellite, resulting in a spectral reflection similar to that of clearings.

The obtained land use classifications, with spatial resolutions of 30 m for the Hainich site and 15 m for the Waldstein Weidenbrunnen site, were adopted as the basic maps for producing additional resolution maps (30 m, 50 m, 75 m, 100 m and 150 m) that were subsequently used as land use information input. For the Waldstein Weidenbrunnen site, the resolution of the land use classification performed with topographical maps was 100 m; therefore, only maps with a resolution of up to 100 m were produced for this site. The overall picture of the land use distribution is not significantly changed through the resampling method nearest neighbor. In principle, the choice of the grid resolution of the maps in the described range affects the percentage composition of the land use classes only in the first decimal place; the overall picture stays the same for all maps (Table 2).

4 Footprint analysis

4.1 Footprint models

The footprint routine used for the basic analyses in this study is the Eulerian analytic flux source area model (FSAM) as presented by Schmid (1994, 1997), which is based on the analytical model by Horst and Weil (1992). It employs K-theory and an analytical solution of the Eulerian advection-diffusion equation by van Ulden (1978). As common for analytical footprint models (e.g. Schuepp et al., 1990; Horst and Weil, 1992, 1994), FSAM is restricted to surface layer scaling and horizontally homogeneous flow conditions (e.g.

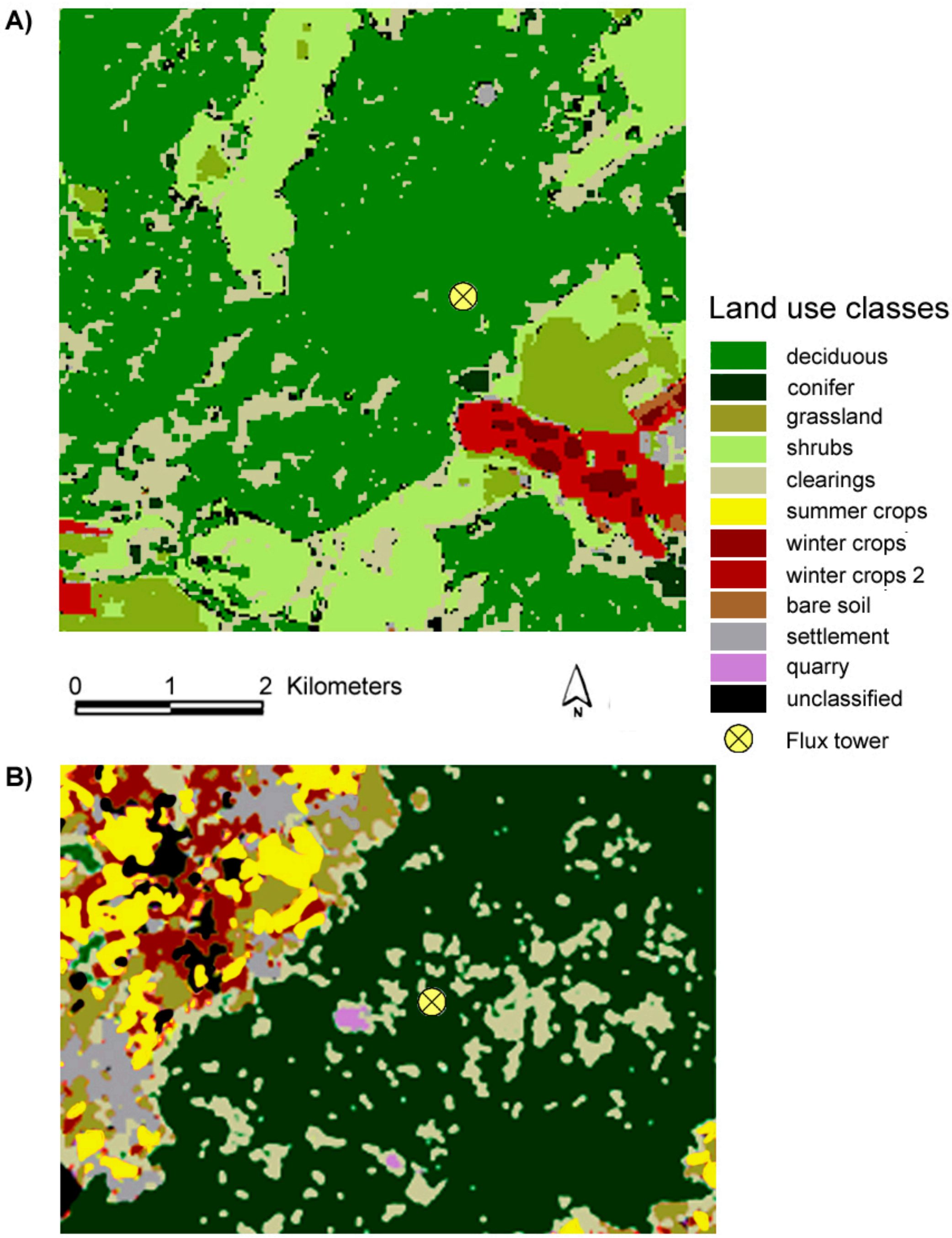

Fig. 1. Land use classification maps of the Hainich site (A) with 30 m resolution and the Waldstein Weidenbrunnen site (B) with 15 m resolution.

Schmid, 2002). It does not take into account turbulent diffusion along the mean wind and assumes Gaussian distribution in the crosswind direction. Vertical flux divergences are omitted. Due to the implementation of a surface layer dispersion model by Gryning et al. (1987) to address the crosswind and vertical concentration distribution functions, FSAM can no longer be analytically solved (Schmid, 1994). Still, the model allows the determination, with reasonable computational expense, of the source area for a specific measurement. Although horizontal homogeneity is often not attainable, the mathematical simplicity and the two-dimensional output of the footprint distribution still make FSAM a useful tool for the examination of complex measurement sites.

The second footprint model used in this study is the Thomson (1987) three dimensional Lagrangian stochastic trajectory model of

Langevin type (e.g. Wilson et al., 1983; Wilson and Sawford, 1996). The simulations are performed releasing $5 \cdot 10^4$ particles from a height close to the ground, which are tracked until the upwind distance accounted for approximately 90 percent of the total flux. The particles are dispersed by turbulent diffusion in vertical, along mean wind and cross mean wind directions. Furthermore, they are carried downwind by horizontal advection. The particles tending downwards are perfectly reflected at the height z_0. The parameterization of the flow statistics and the effect of stability on the profiles were in line with those used in Rannik et al. (2003). The stochastic estimator of the flux footprint function at upwind distance x and cross wind location y, averaged over a small area $\Delta x \Delta y$, is given by Kurbanmuradov et al. (1999) or Rannik et al. (2000, 2003). To save computation time, the flux footprint estimators are pre-calculated for ten stability classes, 23 roughness lengths, and ten observation heights, and subsequently stored into tables of weighting factors.

The determination of the source area using both footprint models is performed for individual 30-minute measurements of the investigated datasets. In the case of the FSAM-model, due to certain restrictions, a portion of the input data set cannot be processed. Such problems occur mostly during stable stratification, when the computed source area grows to an extent that destabilizes the numerical algorithms. The effect leads to a certain bias in the input data set, because a considerable number of the nighttime situations are excluded from the analysis. The relevance of this effect on the site evaluation approach is described by Rebmann et al. (2005) and Göckede et al. (2004). The breakups of the FSAM model, especially for very high roughness lengths, are so frequent that a sound statistical evaluation of the influence of different roughness length classification schemes is no longer possible.

4.2 Roughness length assignment

To facilitate the read out of information provided by land use maps, the footprint routines have been integrated into a software tool designed for this purpose. For each specific measurement, with respect of the actual wind direction, the 90 percent source weight function is projected onto the maps to assign a weighting factor indicating its relative influence on the specific flux measurement to each of the grid cells. Subsequently, a weighted roughness length is computed for each individual measurement, and the assigned weighting factors are summed up for each individual land use class to assess the flux contribution of each of the land use classes within the source area. For more detailed information, please refer to Göckede et al. (2004).

To test the influence of different averaging procedures, two different versions of the software have been applied in the course of this study. The first version reads in one map each for roughness length and land use, while the second version just makes use of a land use map and assigns a user defined fixed roughness length value to each of the land use classes. In the first version, the information provided by the roughness length map has previously been averaged for each pixel according to a flux aggregation method proposed by the European Wind Atlas (Troen and Petersen, 1989). This flux aggregation is not applied in the second version, in which the roughness lengths that are assigned to the various land use classes were not previously averaged. Within the software itself, a parameter aggregation is performed for both versions. The effect of the aggregation procedure is discussed by Göckede et al. (2004).

4.3 Roughness length classification

The investigation of the influence of different roughness length (z_0) classification schemes was based on four different references, which are listed in detail in Table 3. The first z_0

Table 3. Roughness length values (z_0) of land use classes according to different roughness length classifications (Davenport et al., 2000, *Fiedler cited in Hasager and Jensen, 1999, Wieringa, 1992, Troen and Petersen, 1989).

Land use classes	z_0 [m]			
Description	**Davenport 2000**	**Fiedler***	**Wieringa 1992**	**Troen&Petersen 1989**
conifer	1.0	0.9	1.6	0.4
deciduous	2.0	1.2	1.7	0.4
clearings	0.2	0.004	0.35	0.1
shrubs	0.5	0.3	0.45	0.4
grassland	0.03	0.08	0.06	0.03
summer crops	0.25	0.09	0.18	0.1
winter crops	0.1	0.12	0.09	0.1
winter crops2	0.25	0.09	0.18	0.1
bare soil	0.005	0.03	0.004	0.03
settlement	2.0	0.5	0.7	0.4
quarry	0.2	0.004	0.35	0.1
unclassified	0	0	0	0

length classification used is the one of the European Windatlas (Troen and Petersen, 1989) which was developed for wind energy applications and as such applies mainly to open terrain. Larger forested areas are assigned a roughness length value of 0.4 m, which is a very low estimate compared to other classification schemes and measured values (see e.g. Wieringa, 1992). The roughness length values proposed by the second reference, Fiedler cited in Hasager and Jensen (1999), are field measurements of micrometeorological field observations made in various land cover types within the region of the Upper Rhine Valley, Germany. Used as a third z_0 classification are roughness length measurements proofed for quality by Wieringa (1992) from several hundred original publications and compiled for selected ranges of z_0 values observed in studies deemed of high quality. The last roughness length classification, developed by Davenport et al. (2000), consists of effective roughness lengths z_{0eff} in contrast to the other three classifications mentioned above. Effective roughness lengths characterize not only the surface roughness of a homogenous field, but also describe landscape roughness with wake-producing obstacles. Therefore, the z_{0eff} value may be larger than the average of z_0 for all patches (Wieringa, 1992).

5 Results and Discussion

5.1 Results for Area of Interest (AOI) comparing the topographic based (original) and remote sensing method

In a first analysis, flux contributions of defined land use were calculated for both the original method based on topographic maps (Rebmann et al., 2005) and the remote sensing method of same spatial resolution. For this analysis, only the analytic FSAM was applied, thus mainly the non-stable cases were well-represented due to the aforementioned numerical instabilities of the software.

Of particular interest was the flux contribution of the area of interest (AOI) to the measured fluxes. In the case of the Hainich site, which will be of main interest in this section, the contribution of AOI (deciduous forest)

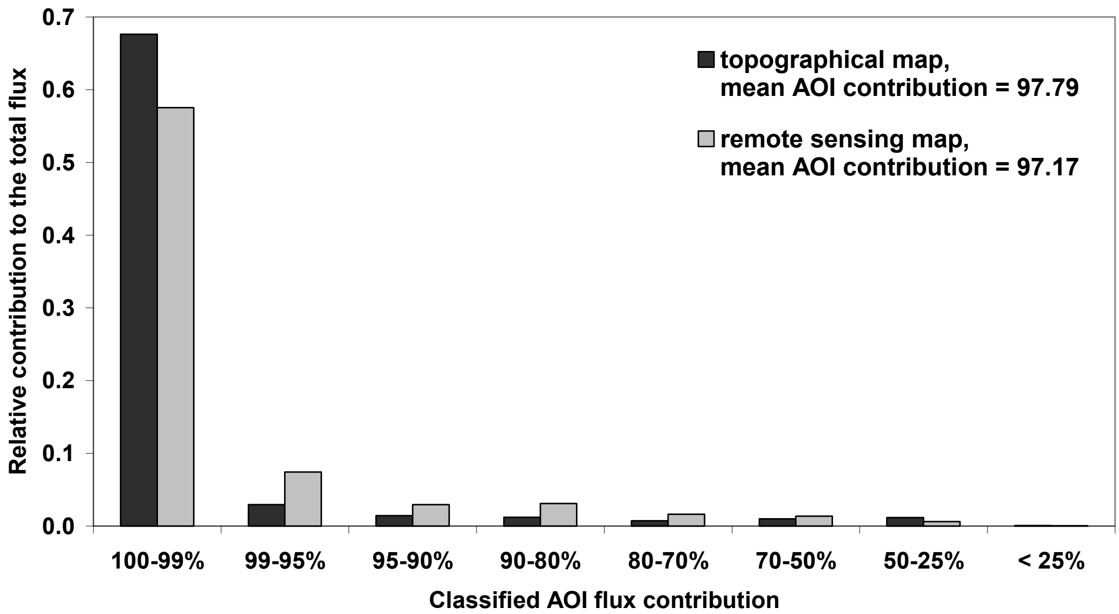

Fig. 2. Relative flux contribution of area of interest (AOI) to the measured flux at the Hainich site for both the original approach (topographical map) and a remote sensing map. Percentage of processed data sets: Analysis with topographical map: 76.0%; Analysis with remote sensing map: 74.6%.

varied from 100% to below 50%, depending on stratification and wind direction. For the visualization, the percentage flux contribution results of AOI were sorted into eight percentage classes (100-99%, 99-95%, 95-90%, 90-80%, 80-70%, 70-50%, 50-25%, below 25%), yielding their relative contribution to the total flux of the observation period. A result of 100% represents a perfect match, i.e. the source area was composed only of the land use type intended to be observed.

For the Hainich site, the comparison of the flux contribution classes of the remote sensing map with the original method based on topographical maps revealed a similar tendency for both approaches (Fig. 2). High relative contribution to the total flux was found in the highest percentage class, whereas the sum of all lower percentage classes only gained a minor relative contribution. The difference within the highest percentage class between the original data set and the remote sensing map reached about 0.10. As for the mean value of the AOI flux contribution, almost no differences are to be found, indicating that the effect of different maps on individual measurements is only small. In general, deviations occur mainly during stable stratification, when source areas may be so large that they include also heterogeneous parts of the surrounding area.

For the Waldstein Weidenbrunnen site, the high contribution from land use classes other than AOI reveals the more heterogeneous land use structure at this flux measurement site in contrast to that at the Hainich site. In general, only a contribution to the total flux of 0.28 was found in the highest percentage class (original data set), whereas the AOI flux percentage classes above 80% had a total sum of 0.70. Using the remote sensing data set, the results shift towards the lower percentage classes, with a peak within the percentage class 70-50%. The highest percentage class only gained a contribution to the total flux of 0.03, while the classes above 80% AOI contribution sum up to 0.26. Here, the differentiation between different stratification cases did not deliver a pronounced tendency as observed for the Hainich site.

When comparing the two different flux measurement sites, the effect of using remote sensing data sets was twofold. While for the Hainich site the greater detail due to the im-

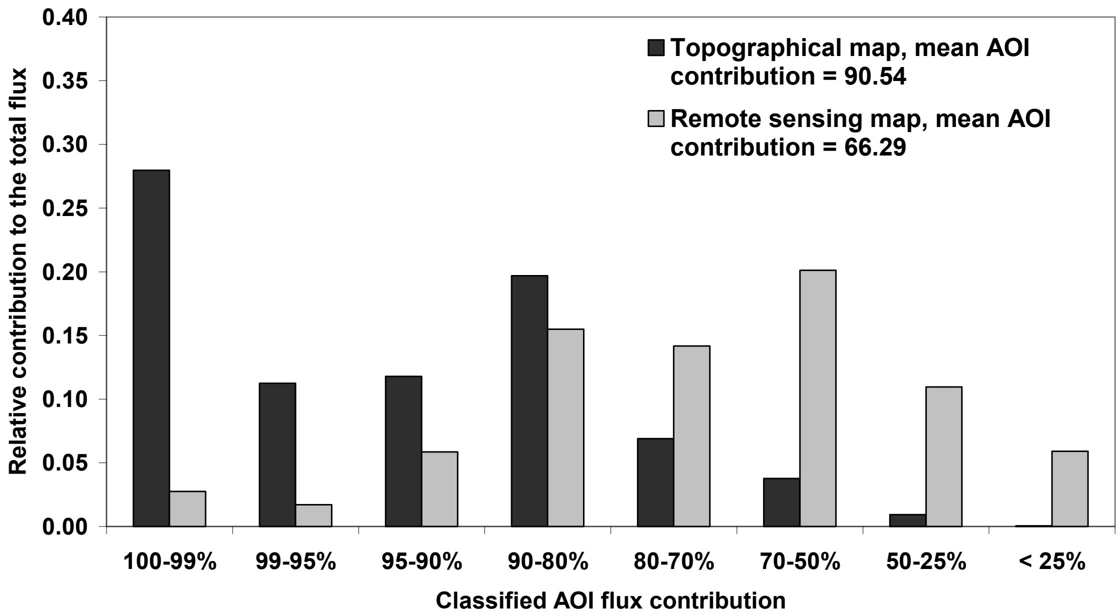

Fig. 3. Relative flux contribution of area of interest (AOI) to the measured flux at the Waldstein Weidenbrunnen site of both original and remote sensing data sets. Percentage of processed data sets: Analysis with topographical map: 82.3%; Analysis with remote sensing map: 76.9%.

proved land use classification did not change the results significantly, markedly different results were found for the Waldstein Weidenbrunnen site. It should be noted that due to illumination the results obtained for the Hainich site using remote sensing methods might be biased by partial misclassification of the land use class clearings within the deciduous forest. This would mean that the area of interest within the remote sensing maps was even larger than described, approaching the AOI percentage of the original land use map. This reinforces the finding that, in the case of the homogeneous Hainich site, the simple approach of a land use classification using topographic maps delivers acceptable results. Regarding the more heterogeneous Waldstein Weidenbrunnen site, the differing results between the original and the remote sensing approaches reflect both possibilities and problems presented by a more detailed land use classification using simple remote sensing methods. The maps derived from ASTER data revealed a considerable number of clearings in an area that was displayed as homogeneous forest in the topographical maps. When the remote sensing method is applied, the resulting reduction of the AOI percentage causes the observed low flux contribution of the AOI (Fig. 3). However, as in this case the assignment of clearings is somewhat questionable due to the use of the single-temporal approach, the significance of the differences found is reduced. If the clearing areas were added in their entirety to the AOI, the comparison of both approaches would resemble the results for the Hainich site. Additionally, it should be noted that the potential influence of the clearing areas on the flux measurements of CO_2 might be limited.

5.2 *Results for different grid resolutions of the map*

For all spatial resolutions, the flux contributions of the AOI were computed with the second version of the software tool used for this investigation, wherein the roughness length values were directly assigned to a certain land use class. However, in the case of the two study sites, the differences between the results of the site evaluation approach using the two aggregation schemes were found to be negligible (Reithmaier, 2003). A more detailed study

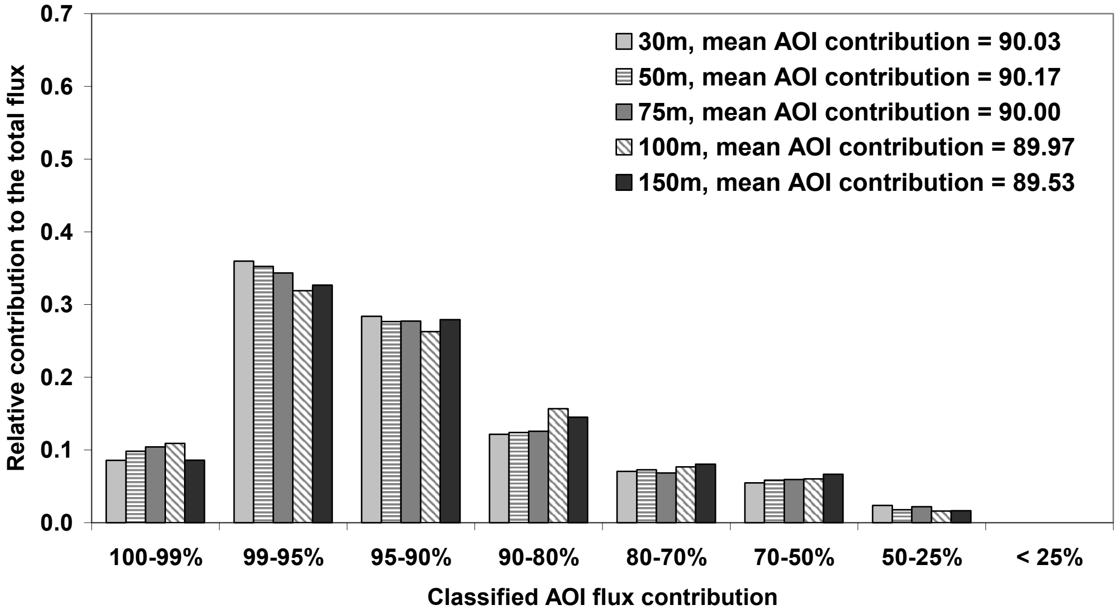

Fig. 4. Relative flux contribution of AOI to the measured flux for different grid resolutions at the Hainich site. As the analysis was performed with the Lagrangian stochastic footprint model, 100% of the available data set was processed.

of the implications of the aggregation procedure is beyond the scope of this study, but will be the subject of future analyses.

In order to exclude the effects introduced by the breakup of the analytic FSAM, and to maximize the available data set, the footprint model portion of the study was performed with the Lagrangian stochastic model of Rannik et al. (2003). Besides the numerical stability, differences between this model and the analytical FSAM occur mainly because of their different treatment of alongwind diffusion and the effects of flow within the canopy. In FSAM, which does not take into account alongwind diffusion or within canopy flow, the typical source area starts at a certain distance upwind of the tower, with the far end having a comparably limited extension in the upwind direction. In contrast to this, the inclusion of alongwind diffusion effects in the Lagrangian stochastic model, as well as the consideration of flow effects within the canopy, move the peak of the source area closer to the mast so that even some downwind areas are included, while the tail of the function, with only very small flux contributions, stretches very far in the upwind direction. As a consequence, for a homogeneous site such as Hainich, the average results for the flux contribution of the AOI are better for the stochastic model, as the source weight function concentrates on the uniform areas close to the mast. At the same time, because the long upwind extension of the source weight function often includes some other land use classes, AOI flux contributions of more than 99% are rarely found.

A comparison of the maps with different spatial resolutions was again performed in order to analyze the percentage classes of the flux contribution of the area of interest (AOI) to the total flux. For the Hainich site, the findings are that similar results are produced for all resolutions. As shown in Fig. 4 for the Lagrangian stochastic model, the highest relative contribution to the total flux is found for the AOI in the percentage class 99-95%, while for all grid resolutions, about 85% of all measurements belong to the percentage classes above 80%. The reason for deviating evaluations for the same site, as displayed in Fig. 2 (FSAM) and Fig. 4 (Lagrangian stochastic model), is to be found in the different characteristics of the source areas as explained in the previous passage. The higher mean AOI contributions cal-

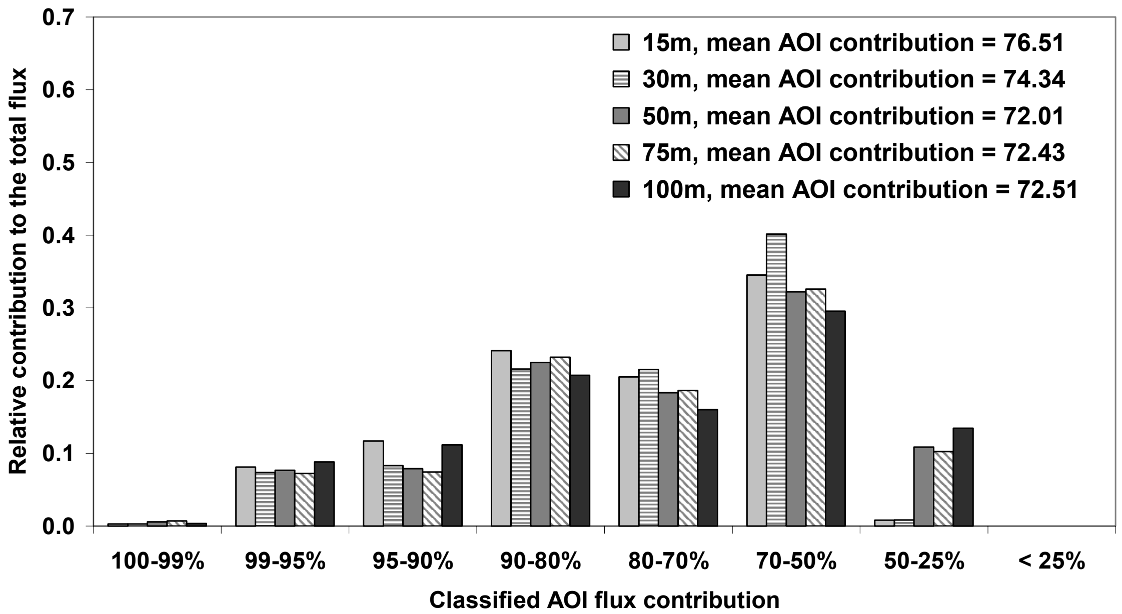

Fig. 5. Same as Fig. 4, for the Waldstein Weidenbrunnen site.

culated by the FSAM model are a consequence of the numerical instabilities, which lead to the exclusion of many stable cases with considerable flux contribution of land use classes other than AOI. In general, for both footprint models no significant trends for higher or lower flux contributions of AOI could be found when modifying the grid resolution. A differentiation in the various stratification cases did not deliver considerable additional information (Reithmaier, 2003).

In contrast to the Hainich site, most of the AOI flux contribution of the Waldstein Weidenbrunnen site (Fig. 5) is located in lower percentage classes (between 50% and 90%) for all grid resolutions. Only a slight trend towards higher mean AOI flux contributions can be observed when running the software with the higher grid resolutions, while there is practically no difference to be found between the grid resolutions 50 m, 75 m, and 100 m. In general, as found at the Hainich site, the composition of flux contribution classes does not show any significant trend when the resolution of the grid is changed.

A parameter that strongly influences the results when changing the grid resolution is the definition of the tower position within the map. This position is defined only by the pixel coordinates within the site evaluation software, and cannot be defined more precise within the subpixel domain. Thus, its uncertainty rises with decreasing grid resolution because, for example, with a grid size of 100 m, the tower might be anywhere within a distance of +/-50 m from the specified location. To test the influence of the tower position, analyses with a shifted tower position were performed using the 15 m resolution map of the heterogeneous Waldstein Weidenbrunnen site. In four different model runs (results not shown), the tower position was moved by three cells in each main wind direction, corresponding to a horizontal distance of 45 m. The impact of the modified tower positions on the determination of the AOI flux contribution proved to be considerable. For individual AOI flux contribution classes, differences of up to 0.07 were observed between the original position and a position shifted by 45 m, while the averaged AOI flux contribution for the total data set varied by up to three percent. These results indicate that the differences in the AOI flux contribution found for model runs with different grid resolutions might be an effect in part of uncertainty when defining the tower position for low grid resolutions.

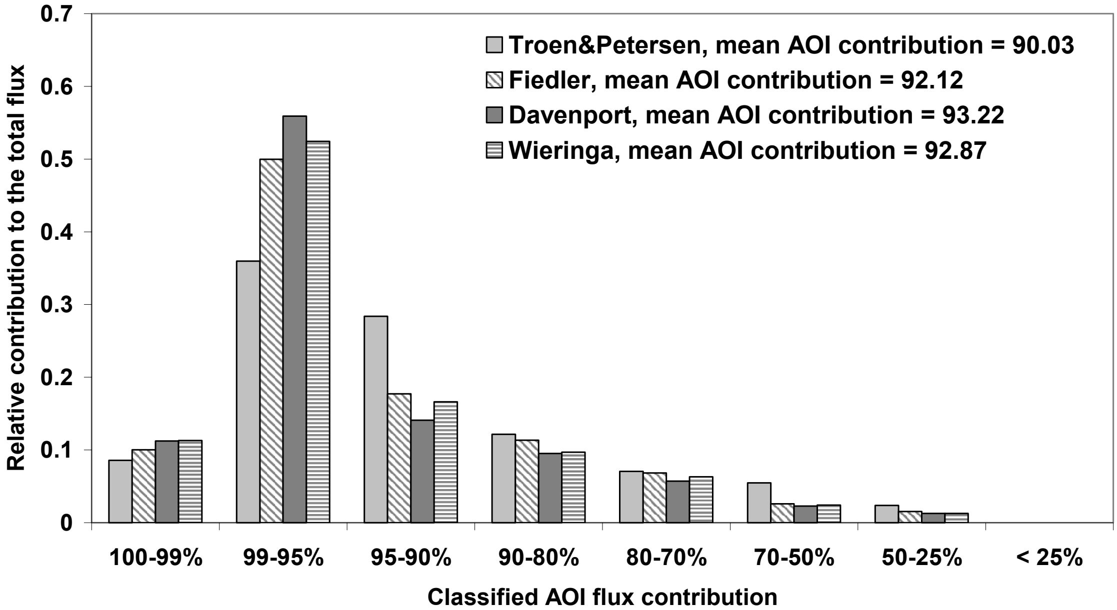

Fig. 6. Relative AOI contribution to the measured flux for four different roughness length classification schemes. Results were obtained with the Lagrangian stochastic footprint model and are based on the 30 m resolution land use map of the Hainich site. 100% of the available data set was processed.

5.3 Results of different roughness length classifications

To investigate the impact of different roughness length classification schemes on the evaluation result, other z_0 classifications found in literature besides the one by Troen and Petersen (1989), namely the Fiedler classification cited in Hasager and Jensen (1999), Wieringa (1992), and Davenport et al. (2000) (see Table 3), were applied to both the Hainich site and the Waldstein Weidenbrunnen site. The preparation of the roughness length maps based on these different z_0 classifications was similar to that for the maps with different resolutions mentioned in Section 5.2 (parameter aggregation), and all calculations were again performed with the Lagrangian stochastic footprint model. The maps with the highest resolution (Hainich: 30 m; Waldstein Weidenbrunnen: 15 m) were chosen for both sites. The assignment of roughness length values to the land use types distinguished by the remote sensing method is summarized in Table 3.

For the Hainich site, Fig. 6 displays the comparison of the influence of different roughness length assignment schemes on the site evaluation approach with respect to the flux contribution of the area of interest. For single AOI flux percentage classes, significant differences of up to 0.2 were found between different roughness length classification schemes. However, for the complete data set, the determination of the mean AOI contribution to the total flux measured only revealed differences of up to three percent between the schemes, indicating only small changes for individual measurements when modifying the roughness length assignment. Overall, the best results for the AOI flux contributions were found in the classification scheme with the highest z_0 value for the dominating land use type (deciduous), which, in case of the Hainich site, is the Davenport scheme. With higher roughness lengths, the source weight function determined by the footprint model is more contracted, with a peak closer to the measurement position. At sites such as Hainich, which are characterized by a homogeneous land use structure in the immediate vicinity of the tower, this contraction reduces the influence of heterogeneities such as clearings so that the

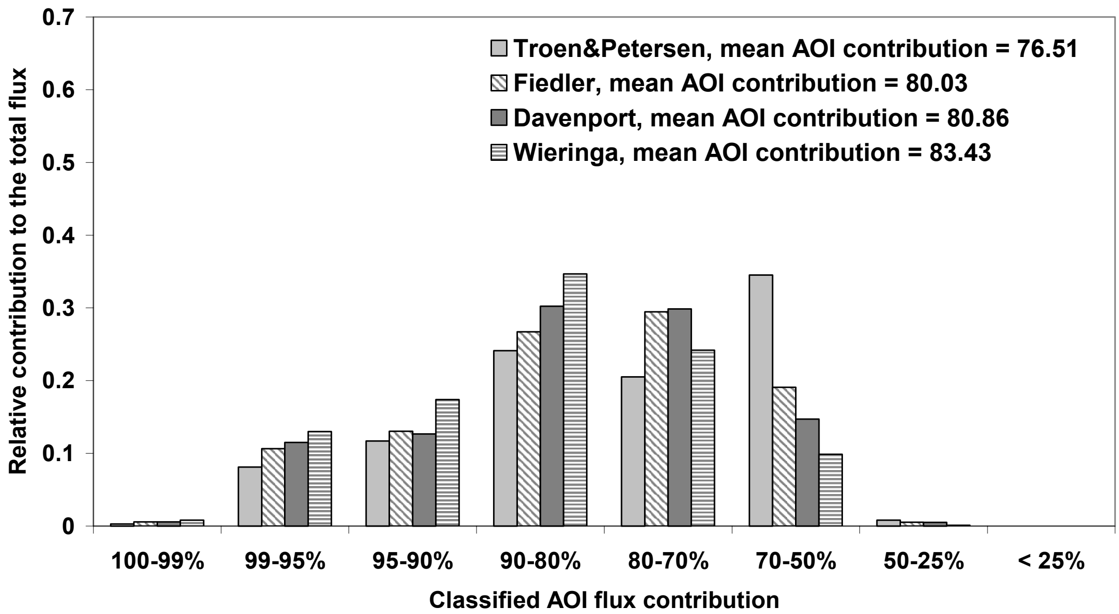

Fig. 7. Same as Fig. 6, for the Waldstein Weidenbrunnen site (based on 15 m grid resolution map).

flux contribution of AOI generally grows with higher roughness lengths.

For the Waldstein Weidenbrunnen site, Fig. 7 shows the comparison of the influence of different roughness length assignment schemes on the AOI flux. Overall, the same trends observed for the Hainich site were noted for Waldstein Weidenbrunnen. Again, the best results for the AOI flux contribution were found in the scheme with the highest z_0 value for the dominant land use type (conifer), which in this case is the Wieringa (1992) classification scheme. The differences between various schemes reached 0.25 for single AOI percentage classes, while variations of up to seven percent were found for the mean AOI flux contribution for the total data set. These higher deviances indicate that the choice of the roughness length assignment scheme has a larger impact on the model output at heterogeneous sites than at homogeneous sites such as Hainich. The importance of the choice of the roughness length assignment scheme is also made clear by the observation that when using the Troen and Petersen (1989) scheme with the lowest z_0 values, only about 65% of all measurements are assigned to the highest AOI percentage classes (> 80%), while with the Wieringa (1992) scheme more than 90% of all measurements are classified into that range.

6 Conclusions

In this study, we tested the applicability of satellite remote sensing derived land use maps as input for a footprint-based approach to evaluate complex micrometeorological flux measurements sites proposed by Göckede et al. (2004). As this approach is intended to provide a practical quality assessment tool that is applicable to various measurement sites, as a basic requirement the remote sensing data had to be commercially available and low-cost, while at the same time the procedure to derive land use maps from this information must be basic and timesaving. Thus, a simple land use classification method based on Landsat ETM+ and ASTER remote sensing data sets was applied to derive land use maps for the two German FLUXNET sites Hainich and Waldstein Weidenbrunnen, and the results of the site evaluation approach using these data were compared to those using the previously employed land use information read out from topographical maps. In addition, the study tested the effects of different grid resolutions of the maps and of the application of several roughness length assignment schemes on the output of the model.

A comparison of the site evaluation results based on land use information from topographical maps with those using a map derived from remote sensing data revealed no significant differences between both approaches for the homogeneous Hainich site. For the Waldstein Weidenbrunnen site, distinct differences were observed, which are mainly a consequence of the recording by the remote sensing method of several larger clearings in the forest areas, which were not identified in the topographical maps.

The test of different grid resolutions of the land use maps revealed a negligible influence of this parameter on the outcome of the site evaluation approach. Only for the heterogeneous Waldstein Weidenbrunnen site a slight tendency toward a higher influence of the area of interest was found when increasing the grid resolution. On the other hand, it could be shown that the correct specification of the tower position has a considerable influence on the model results when the land use structure in the region close to the tower is inhomogeneous. Since it was not possible in the site evaluation software employed here to specify the tower position in more detail in the subpixel domain, the best results could thus be produced using the map with the highest resolution available, which defined the tower position with the highest accuracy.

Applying the four different roughness length classification schemes in the context of the site evaluation approach revealed only a small influence on the output of the model for the homogeneous Hainich site, while distinct differences could be observed for the heterogeneous Waldstein Weidenbrunnen site. In general, different roughness length schemes caused significant differences for single percentage classes of the AOI, while the mean AOI flux contribution for the total data set varied by a few percent. Based on the results presented, a general recommendation cannot be made for the choice of a suitable scheme for a specific site.

Overall, for the two FLUXNET sites analyzed in this study it could be shown that the site evaluation results of the approach proposed by Göckede et al. (2004) using only simple topographical maps as a source for the land use information are generally valid when compared to the results derived with remote sensing information. However, the accuracy of the approach can be improved by the use of land use maps derived by remote sensing methods, which offer a higher horizontal resolution and a more detailed differentiation of land use classes for a larger area. Even using a simple remote sensing approach as described in this study, which suffers some additional uncertainty resulting in possible misclassification of pixels, more detailed site evaluation studies were possible and the overall processing time could be reduced. As a perspective for future analyses, utilizing high quality satellite data and advanced remote sensing methods, which was beyond the scope of this study, would offer the opportunity to extend the practical site evaluation approach to intensive process studies on heterogeneous sites, including the analysis of different age classes, tree species, and such.

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References

Aubinet M, Grelle A, Ibrom A, Rannik Ü, Moncrieff J, Foken T, Kowalski AS, Martin PH, Berbigier P, Bernhofer C, Clement R, Elbers J, Granier A, Grünwald T, Morgenstern K, Pilegaard K, Rebmann C, Snijders W, Valentini R, Vesala T (2000) Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Adv Ecol Res 30: 113-175

Baldocchi DD, Finnigan JJ, Wilson K, Paw U KT, Falge E (2000) On measuring net ecosystem carbon exchange over tall vegetation on complex terrain. Boundary-Layer Meteorol 96: 257-291

Baldocchi DD, Falge E, Gu L, Olson R, Hollinger D, Running S, Anthoni P, Bernhofer C, Davis K, Fuentes JD, Goldstein A, Katul G, Law BE, Lee X, Malhi Y, Meyers T, Munger JW, Oechel W, Pilegaard K, Schmid HP, Valentini R, Verma S, Vesala T, Wilson K, Wofsy S (2001) FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapour and energy flux densities. Bull Amer Meteorol Soc 82: 2415-2435

Congalton RG (1991) A review of assessing the accuracy of classifications of remotely sensed data. Remote Sens Environ 37: 35-46

Davenport AG, Grimmond CSB, Oke TR, Wieringa J (2000) Estimating the roughness of cities and sheltered country. In: 15th conference on probability and statistics in the atmospheric sciences / 12th conference on applied climatology, Ashville, NC, American Meteorological Society, 96-99

Foken T, Wichura B (1996) Tools for quality assessment of surface-based flux measurements. Agric For Meteorol 78: 83-105

Foken T, Mangold A, Rebmann C, Wichura B (2000) Characterization of a complex measuring site for flux measurements. In: Proceedings of the 14th Symposium on Boundary Layer and Turbulence, Aspen, CO, American Meteorological Society, 388-389

Foken T (2003) Angewandte Meteorologie, Mikrometeorologische Methoden. Springer, Berlin, Heidelberg, New York, 289 pp

Foken T, Göckede M, Mauder M, Mahrt L, Amiro BD, Munger JW (2004) Post-field data quality control. In: Lee, X, Massman, WJ, Law, BE (eds), Handbook of Micrometeorology: A guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp 181-208

Gerstberger P, Foken T, Kalbitz K (2004) The Lehstenbach and Steinkreuz catchments in NE Bavaria, Germany. In: Matzner, E (ed), Biogeochemistry of Forested Catchments in a Changing Environment, Ecological Studies, Vol. 172. Springer, Berlin, Heidelberg, New York, pp 15-44

Göckede M, Rebmann C, Foken T (2004) A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. Agric For Meteorol 127: 175-188

Grignetti A, Salvatori R, Casacchia R, Manes F (1997) Mediterranean vegetation analysis by multi-temporal satellite sensor data. Int J Remote Sens 18: 1307-1318

Gryning S-E, Holtslag AAM, Irwin JS, Sivertsen B (1987) Applied dispersion modelling based on meteorological scaling parameters. Atmos Environ 21: 79-89

Hasager CB, Jensen NO (1999) Surface-flux aggregation in heterogeneous terrain. Quart J Roy Meteorol Soc 125: 2075-2102

Hasager CB, Nielsen NW, Jensen NO, Boegh E, Christensen JH, Dellwik E, Soegaard H (2003) Effective roughness calculated from satellite-derived land cover maps and hedge-information used in a weather forecasting model. Boundary-Layer Meteorol 109: 227-254

Horst TW, Weil JC (1992) Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary-Layer Meteorol 59: 279-296

Horst TW, Weil JC (1994) How far is far enough - the fetch requirements for micrometeorological measurement of surface fluxes. J Atmos Ocean Technol 11: 1018-1025

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (2001) IPCC Third Assessment Report: Climate Change 2001. The scientific basis. Cambridge University Press, Cambridge, 944 pp

Kaimal JC, Finnigan JJ (1994) Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press, New York, 289 pp

Knohl A, Schulze ED, Kolle O, Buchmann N (2003) Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. Agric For Meteorol 118: 151-167

Kurbanmuradov O, Rannik Ü, Sabelfeld K, Vesala T (1999) Direct and adjoint monte carlo for the footprint problem. Monte Carlo Methods and Applications 5: 85-111

Lillesand TM, Kiefer RW (2000) Remote sensing and image interpretation. John Wiley and Sons, Inc., New York, 724 pp

Oechel WC, Vourlitis GL, Verfaillie J, Crawford T, Brooks S, Dumas E, Hope A, Stow D, Boynton B, Nosov V, Zulueta R (2000) A scaling approach for quantifying the net CO_2 flux of the Kuparuk River Basin, Alaska. Global Change Biol 6: 160-173

Rannik Ü, Aubinet M, Kurbanmuradov O, Sabelfeld KK, Markkanen T, Vesala T (2000) Footprint analysis for measurements over a heterogeneous forest. Boundary-Layer Meteorol 97: 137-166

Rannik Ü, Markkanen T, Raittila J, Hari P, Vesala T (2003) Turbulence statistics inside and over forest: Influence on footprint prediction. Boundary-Layer Meteorol 109: 163-189

Rebmann C, Göckede M, Foken T, Aubinet M, Aurela M, Berbigier P, Bernhofer C, Buchmann N, Carrara A, Cescatti A, Ceulemans R, Clement R, Elbers JA, Granier A, Grünwald T, Guyon D, Havránková K, Heinesch B, Knohl A, Laurila T, Longdoz B, Marcolla B, Markkanen T, Miglietta F, Moncrieff JB, Montagnani L, Moors E, Nardino M, Ourcival J-M, Rambal S, Rannik Ü, Rotenberg E, Sedlak P, Unterhuber G, Vesala T, Yakir D (2005) Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling. Theor Appl Climatol, doi: 10.1007/s00704-004-0095-y

Reithmaier L (2003) Application of remote sensing methods for micrometeorological site evaluation. Diploma Thesis, University of Bayreuth, Bayreuth, 150 pp

Richards JA (1993) Remote sensing Digital Image Analysis - An introduction. Springer, Berlin, Heidelberg, New York, 340 pp

Scherer D, Parlow E, Beha H-D (1996) Roughness parameter derivation from ERS-1 and Landsat-TM satellite data for the agglomeration of Basel/Switzerland. In: Parlow, E (ed), Progress in Environmental Remote Sensing Research and Applications. Balkema, Rotterdam, pp 325-329

Schmid HP (1994) Source areas for scalars and scalar fluxes. Boundary-Layer Meteorol 67: 293-318

Schmid HP (1997) Experimental design for flux measurements: matching scales of observations and fluxes. Agric For Meteorol 87: 179-200

Schmid HP (2002) Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. Agric For Meteorol 113: 159-183

Schuepp PH, Leclerc MY, MacPherson JI, Desjardins RL (1990) Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation. Boundary-Layer Meteorol 50: 355-373

Smits PC, Dellepiane SG, Schowengerdt RA (1999) Quality assessment of image classification algorithms for land-cover mapping: a review and a proposal for a cost-based approach. Int J Remote Sens 20: 1461-1486

Soegaard H, Jensen NO, Boegh E, Hasager CB, Schelde K, Thomsen A (2003) Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modelling. Agric For Meteorol 114: 153-173

Song C, Woodcock CE, Seto KC, Lenney MP, Macomber SA (2001) Classification and change detection using Landsat TM data: When and how to correct atmospheric effects? Remote Sens Environ 75: 230-244

Stehmann SV (1997) Selecting and interpreting measures of thematic classification accuracy. Remote Sens Environ 62: 77-89

Thomson DJ (1987) Criteria for the selection of stochastic models of particle trajectories in turbulent flows. J Fluid Mech 180: 529-556

Troen I, Petersen EL (1989) European Wind Atlas. Published for the Commission of the European Communities, Directorate General for Science, Research and Development (Brussels, Belgium). Risø National Laboratory, Roskilde, Denmark, 656 pp

Valentini R, Matteucci G, Dolman AJ, Schulze E-D, Rebmann C, Moors EJ, Granier A, Gross P, Jensen NO, Pilegaard K, Lindroth A, Grelle A, Bernhofer C, Grünwald T, Aubinet M, Ceulemans R, Kowalski AS, Vesala T, Rannik Ü, Berbigier P, Loustau D, Guomundsson J, Thorgeirsson H, Ibrom A, Morgenstern K, Clement R, Moncrieff J, Montagnani L, Minerbi S, Jarvis PG (2000) Respiration as the main determinant of carbon balance in European forests. Nature 404: 861-865

van Ulden AP (1978) Simple estimates for the vertical diffusion from sources near the ground. Atmos Environ 12: 2125-2129

Wieringa J (1992) Updating the Davenport roughness classificaton. J Wind Eng Ind Aerodyn 41: 357-368

Wilson JD, Legg BJ, Thomson DJ (1983) Calculation of particle trajectories in the presence of a gradient in turbulent-velocity variance. Boundary-Layer Meteorol 27: 163-169

Wilson JD, Sawford BL (1996) Review of Lagrangian stochastic models for trajectories in the turbulent atmosphere. Boundary-Layer Meteorol 78: 191-210

Xiao XM, Boles S, Liu JY, Zhuang DF, Liu ML (2002) Characterization of forest types in Northeastern China, using multi-temporal SPOT-4 VEGETATION sensor data. Remote Sens Environ 82: 335-348

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Appendix F:
Use of footprint modelling for the characterisation of complex measurement sites

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Abstract: Horizontal heterogeneity can significantly affect the flux data quality at monitoring sites with a complex terrain structure. In heterogeneous conditions, there is a violation of basic assumptions for the adoption of the eddy covariance technique, such as horizontal homogeneity, and non-advective conditions. In addition, uncertainty concerning the sources or sinks influencing a measurement compromises the data interpretation. The consideration of the spatial context of a measurement, defined by a footprint analysis, can therefore provide an important tool for data quality assessment.

This study presents an update of the footprint-based quality evaluation concept for complex flux measurement sites by Göckede et al. (2004). For the determination of the spatial context of the measurements, a forward Lagrangian stochastic trajectory model (Rannik et al., 2003) is used. In a pre-processing step, effective roughness lengths are determined with a flux aggregation model (Hasager and Jensen, 1999). Detailed terrain data is included by the use of remote sensing methods.

The approach determines spatial structures in the quality of flux data for varying meteorological conditions. These results help to identify terrain influences affecting the quality of flux data, such as dominating obstacles in the fetch, or slopes biasing the wind field, 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, allowing to check to what extent the measured fluxes at a site are representative for a specific type of land use.

Keywords: eddy covariance, flux aggregation, footprint modelling, heterogeneity, quality assurance, quality control

1 Introduction

In order to improve the understanding of the role of different types of ecosystems as sinks or sources for greenhouse gases, during the last decades the number of flux monitoring stations, organised e.g. in FLUXNET (e.g. Baldocchi et al., 2001) or EUROFLUX (e.g. Valentini et al., 2000), has continuously grown. At the same time, the focus of these observations has shifted more and more from ideal, homogeneous sites to complex and heterogeneous conditions (e.g. Schmid, 2002). To measure the exchange fluxes between biosphere and atmosphere, most often the eddy covariance technique is employed (e.g.

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Aubinet et al., 2000; Baldocchi et al., 2000). However, the adoption of this method in complex terrain potentially violates certain basic theoretic assumptions, such as the need for horizontal homogeneity, steady-state, and non-advective conditions (e.g. Kaimal and Finnigan, 1994; Foken, 2003). In addition, the operation of a flux monitoring station in terrain with a variable land use structure raises the question of which type of vegetation the measured fluxes represent.

Neglecting these problems introduces additional uncertainties into the results obtained at the flux monitoring stations, e.g. in the assessment of the net carbon balance for a specific type of vegetation (e.g. Foken et al., 2004). Therefore, approaches determining the flux data quality and the spatial representativeness of the measurements should be employed to allow for a profound data interpretation. Concerning the fulfilment of the theoretical assumptions for the use of the eddy covariance technique, Foken and Wichura (1996) have developed a tool that assigns quality flags to the measurements according to criteria such as the stationarity of the flow, or the state of development of the turbulent flow field. Concerning the spatial context of the measurements, footprint models can be applied to determine the region upwind of the sensor position that influences the measurements, the so-called source area.

Intending to provide a tool for the evaluation of complex measurement sites, Göckede et al. (2004) developed an approach that brings together the flux data quality assessment scheme by Foken and Wichura (1996) with footprint modelling. This method successfully demonstrated the value of source area analyses for the determination of the influence of a heterogeneous terrain structure on the flux measurements, and was applied thoroughly in an extensive study by Rebmann et al. (2004) to 18 CARBOEUROFLUX sites. Still, their concept suffered several weaknesses that compromised the accuracy of the obtained results. First of all, to determine the source area of the measurements, the analytic flux source area model (FSAM) by Schmid (1994, 1997) was employed. FSAM is a very easy to use footprint model that allows for a fast two-dimensional computation of the source area for fluxes with reasonable computational expense and satisfying accuracy. However, the model was not designed for operation above tall vegetation, so that within-canopy flow and alongwind diffusion were neglected, while the roughness lengths describing the influence of the surface on the flow had to be kept arbitrarily low for forest in order to avoid frequent model breakups. As a second weak point in the approach of Göckede et al. (2004), a simple procedure was introduced to derive a footprint-based average roughness length for individual measurements. This concept neglected the requirement for a non-linear flux aggregation to derive an effective value of the roughness length (e.g. Claussen, 1990), because it allowed consideration only of the composition of land use types within the source area of a measurement, but not their structure. A last weak point in the existing approach is the use of very basic land use information, derived from topographical maps, to represent the characteristics of the terrain surrounding the flux tower.

The present study was designed to overcome these weaknesses in the approach by Göckede et al. (2004), and thus to improve the accuracy of the developed site evaluation procedure. Firstly, the analytic FSAM (Schmid, 1994, 1997) was replaced by the forward Lagrangian stochastic trajectory model as proposed by Rannik et al. (2003). This approach is especially designed to model the source area for fluxes over tall vegetation, and considers within-canopy transport processes. The provision of terrain information was improved by applying satellite remote sensing data sets to derive detailed land use maps of the study area. Concerning the determination of areally averaged effective roughness length values as input for the footprint model, several approaches were tested according to their practicability within the context of the approach presented, and for the quality of the results obtained. As a consequence, the footprint-based computation of a roughness length for individual measurements was replaced by running the microscale flux aggregation model by Hasager and Jensen (1999) in a pre-processing step. With this method, effective roughness length values can be obtained that consider the response of the atmospheric flow for every roughness step change in arbitrary surface conditions.

This study focuses on the visualisation of spatial structures of the quality assessment results of the Foken and Wichura (1996) approach, and on the determination of a 'footprint climatology' for different stratification regimes. The flux contributions of different types of land use to the fluxes measured can be evaluated, a feature especially useful for flux monitoring stations in heterogeneous terrain that aim at the examination of a specific type of vegetation. In addition, footprint-averaged mean values of arbitrary input parameters can be calculated, which can be used for example to visualise wind direction sectors with vertical wind speed components significantly deviating from zero, or to evaluate the performance of a coordinate rotation method. The approach presented is intended as a supporting tool for the interpretation of results obtained at heterogeneous meteorological monitoring sites. On the one hand it can be used to identify and evaluate terrain effects on long-term flux measurements, and thus to filter out low-quality data. On the other hand, the approach might be employed to determine an optimal sensor position for measurement that shall be representative for a specific type of land use.

2 Input dataset

2.1 SITE DESCRIPTION AND METEOROLOGICAL DATA

All data used within this study were obtained at the Waldstein Weidenbrunnen site (Gerstberger et al., 2004), which is located in the Fichtelgebirge mountains near Bayreuth, Germany. The flux measurement tower (50°08'31"N, 11°52'01"E, 775 m a.s.l.) has a height of 33 m and is part of the FLUXNET network (Baldocchi et al., 2001). 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. The most important surface heterogeneities affecting the measurements are a large clearing situated approximately 250 m west of the tower, and the summit of the 'Großer Waldstein' (877 m a.s.l.), which lies at a distance of about 1700 m in the southwesterly sector.

The meteorological dataset employed for this analysis covers the period 21st May to 31st July, 2003. The eddy covariance measurement complex consisted of a Gill R3 sonic anemometer, and a LiCor 7500 open path infrared gas analyser. Data were stored as 20 Hz raw data, and subsequently processed with a standard procedure for eddy covariance data developed at the University of Bayreuth. This software package includes the Planar-Fit coordinate rotation (Wilczak et al., 2001), a spectral correction following Moore (1986), and the WPL-correction to account for density fluctuations (Webb et al., 1980; Liebethal and Foken, 2003). In addition, the Foken and Wichura (1996) flux data quality assessment scheme as described in Section 0 is applied.

2.2 TERRAIN DATA

A matrix describing the land use structure of the terrain surrounding the flux measurement tower was produced using a single satellite data scene (ASTER: Advanced Spaceborne Thermal Emission and Reflectance) from April 2003. This source was chosen because of the commercial availability as well as the spatial and spectral characteristics, which allow a simple land use classification approach with sufficient accuracy (Reithmaier, personal communication).

TABLE I

Differentiated land use classes within the observation area at the Waldstein Weidenbrunnen site. The values for the roughness length z_0 are taken from Hasager et al. (2002).

Class	[%] of area	z_0 [m]	Description
conifer	61.1	1.8	conifer trees (mainly spruce) of several age classes
clearings	12.3	0.3	small open areas with scattered bushes or trees
grassland	5.6	0.08	permanent grassland, pasture land
summer crops	6.5	0.03	crops with peak in development in late summer
winter crops	6.2	0.05	crops with peak in development in early summer
settlement	4.8	1.2	rural settlements, buildings, sealed areas
quarry	0.3	0.5	area of mining activities
unclassified	3.2		

The produced land use matrix covers an area of 7.1 km in an east-west direction and 5.1 km in a north-south direction, with a horizontal resolution of 15 m. The remote sensing method allowed a differentiation of the land surface into seven land use classes (Table 1), of which the dominant land use class is conifer, covering more than 60% of the total classified area of about 36 km². The large forested areas are intercepted only by the land use classes clearings (12.3%) and quarry (0.3%), the agricultural land classes surrounding the forest play a marginal role. The assignment of roughness length values to the land use classes as presented in Table 1 follows the scheme proposed by Hasager et al. (2002).

3 Methodology on flux aggregation

Flux aggregation methods are an important tool to include subgrid-scale effects into numerical weather prediction, or climate and hydrological modelling (e.g. Mahrt, 1987; Mason, 1988; Claussen, 1991; Mahrt, 1996; Hasager and Jensen, 1999). In heterogeneous terrain, the length scale of variation of surface properties such as temperature, humidity, or aerodynamic roughness, might be so small that it cannot be resolved by the cell size of these models. Accordingly, these parameters have to be averaged to provide effective values for the whole grid cell which allows production of representative areally averaged fluxes of momentum, sensible and latent heat, and other scalars (Hasager et al., 2003). By definition, these effective parameters have values that, in homogeneous terrain, would produce fluxes equal to the spatial average found in heterogeneous terrain (Fiedler and Panofsky, 1972; Wieringa, 1986; Mason, 1988; Claussen, 1991).

In the context of footprint studies, aggregation methods have to be employed to provide an effective value of the surface roughness length z_0, which is required as an input parameter. In heterogeneous terrain, the roughness length for a specific measurement position might change with the varying source weight function, thus a suitable method has to be applied to read out an effective z_0 value for each individual measurement.

3.1 CONCEPTS FOR FLUX AGGREGATION

An average roughness length value for a heterogeneous grid element can easily be approximated as the arithmetic mean of the individual z_0 values of the patches composing this area. However, this so-called parameter aggregation is physically incorrect (e.g. Claussen, 1990; Foken, 2003), as strong turbulence in small regions can dominate the area-averaged fluxes (Mahrt, 1987; Schmid and Bünzli, 1995). To account for this nonlinearity, several approaches to a flux aggregation method have been developed, with varying degrees of sophistication. One of these is the logarithmic averaging of z_0, which can be further refined including the apparent friction velocity (e.g. Taylor, 1987; Mason, 1988; Claussen, 1990). Furthermore, the effective z_0 value can be estimated with the drag-law method (Claussen, 1991), which is based on the blending height concept (Wieringa, 1986; Mason, 1988), and the more complex mosaic approach (Avissar and Pielke, 1989; Avissar, 1991).

All aggregation procedures listed above have in common that they derive an areally averaged roughness length taking into account only the composition of land use types within the specific area. It has been shown by experiments (Klaassen and Claussen, 1995; Flesch and Wilson, 1999; van Breugel et al., 1999; Klaassen et al., 2002) and theoretical or modelling studies (Schmid and Bünzli, 1995; Mölders et al., 1996; Goode and Belcher, 1999; Hasager and Jensen, 1999) that fluxes in a heterogeneous landscape are not only influenced by the local surface conditions, but are also dependent on the properties of adjacent areas. This effect is described by internal boundary layer theory (e.g. Garratt, 1992; Kaimal and Finnigan, 1994). Especially flow across a transition from a smooth to a rough surface leads to an overshoot of turbulence up to a certain downwind distance (Klaassen et al., 2002), so that the average flux of a grid cell can be significantly enhanced in strongly heterogeneous terrain (Friedrichs et al., 2000). Thus, the texture of the surface variability, termed 'second order roughness' by Schmid and Bünzli (1995), has to be included into the aggregation process in order to avoid an underestimation of the effective roughness length.

Schmid and Bünzli (1995) could demonstrate with a thorough numerical study that the stress deviation due to the overshoot of turbulence for a flow across a roughness step-change from smooth to rough is the dominant process for the areally averaged fluxes of a heterogeneous grid cell. The authors reason that the quality of a flux aggregation model is highly dependent on its ability to simulate this advective enhancement of vertical momentum transfer at transitions from smooth to rough surfaces. First modelling approaches to consider such effects, the so-called subgrid-models (Seth et al., 1994; Mölders et al., 1996), have been developed as advanced versions of the mosaic approach that do not rearrange the land use patches within the grid cell. However, high computational resources are required, and because of the scale-dependency of the drag and transfer coefficients (Mahrt and Sun, 1995), the applicability is restricted to scales larger than 4 km (Mölders et al., 1996).

3.2 MICROSCALE AGGREGATION MODEL

A more practicable approach to aggregate roughness lengths under consideration of local advection effects was developed by Hasager and Jensen (1999). This microscale aggregation model takes into account the response of the atmospheric flow for every roughness step change in arbitrary surface conditions. The physics consist 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 is provided by high resolution two-dimensional land use maps, with a fixed roughness length assigned to each land use class as described in Section 2.2. In the context of the site evaluation approach presented, the Hasager and Jensen (1999) microscale aggregation model is used as a pre-processing step to produce tables of effective z_0-values for different flow conditions as input for the footprint model. In the case of the Waldstein Weidenbrunnen site, these tables contain results for twelve wind direction sectors, 14 different settings for the stability of atmospheric stratification, and five temperature regimes.

4 Source area analysis

The footprint analyses are performed with the Thomson (1987) forward Lagrangian stochastic (LS) trajectory model of Langevin type (e.g. Wilson et al., 1983; Wilson and Sawford, 1996). The exact formulation of the parameterisations, including the definition of the flow statistics and the effect of stability on the profiles, is proposed by Rannik et al. (2003). The model can be applied to diabatic conditions, and also considers within-canopy flow effects. In contrast to the footprint model for flow over tall vegetation by Baldocchi (1997), who separates the model domain into canopy layer and atmospheric surface layer, the roughness sublayer (RSL) is introduced as the third vertical layer, which stretches upward from the canopy height h to the RSL top at z_*. However, this additional layer is not considered for all profiles describing the turbulent flow properties. Like all LS models, the Rannik et al. (2003) model can also treat three-dimensional turbulent diffusion (e.g. Reynolds, 1998). As a forward approach relying on the inverted plume assumption (e.g. Schmid and Oke, 1988; Schmid, 2002), it is restricted to horizontally homogeneous flow conditions.

For the study presented, the simulations were performed releasing $5 \cdot 10^4$ particles from a height close to the ground, which were tracked until the upwind distance accounted for approximately 90 percent of the total flux. To save computation time, the flux footprint estimators were pre-calculated for a fixed set of stability classes, roughness lengths, and observation heights, leaving Obukhov length L, roughness length z_0, and measurement height z_m as the only input parameters required. The flow statistics required as model input were adopted from Rannik et al. (2003).

To link the meteorological measurements with the terrain information, a footprint analysis was performed for each individual measurement of the observation period. This concept is described in detail by Göckede et al. (2004), and is thus only briefly outlined here. The obtained source weight function was projected onto the land use matrix by assigning weighting factors ranging from zero to one to all matrix cells. These weighting factors were sorted by the different land use classes and subsequently summarised, 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 had to be combined for the complete observation period. This was 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 five different quantities observed. The quantities considered are momentum flux, sensible heat flux, latent heat flux, CO_2-flux, and the contribution of the land use type to be observed within the source area to the total flux measured. For the vertical wind component w this procedure was slightly modified. Instead of quality flags, the mean values for w before and after performing the Planar-Fit rotation (Wilczak et al., 2001) were stored into the database.

Finally, for each matrix cell, the entries in the database were 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 were summed up and subsequently normalised with the highest sum found in

TABLE II

Derivation of final quality flags from flags for stationarity and integral turbulence characteristics. Adapted from Foken et al. (2004).

Stationarity flag	1	2	1-2	3-4	1-4	5	<= 6	<= 8	<= 9
Integral turbulence characteristic 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

the entire matrix. To assess the overall data quality, the weighting factors were 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. For the vertical wind speed, under consideration of the weighting factors obtained with the footprint model for each matrix cell the average value of w before and after the Planar-Fit rotation was calculated. This approach can in principle be applied to any quantity for which the determination of the horizontally variable structure of the mean values is required.

5 Flux 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 proposed 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 the so-called integral turbulence characteristics. The combination of these two ratings yields the final flux data quality flag (Table 2). As no commonly valid integral turbulence characteristics have been developed for the latent heat flux and the CO_2 flux, for the rating of these parameters only the stationarity of the flow and the integral turbulence characteristics of the vertical wind component are considered. Details on the quality flag assignment as well as a discussion on the validity of this approach in complex terrain conditions are presented by Göckede et al. (2004).

6 Results

At monitoring sites, such as organised in the FLUXNET program, usually a target land use type is specified, for which the measurements shall be representative. In case the surrounding terrain is not homogeneous, depending on the position of the source area a varying portion of the flux is emitted by different land use types, compromising the interpretation of the results. Thus, the evaluation of the relative flux contribution of the target land use type to the total flux can serve as a measure of quality, e.g. to sort out measurements which are significantly disturbed in order to estimate the carbon balance of the target land use type. The frequency distribution of the flux percentage of the target land use type spruce forest at the Waldstein Weidenbrunnen site is shown in Figure 1.

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

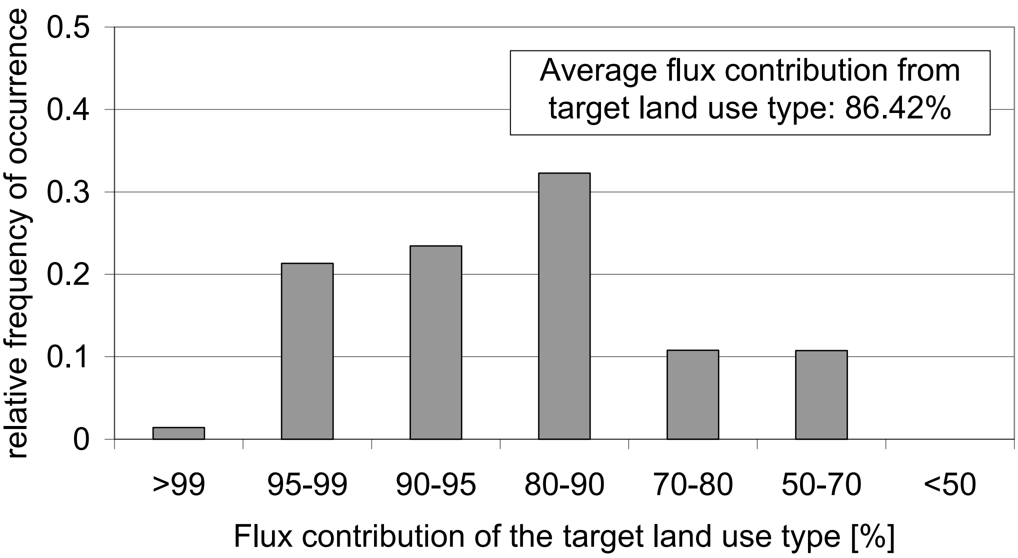

Figure 1. Classified distribution of the relative flux contribution of the target land use type to the total flux measured.

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 the approach presented, this process can also be performed for different stratification regimes, in order to show the varying area of influence on the measurements with changing atmospheric stability. In Figure 2, this is shown as an example of stable stratification.

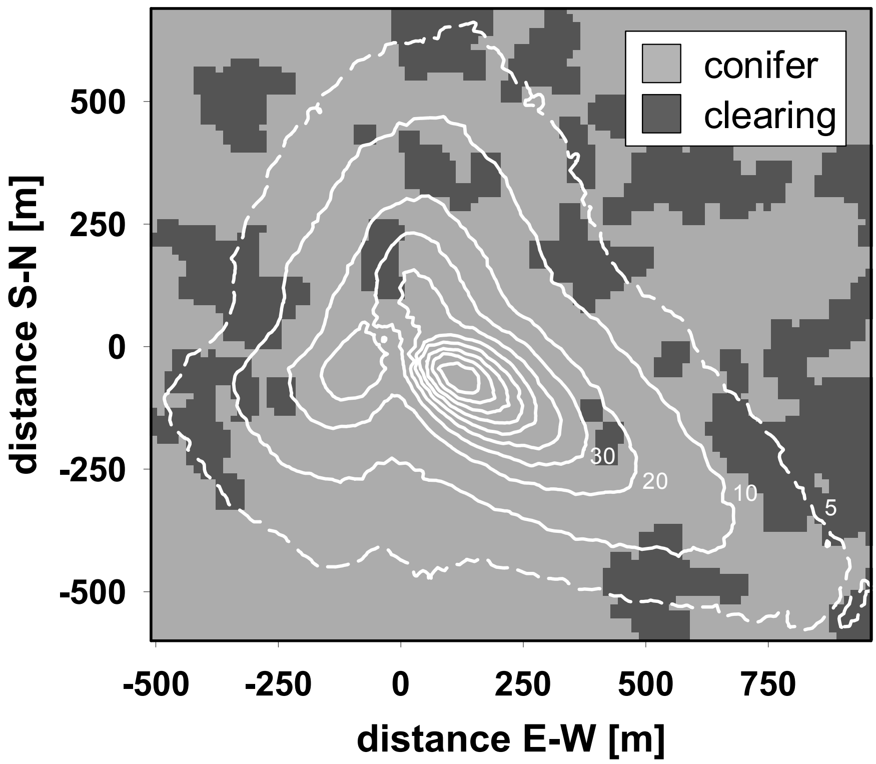

Figure 2. Footprint climatology for the Waldstein Weidenbrunnen site for stable stratification. The three-dimensional weighting function is indicated by the white lines. Values are in percentages to the peak of the function, with solid lines ranging from 90 to 10 percent, and the dashed line as 5 percent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

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 southeast 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 4 and 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 the centremost part of this area, the land use structure is almost homogeneous, consisting of spruce forest, while in the outer percentage rings many clearings are located.

In order to include a visualisation of the overall data quality of the quantities observed, different greyscales can be used in the background of the figures to indicate the results of the data quality assessment. In Figure 3, the greyscales show the dominant data quality flag for the latent heat flux, under stable stratification conditions. The white isopleths, specifying the relative flux contributions for the Waldstein Weidenbrunnen site for stable stratification, are included to highlight the region of highest influence on the observations.

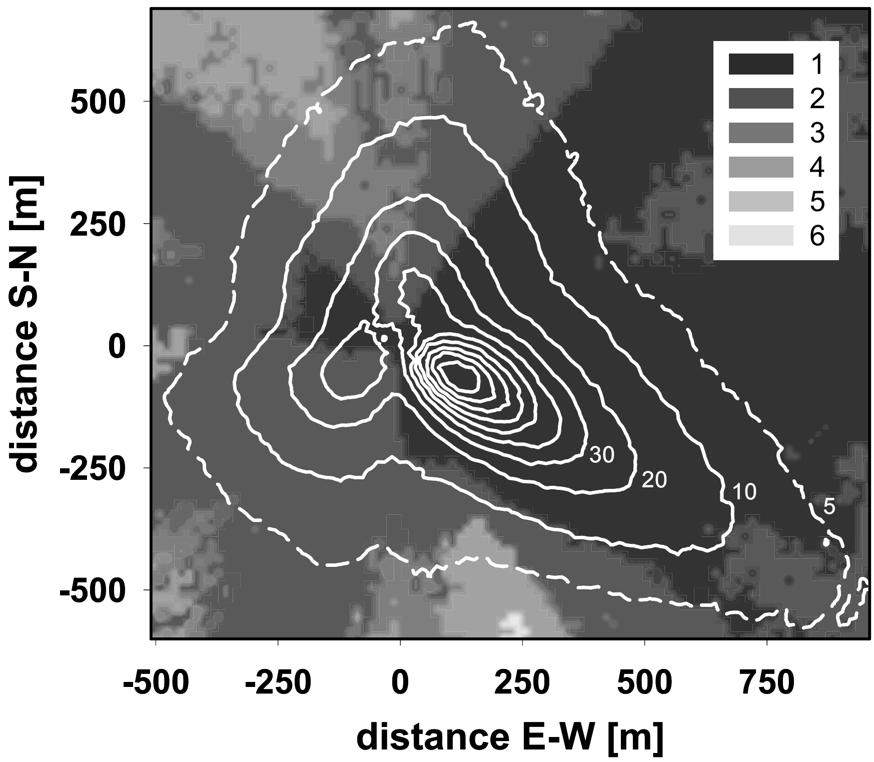

Figure 3. Spatial distribution of the quality assessment results for the latent heat flux during stable stratification. The footprint climatology for stable stratification is indicated by the white isolines. Greyscales indicate the average data quality for each matrix cell. Of the 9 possible quality classes ranging from 1 (best) to 9 (worst), only classes 1 to 6 are present in this part of the terrain.

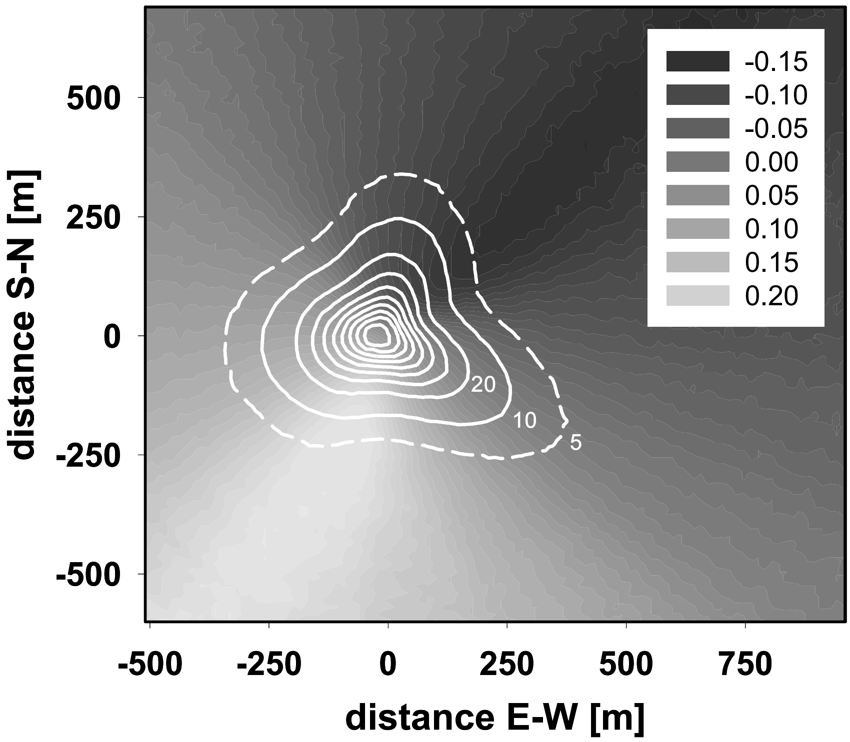

Figure 4. Spatial distribution of the average values of the mean unrotated vertical wind component *w*. The footprint climatology for all stratification cases is indicated by the white isolines. The greyscales show the mean unrotated *w* values [m s^{-1}] that have been calculated for each matrix cell under consideration of the footprint results.

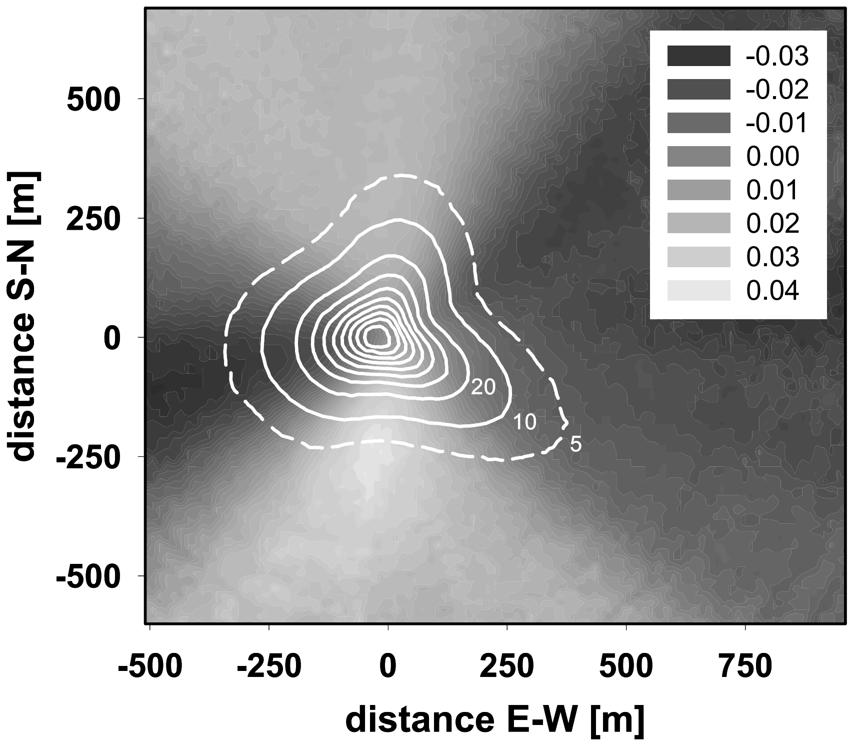

Figure 5. Spatial distribution of the average values of the mean vertical wind component *w*, [m s^{-1}] after performing the Planar-Fit correction. The footprint climatology for all stratification cases is indicated by the white isolines. The greyscales show the mean *w* values that have been calculated for each matrix cell under consideration of the footprint results. Please note that the range of values is significantly smaller than that shown in Figure 4.

For most parts of the measurement site, the overall rating of the latent heat flux was very good (classes 1-3), indicating that with the employed open path gas analyser water vapour measurements of high quality can obtained even in complex terrain. However, the visualisation of the results also reveals two distinct wind sectors with only medium quality (classes 4-6), one in the south and the other in the northwest of the tower position. This reduction of the overall data quality is induced by topographical effects that disturb the turbulent flow field, explained in more detail in the following paragraph. Thus, the data quality of the latent heat flux seems to be closely connected to the evaluation of the vertical wind component, as shown below in Figures 4 and 5.

In addition to the visualisation of spatial structures of quality flags the approach presented can also be employed to produce maps of footprint-averaged meteorological parameters. To do so, under consideration of the weighting factors of the source area analysis a weighted mean value of the specific parameter is computed for each matrix cell. This method can for example be applied to show spatial structures of the average values of the vertical wind component *w*, in order to find out what kind of rotation method should be applied, and afterwards to check whether the coordinate rotation was performed correctly. In Figure 4, the results for the unrotated values of the mean vertical wind component *w* at the Waldstein Weidenbrunnen site are shown.

The results displayed in Figure 4 indicate a general tilt in the unrotated wind field, with high positive averaged values of *w* in the southwesterly wind sector, and a trend for negative values in the northeasterly direction. Along an axis stretching from the southeast to the northwest, the mean values for the unrotated *w* are approximately zero. These results indicate the usefulness of a Planar-Fit coordinate rotation at this site, in order to minimise the effect of the general slope of the wind field that is induced by the local topography. The slightly higher deviations from zero in the southwesterly wind sector might be caused by the summit of the 'Großer Waldstein', which lies at a distance of about 1700 m in this direction. The results for the vertical wind component *w* after performing the Planar-Fit coordinate rotation are shown in Figure 5.

The results presented in Figure 5 indicate that the application of the Planar-Fit coordinate rotation at the Waldstein Weidenbrunnen site was very effective. Even in the wind sectors with the highest disturbances of the unrotated *w*, the elimination of the general slope of the wind field has reduced the deviations from zero to a level that is insignificant for the computation of the fluxes at this site. However, this example also demonstrates that even after the rotation, mean values for *w* may remain in case the average wind field is not an even plane, but an individually tilted slope in different wind sectors. The highest deviations shown in Figure 5 are again to be found in the southwesterly sector, and are, again, probably caused by the summit of the 'Großer Waldstein'. The positive deviations found within the northern wind sector may be induced by a steep slope in the topography in this direction. As the remaining mean values for *w* are very small in this case, no additional correction is necessary. At other sites, 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 should be performed.

7 Discussion

The site evaluation approach was designed as an update of the method proposed by Göckede et al. (Göckede et al., 2004), which overcomes certain conceptual weaknesses of this previous version. A direct comparison between results obtained by both versions reveals significant differences (Figure 6), illustrating the important influence of the improvements implemented in the approach presented here.

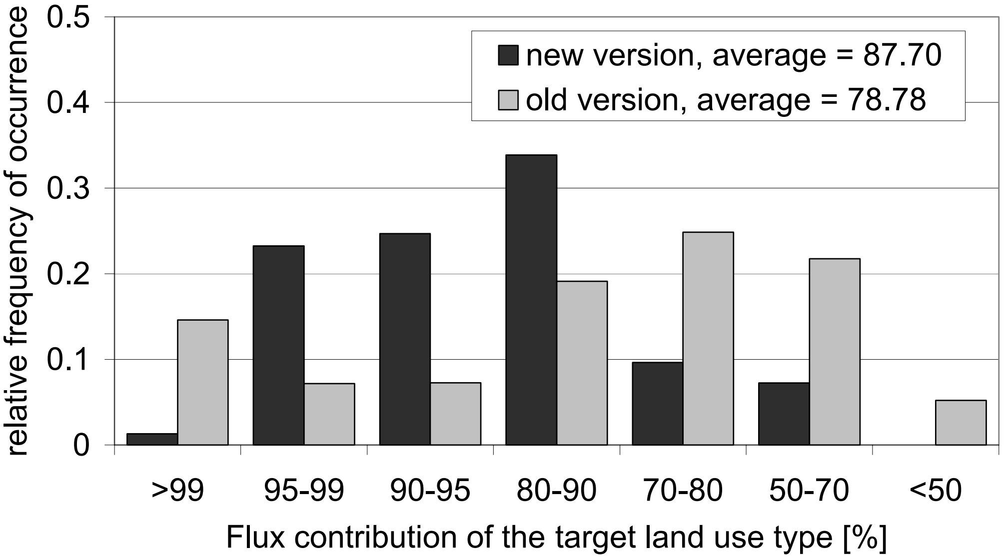

Figure 6. Comparison between results from the old version of the approach (Göckede et al., 2004) and from the new version as presented. Shown are the classified distribution of the relative flux contribution of the target land use type to the total flux measured as computed with the different approaches.

In a similar way as shown in Figure 1, Figure 6 presents the classified flux contributions of the target land use type for the Waldstein Weidenbrunnen site for the old version of the approach by Göckede et al. (2004) and the new version as presented herein. As the use of the old version implies that a part of the input data set is discarded due to model breakups, for means of comparison the data set was also reduced for the new version. Thus, for both versions only about 83 percent of the available data set could be used, and as a consequence, the results of the new version deviate slightly from those shown in Figure 1. Figure 6 demonstrates that the use of the new version of the site evaluation approach produces classified flux contributions of the target land use type mainly between 80 and 99 percent of the total flux, while the principal part of the results of the old version was situated in the range between 50 and 90 percent. This shift to the higher flux contribution classes for the new version is emphasised by an increase of the average flux contribution of the target land use type of about 9 percent. However, this comparison cannot add arguments about which version of the model delivers the better results, as reference values are not available in this example, and the site characteristics do not allow for a thorough model evaluation.

Although some of the main shortcomings of the old version by Göckede et al. (2004) have been improved, the approach presented is still based on certain simplifications in order to provide a site evaluation tool that is practical and easy to use. The most important of these concerns the application of footprint models in flow conditions over complex terrain. As already stated in Section 4, the applied forward LS footprint approach of Rannik et al. (2003) 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 cause further uncertainty. However, to eliminate these shortcomings, the adoption of a backward LS model and intensive measurements to adapt it to individual sites would be necessary, so that practical application would no longer be possible.

The adoption of the correct flow statistics is a critical task for both analytic and LS footprint models. As usually no information is available to produce individual velocity statistic profiles for each model run, ensemble-averaged data are used. These profiles, which are averaged over many sampling runs for a specific site, or frequently even taken over from observations at other, 'representative' sites, do not explicitly resolve the effect of local stability on the flow properties, and the large run-to-run variations in scalar fluxes (Lee, 1998). Hsieh et al. (2003) could show that the adoption of velocity profiles for individual runs did not improve the prediction of within-canopy heat fluxes by a two-dimensional Lagrangian dispersion model. However, this problem emphasises the fact that any footprint model can only be as good as the description of the underlying turbulent flow conditions. Especially for the use of the LS footprint models, which can in principle treat complex flow with three-dimensional turbulent diffusion and non-Gaussian inhomogeneous turbulence, it must be remembered that the representativeness of input flow parameters under these conditions is often questionable (Schmid, 2002). As regards reliability, the operation of footprint models for flow within or above tall canopies (e.g. Baldocchi, 1997; Rannik et al., 2000, 2003) poses special problems. As only few generally valid characteristics are known for these conditions (e.g. Lee, 1998; Finnigan, 2000), the canopy turbulence has to be described with crude generalisations and certain ad hoc assumptions (Schmid, 2002). In spite of experimental difficulties (e.g. Mahrt, 1998), 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. Lee, 2003; Marcolla et al., 2003; Markkanen et al., 2003). However, to date no unified theoretical framework exists for this type of flow. In the course of this study, the flow statistics as determined by Rannik et al. (2003) for the Hyytiälä site in Finland were adopted for the footprint modelling. The validity of these statistics at the Waldstein Weidenbrunnen site will be tested intensively using a high quality dataset of profile turbulence measurements which will be available soon.

A related problem already addressed by Schmid (2002) in his conclusions regarding future directions of footprint applications concerns the treatment of flow affected by significant step changes in surface properties, e.g. at forest edges or clearings. Such step changes may have significant influence on the atmospheric flow conditions far downwind of their position (e.g. Klaassen et al., 2002; Leclerc et al., 2003), as discussed in more detail in Section 3.1. Therefore, if such inhomogeneities are present, the measured flux data may significantly deviate from the surface-atmosphere exchange of the source area computed by a footprint method that assumes horizontal homogeneous flow (Foken and Leclerc, 2004). In principle, inhomogeneous flow situations can be resolved by backward LS footprint models (Kljun et al., 2002), but a method for an accurate representation of the horizontally heterogeneous statistics as input for the model still has to be developed. Also, the consideration of the topography of the surrounding landscape has not been implemented by existing footprint models to date. To include these aspects into the site evaluation approach will be the principal focus of future work on this subject.

8 Conclusions

An approach has been developed that provides an additional tool for flux data quality evaluation at 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 analysis can provide results for different stratification regimes, and may also be applied to produce maps of footprint-averaged meteorological parameters such as the vertical wind component *w*. Another important output option is the determination of the contribution of each land use type to the measured flux.

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 can be employed to evaluate the performance of a coordinate rotation method such as the Planar Fit approach, and in addition 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.

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References

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. and Vesala, T.: 2000, 'Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology', *Adv. Ecol. Res.* **30**, 113-175.

Avissar, R. and Pielke, R. A.: 1989, 'A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology', *Mon. Weather Rev.* **117**, 2113-2136.

Avissar, R.: 1991, 'A statistical-dynamical approach to parameterize subgrid-scale land-surface heterogeneity in climate models', *Surv. Geophys.* **12**, 155-178.

Baldocchi, D. D.: 1997, 'Flux footprints within and over forest canopies', *Boundary-Layer Meteorol.* **85**, 273-292.

Baldocchi, D. D., Finnigan, J. J., Wilson, K., Paw U, K. T. and Falge, E.: 2000, 'On measuring net ecosystem carbon exchange over tall vegetation on complex terrain', *Boundary-Layer Meteorol.* **96**, 257-291.

Baldocchi, D. D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Fuentes, J. D., Goldstein, A., Katul, G., Law, B. E., Lee, X., Malhi, Y., Meyers, T., Munger, J. W., Oechel, W., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K. and Wofsy, S.: 2001, 'FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapour and energy flux densities', *Bull. Amer. Meteorol. Soc.* **82**, 2415-2435.

Claussen, M.: 1990, 'Area-averaging of surface fluxes in a neutrally stratified, horizontally inhomogeneous atmospheric boundary layer', *Atmos. Environ.* **24A**, 1349-1360.

Claussen, M.: 1991, 'Estimation of areally-averaged surface fluxes', *Boundary-Layer Meteorol.* **54**, 387-410.

Fiedler, F. and Panofsky, H. A.: 1972, 'The geostrophic drag coefficient and the 'effective' roughness length', *Quart. J. Roy. Meteorol. Soc.* **98**, 213-220.

Finnigan, J. J.: 2000, 'Turbulence in Plant Canopies', *Annu. Rev. Fluid Mech.* **32**, 519-571.

Flesch, T. K. and Wilson, J. D.: 1999, 'Wind and remnant tree sway in forest cutblocks. I. Measured winds in experimental cutblocks', *Agric. For. Meteorol.* **93**, 229-242.

Foken, T. and Wichura, B.: 1996, 'Tools for quality assessment of surface-based flux measurements', *Agric. For. Meteorol.* **78**, 83-105.

Foken, T.: 2003, *Angewandte Meteorologie, Mikrometeorologische Methoden*, Springer, Berlin, Heidelberg, New York, 289 pp.

Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B. D. and Munger, J. W.: 2004, 'Post-field data quality control', in X. Lee, W. J. Massman and B. E. Law (ed.), *Handbook of Micrometeorology: A guide for Surface Flux Measurements*, Kluwer Academic Publishers, Dordrecht, pp. 181-208.

Foken, T. and Leclerc, M. Y.: 2004, 'Methods and limitations in validation of footprint models', *Agric. For. Meteorol.* **127**, 223-234.

Friedrichs, K., Molders, N. and Tetzlaff, G.: 2000, 'On the influence of surface heterogeneity on the Bowen-ratio: A theoretical case study', *Theor. Appl. Climatol.* **65**, 181-196.

Garratt, J. R.: 1992, *The atmospheric boundary layer*, Cambridge University Press, Cambridge, 316 pp.

Gerstberger, P., Foken, T. and Kalbitz, K.: 2004, 'The Lehstenbach and Steinkreuz catchments in NE Bavaria, Germany', in E. Matzner (ed.), *Biogeochemistry of Forested Catchments in a Changing Environment, Ecological Studies*, Vol. **172**, Springer, Berlin, Heidelberg, New York, pp. 15-44.

Göckede, M., Rebmann, C. and Foken, T.: 2004, 'A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites', *Agric. For. Meteorol.* **127**, 175-188.

Goode, K. and Belcher, S. E.: 1999, 'On the parameterisation of the effective roughness length for momentum transfer over heterogeneous terrain', *Boundary-Layer Meteorol.* **93**, 133-154.

Hasager, C. B. and Jensen, N. O.: 1999, 'Surface-flux aggregation in heterogeneous terrain', *Quart. J. Roy. Meteorol. Soc.* **125**, 2075-2102.

Hasager, C. B., Nielsen, N. W., Soegaard, H., Boegh, E., Christensen, J. H., Jensen, N. O., Schultz Rasmussen, M., Astrup, P. and Dellwik, E.: 2002, *SAT-MAP-CLIMATE Project results*, Risö National Laboratory, Roskilde, 71 pp.

Hasager, C. B., Nielsen, N. W., Jensen, N. O., Boegh, E., Christensen, J. H., Dellwik, E. and Soegaard, H.: 2003, 'Effective roughness calculated from satellite-derived land cover maps and hedge-information used in a weather forecasting model', *Boundary-Layer Meteorol.* **109**, 227-254.

Hsieh, C. I., Siqueira, M., Katul, G. and Chu, C. R.: 2003, 'Predicting scalar source-sink and flux distributions within a forest canopy using a 2-D Lagrangian stochastic dispersion model', *Boundary-Layer Meteorol.* **109**, 113-138.

Kaimal, J. C. and Finnigan, J. J.: 1994, *Atmospheric Boundary Layer Flows: Their Structure and Measurement*, Oxford University Press, New York, 289 pp.

Klaassen, W. and Claussen, M.: 1995, 'Landscape variability and surface flux parameterization in climate models', *Agric. For. Meteorol.* **73**, 181-188.

Klaassen, W., van Breugel, P. B., Moors, E. J. and Nieveen, J. P.: 2002, 'Increased heat fluxes near a forest edge', *Theor. Appl. Climatol.* **72**, 231-243.

Kljun, N., Rotach, M. W. and Schmid, H. P.: 2002, 'A three-dimensional backward Lagrangian footprint model for a wide range of boundary-layer stratifications', *Boundary-Layer Meteorol.* **103**, 205-226.

Leclerc, M. Y., Karipot, A., Prabha, T., Allwine, G., Lamb, B. and Gholz, H. L.: 2003, 'Impact of nonlocal advection on flux footprints over a tall forest canopy: a tracer flux experiment', *Agric. For. Meteorol.* **115**, 19-30.

Lee, X.: 1998, 'On micrometeorological observations of surface-air exchange over tall vegetation', *Agric. For. Meteorol.* **91**, 39-49.

Lee, X.: 2003, 'Fetch and footprint of turbulent fluxes over vegetative stands with elevated sources', *Boundary-Layer Meteorol.* **107**, 561-579.

Liebethal, C. and Foken, T.: 2003, 'On the significance of the Webb correction to fluxes', *Boundary-Layer Meteorol.* **109**, 99-106.

Mahrt, L.: 1987, 'Grid-averaged surface fluxes', *Mon. Weather Rev.* **115**, 1550-1560.

Mahrt, L. and Sun, J. L.: 1995, 'Dependence of surface exchange coefficients on averaging scale and grid size', *Quart. J. Roy. Meteorol. Soc.* **121**, 1835-1852.

Mahrt, L.: 1996, 'The bulk aerodynamic formulation over heterogeneous surfaces', *Boundary-Layer Meteorol.* **89**, 87-119.

Mahrt, L.: 1998, 'Flux sampling errors for aircraft and towers', *J. Atmos. Ocean. Technol.* **15**, 416-429.

Marcolla, B., Pitacco, A. and Cescatti, A.: 2003, 'Canopy architecture and turbulence structure in a coniferous forest', *Boundary-Layer Meteorol.* **108**, 39-59.

Markkanen, T., Rannik, Ü., Marcolla, B., Cescatti, A. and Vesala, T.: 2003, 'Footprints and fetches for fluxes over forest canopies with varying structure and density', *Boundary-Layer Meteorol.* **106**, 437-459.

Mason, P. J.: 1988, 'The formation of areally-averaged roughness lengths', *Quart. J. Roy. Meteorol. Soc.* **114**, 399-420.

Mölders, N., Raabe, A. and Tetzlaff, G.: 1996, 'A comparison of two strategies on land surface heterogeneity used in a mesoscale beta meteorological model', *Tellus A* **48**, 733-749.

Moore, C. J.: 1986, 'Frequency response corrections for eddy correlation systems', *Boundary-Layer Meteorol.* **37**, 17-35.

Rannik, Ü., Aubinet, M., Kurbanmuradov, O., Sabelfeld, K. K., Markkanen, T. and Vesala, T.: 2000, 'Footprint analysis for measurements over a heterogeneous forest', *Boundary-Layer Meteorol.* **97**, 137-166.

Rannik, Ü., Markkanen, T., Raittila, J., Hari, P. and Vesala, T.: 2003, 'Turbulence statistics inside and over forest: Influence on footprint prediction', *Boundary-Layer Meteorol.* **109**, 163-189.

Rebmann, C., Göckede, M., Foken, T., Aubinet, M., Aurela, M., Berbigier, P., Bernhofer, C., Buchmann, N., Carrara, A., Cescatti, A., Ceulemans, R., Clement, R., Elbers, J. A., Granier, A., Grünwald, T., Guyon, D., Havránková, K., Heinesch, B., Knohl, A., Laurila, T., Longdoz, B., Marcolla, B., Markkanen, T., Miglietta, F., Moncrieff, J. B., Montagnani, L., Moors, E., Nardino, M., Ourcival, J.-M., Rambal, S., Rannik, Ü., Rotenberg, E., Sedlak, P., Unterhuber, G. and Vesala, T.: 2004, 'Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling', *Theor. Appl. Climatol.*, doi: 10.1007/s00704-004-0095-y.

Reynolds, A. M.: 1998, 'A two-dimensional Lagrangian stochastic dispersion model for convective boundary layers with wind shear', *Boundary-Layer Meteorol.* **86**, 345-352.

Schmid, H. P. and Oke, T. R.: 1988, 'Estimating the source area of a turbulent flux measurement over a patchy surface', *In: Proceedings of the 8th Symposium on Turbulence and Diffusion*, Boston, MA, American Meteorological Society, pp. 123-126.

Schmid, H. P. and Oke, T. R.: 1990, 'A model to estimate the source area contributing to turbulent exchange in the surface layer over patchy terrain', *Quart. J. Roy. Meteorol. Soc.* **116**, 965-988.

Schmid, H. P.: 1994, 'Source areas for scalars and scalar fluxes', *Boundary-Layer Meteorol.* **67**, 293-318.

Schmid, H. P. and Bünzli, D.: 1995, 'The influence of surface texture on the effective roughness length', *Quart. J. Roy. Meteorol. Soc.* **121**, 1-21.

Schmid, H. P.: 1997, 'Experimental design for flux measurements: matching scales of observations and fluxes', *Agric. For. Meteorol.* **87**, 179-200.

Schmid, H. P.: 2002, 'Footprint modeling for vegetation atmosphere exchange studies: a review and perspective', *Agric. For. Meteorol.* **113**, 159-183.

Seth, A., Giorgi, F. and Dickinson, R. E.: 1994, 'Simulating fluxes from heterogeneous land surfaces: Explicit subgrid method employing the biosphere-atmosphere transfer scheme (BATS)', *J. Geophys. Res.-Atmos.* **99**, 18651-18667.

Taylor, P. A.: 1987, 'Comments and further analysis on effective roughness lengths for use in numerical three-dimensional models', *Boundary-Layer Meteorol.* **39**, 403-418.

Thomson, D. J.: 1987, 'Criteria for the selection of stochastic models of particle trajectories in turbulent flows', *J. Fluid Mech.* **180**, 529-556.

Valentini, R., Matteucci, G., Dolman, A. J., Schulze, E.-D., Rebmann, C., Moors, E. J., Granier, A., Gross, P., Jensen, N. O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A. S., Vesala, T., Rannik, Ü., Berbigier, P., Loustau, D., Guomundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S. and Jarvis, P. G.: 2000, 'Respiration as the main determinant of carbon balance in European forests', *Nature* **404**, 861-865.

van Breugel, P. B., Klaassen, W. and Moors, E. J.: 1999, 'Fetch requirements near a forest edge', *Phys. Chem. Earth Pt.* **B 24**, 125-131.

Webb, E. K., Pearman, G. I. and Leuning, R.: 1980, 'Correction of flux measurements for density effects due to heat and water vapour transfer', *Quart. J. Roy. Meteorol. Soc.* **106**, 85-100.

Wieringa, J.: 1986, 'Roughness-dependent geographical interpolation of surface wind speed averages', *Quart. J. Roy. Meteorol. Soc.* **112**, 867-889.

Wilczak, J. M., Oncley, S. P. and Stage, S. A.: 2001, 'Sonic anemometer tilt correction algorithms', *Boundary-Layer Meteorol.* **99**, 127-150.

Wilson, J. D., Legg, B. J. and Thomson, D. J.: 1983, 'Calculation of particle trajectories in the presence of a gradient in turbulent-velocity variance', *Boundary-Layer Meteorol.* **27**, 163-169.

Wilson, J. D. and Sawford, B. L.: 1996, 'Review of Lagrangian stochastic models for trajectories in the turbulent atmosphere', *Boundary-Layer Meteorol.* **78**, 191-210.

Appendix G: Approaches to validate footprint models using natural tracer measurements from a field experiment

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Abstract

Although footprint modeling has become an important and widely used tool in micrometeorology, the validation of existing models remains an outstanding problem. This study presents approaches using natural tracer measurements to evaluate the performance of footprint models, which are intended to provide an inexpensive and practical alternative to footprint evaluation experiments releasing artificial trace gases. The approaches tested and discussed here are based on either eddy-covariance measurement complexes or small aperture scintillometers operated during field scale experiments in an area of well-defined heterogeneity.

We tested two different footprint validation approaches based on natural tracer measurements: firstly, a comparison of measured flux differences and modeled land use differences for pairs of measurement positions and secondly, a correlation analysis between measured and modeled quantities using reference measurements. We used two different footprint models to test these footprint validation approaches, an analytical flux source area model and a forward Lagrangian stochastic trajectory model. For the test we utilized measurements from an intensive field scale measurement campaign from summer 2002 instead of performing a new experiment to derive the required data set.

The results of this study clearly demonstrate that the two approaches tested here based on natural tracers provide a valuable tool for footprint validation purposes. In the first approach, the comparison of measured flux differences and modeled land use differences, agreement between the measured fluxes and the footprint calculations could only be revealed qualitatively, while the second approach, the correlation analysis between measured and modeled quantities, also allowed the comparison of the two footprint models on a quantitative basis. However, due to experimental shortcomings of the employed data set, additional scatter compromised the accuracy of the results; therefore, no significant differences between both footprint models could be found in this study.

Keywords: Footprint model validation, natural tracers, flux footprints, eddy-covariance, scintillometer

1 Introduction

The adoption of footprint models to determine the spatial context of a measurement has become an important tool in many fields of micrometeorological research. Due to the growing interest in micrometeorology in the study of exchange processes in heterogeneous areas with naturally variable land cover

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(Schmid, 2002), e.g. in long term monitoring programs such as FLUXNET (Baldocchi et al., 2001), the computation of the source area has become a valuable instrument for the quality assessment of micrometeorological measurements (e.g. Göckede et al., 2004). Footprint models can be employed to assess the influence of disturbing terrain elements on individual measurements, or to determine a representative composition of land use types in the fetch of the sensor. Footprint calculations are also necessary to link measurements at different scales, such as tower measurements with remote sensing information, or eddy-covariance flux data with soil chamber measurements. In addition, the application of footprint models is gaining importance in the arranging of field experiments (Horst and Weil, 1994; 1995; Schmid, 1997).

Since the first footprint models for concentration (Schmid and Oke, 1990) and for fluxes (Leclerc and Thurtell, 1990; Schuepp et al., 1990) were developed, many footprint models using different mathematical concepts have been published; these are summarized in a comprehensive survey by Schmid (2002). Despite the widespread application of these models, the issue of their validation remains an outstanding problem in micrometeorology (Foken and Leclerc, 2004). Most of the existing footprint approaches have been compared either to measurement data or to existing footprint models as references (e.g. Horst and Weil, 1992, 1994; Flesch et al., 1995; Haenel and Grünhage, 1999; Rannik et al., 2000, 2003; Kljun et al., 2002). However, these studies typically assume idealized conditions, which do not correspond to the complex conditions at real sites where footprint models are frequently used (Foken and Leclerc, 2004). The effect of horizontally inhomogeneous flow on the accuracy of the footprint model results still remains widely unexplored, as does the presence of large step changes of surface properties in the source area of the sensor. This is due to the lack of experiments that seek to validate footprint models in natural, non-ideal conditions (e.g. Finn et al., 1996; Leclerc et al., 1997; Cooper et al., 2003; Leclerc et al., 2003a, 2003b).

Foken and Leclerc (2004) present a thorough survey on possible concepts for footprint validation studies. In addition to a theoretical approach comparing footprint calculations with an LES-generated data set (Leclerc et al., 1997), they discuss three approaches to footprint validation using experimental data sets: 1.) The use of artificial tracer gases to validate footprint estimates, adopted e.g. by Finn et al. (1996) and Leclerc et al. (2003a, 2003b), 2.) the use of natural tracer measurements (e.g. Rannik et al., 2000; Cooper et al., 2003), and 3.) experiments in an area with isolated heterogeneities that influence the measurements (Foken et al., 1999, 2000). Here the term 'natural tracer' summarizes all types of micrometeorological quantities that can be measured without releasing artificial trace gases. These may be measurements of either scalars or fluxes; however, it has to be considered that fluxes such as the sensible heat flux are not passive tracers. Discussing the use of natural tracer experiments for footprint validation, Foken and Leclerc (2004) highlight the possibilities of this approach, for example the rather simple instrumental setup allows for a cost-efficient realization of such experiments, but the authors also point out the small number of studies published so far.

In this study we test two different experimental approaches to evaluate the applicability of natural tracer measurements for footprint model validation studies. A prerequisite for an experimental setup that makes a footprint validation approach possible is the existence of variable sources or sinks of the quantity to be observed in the terrain surrounding the sensor. Using standard instrumentation such as eddy-covariance measurement complexes, usually multiple sources or sinks are present for each quantity observed. Thus, the success of a validation experiment using natural tracers is dependent on the differences of emission rates from the various types of sources, and also on the size and arrangement of the patches with different source strengths in the terrain. In addition, for natural tracers the source strengths are not known a priori; thus, a single measurement device is not sufficient. As possible alternatives, either additional sensors must monitor the fluxes from different types of surfaces within the experimental area, or an approach comparing at least two measurement positions monitoring combined fluxes from different surfaces can be used. Instead of performing a new experiment with an idealized instrumental setup, we tested these two alternatives using an existing data set that was not especially designed for footprint validation purposes. This field scale experiment provided favorable conditions for our studies, as several sensors were operated at a heterogeneous measurement site of simple land use structure. We concentrated on sensible heat flux data that were simultaneously measured by four eddy-covariance measurement complexes and three scintillometers. The scintillometers were included because their random errors are relatively small, and flow distortion effects are almost absent (e.g. DeBruin et al., 2002), thus these instruments provide a very good data source for comparison studies. However, the use of scintillometers in a heterogeneous environment poses additional problems, which are discussed in more detail in Section 6. To determine flux source areas for the scintillometers we developed a special software package.

To test the footprint validation approaches using natural tracers, we compared the performance of the Eulerian analytic footprint model FSAM (Schmid, 1997) and the forward Lagrangian stochastic (hereafter referred to as LS) trajectory model by Thomson (1987) in the version as parameterized by Rannik et al. (2000, 2003). Kljun et al. (2002) used these two footprint models to evaluate their backward LS model LPDM-B. The comparison of LPDM-B with FSAM resulted in only satisfactory agreement, while the agreement in terms of peak location and footprint shape between LPDM-B and the Rannik et al. (2000) model was excellent. These deviating results were attributed to certain limitations in FSAM that are too restrictive for real situations (Kljun et al., 2002), limitations which are overcome by the LS footprint model. Thus, in addition to testing the validation approaches, a further objective of this study is to analyze whether these model differences are detectable by a natural tracer validation experiment, or whether they have insignificant effect on the computed source areas under the chosen conditions.

2 Experimental setup and meteorological data set

For this study, we used data from the measurement campaign STINHO-2 (**ST**ructure of the turbulent transport over **INHO**mogeneous surface). This experiment was organized in the context of the VERTIKO (**VERTI**cal transport under **CO**mplex natural conditions) project, and took place in June and July of 2002 at the Falkenberg Boundary-Layer measurement site of the Lindenberg observatory, which belongs to the German Meteorological Service. This site is situated at 14°07'27"E and 52°10'01"N at an altitude of 73 m a.s.l., and is embedded in a heterogeneous landscape with a slightly undulating orography formed by the inland glaciers of the last ice age (e.g. Beyrich et al., 2002b). The Falkenberg Boundary-Layer measurement site itself is flat and consists of about 0.18 km² of managed meadow with short grass, while the surrounding agricultural areas are cultivated with varying kinds of crops. Shortly before starting the measurements used in this study, a part of the observation area was ploughed, creating an additional brownfield part in its centre. The measurement setup of the instrumentation of the STINHO-2 experiment used for this study is sketched in Figure 1. For the footprint calculations, a land use map and a roughness length map with regular

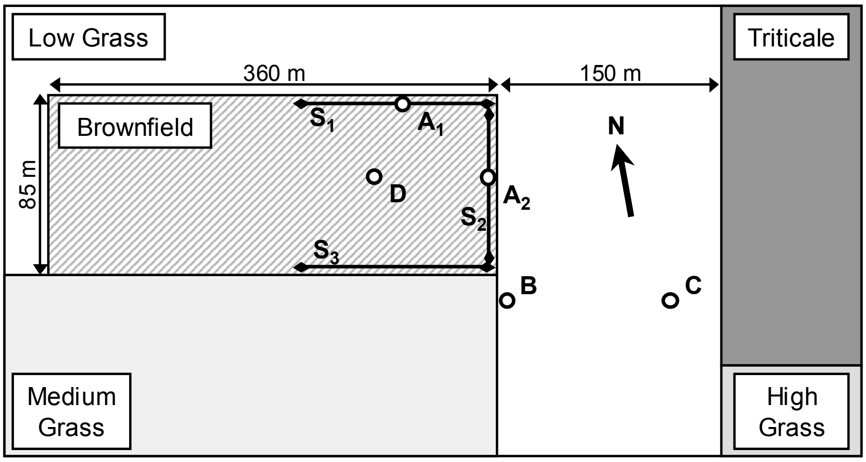

Fig. 1: Experimental setup of the employed sensors of the STINHO-2 experiment in the central part of the Falkenberg Boundary-Layer measurement site. Open circles A to D indicate the measurement positions of the eddy-covariance complexes (see also Table 1). Complex A was moved twice between positions A_1 and A_2, please refer to the text for more information. Black lines labeled with S_1 to S_3 show the three scintillometer measurement paths. The roughness length of the brownfield was $z_0 = 0.01$ m. The canopy height of the Low Grass was 0.05 m ($z_0 = 0.03$ m), Medium Grass 0.20 m ($z_0 = 0.05$ m), High Grass 0.5 m ($z_0 = 0.08$ m), and Triticale 1.0 m ($z_0 = 0.10$ m).

grid spacing were generated to approximate the structure of the central part of this area.

Four eddy-covariance complexes operated by the University of Bayreuth and the German Meteorological Service were set up to monitor the exchange fluxes at different parts of the Falkenberg Boundary-Layer measurement site. The instrument positions A to D are shown in Figure 1, instrumentation and measurement height of all complexes are given in Table 1. Simultaneous measurements with all four eddy-covariance complexes took place from July 2nd to 10th. To adapt the instrumental setup to the prevailing wind direction, the position of measurement complex A was moved from position A_1 to A_2 on July 4th, 19:30 UTC, and back closely to the original position A_1 on July 5th, 8:00 UTC.

Except for minor modifications, the determination of fluxes from the raw data followed the concept proposed by Aubinet et al. (2000) for all eddy-covariance complexes. Turbulent raw data were rotated according to the planar fit method (Wilczak et al., 2001), and subsequently the Moore- (Moore, 1986), Schotanus- (Liu et al., 2001), and WPL-corrections (Webb et al., 1980) were performed. In case no eddy-covariance measurements of the latent heat flux were available, the Schotanus-correction was performed using additional psychrometer data. The corrected fluxes were checked for their quality according to a scheme proposed by Foken and Wichura (1996) as presented by Foken et al. (2004), which assigns quality flags on a scale from one (best) to nine (worst) to each flux measurement. In order to assure high

Table 1
Instrumentation and measurement height of the eddy-covariance measurement complexes employed.

Position	Measurement height	Sonic anemometer	H_2O measurement device
A	2.00 m	Campbell CSAT3	LiCor LI-7500
B	2.35 m	METEK USA1	-
C	2.35 m	METEK USA1	-
D	3.26 m	METEK USA1	-

quality of the data, all data points exceeding a threshold of quality flag greater than six, indicating significant deviations from the theoretical assumptions required for the determination of fluxes from eddy-covariance data, were excluded from the analysis.

In addition to the eddy-covariance measurements, the University of Leipzig team operated three displaced-beam small aperture scintillometers (DBSAS) at the northern, eastern, and southern border of the brownfield area. These instruments of type SLS-20 were manufactured by Scintec AG (Tübingen, Germany) (Thiermann, 1992). They operate a transmitter that splits a laser diode beam with a wavelength of 670 nm into two parallel beams with orthogonal polarizations and a displacement of 2.7 mm. Using DBSAS, the structure parameter of refraction index C_n^2 can be determined by the evaluation of the intensity fluctuations detected for either of the two beams, while the inner scale of turbulence l_0 can be derived from the correlation between the intensity fluctuations at the two receivers. The procedure to derive these parameters from the measurement data, and, subsequently, to calculate momentum flux τ and sensible heat flux H is given in detail by Thiermann and Grassl (1992) and DeBruin et al. (2002). An uncertainty analysis of the employed parameters is presented in Andreas (1992).

For the scintillometers S_1 at the northern boundary of the brownfield (path length = 140 m) and S_2 at the eastern boundary (path length = 86 m) data from July 5th, 0:00 UTC, to July 10th, 0:00 UTC, was available, while scintillometer S_3 at the southern boundary (path length = 140 m) was operated from July 5th, 0:00 UTC to July 7th, 9:40 UTC, and moved to another position afterwards. The sensible heat flux H was computed as 10-minute means, and subsequently averaged to 30-minute values for comparison with the eddy-covariance data. For each 10-minute mean, a quality index termed NOK (for **N**umber **OK**) ranging between 0 (worst) and 100 (best) was provided. To obtain this value, the system software separates the averaging period into blocks of equal length. The NOK value indicates the percentage of blocks that passed the internal quality control procedure, and thus could be used to determine the flux. For this study, a 30-minute average was computed if, according to the NOK results, high-quality measurements were obtained for at least one third of the period.

3 Footprint modeling

3.1 Analytical footprint model

Analytical footprint models are generally fast and easy to use. However, their mathematical simplicity is achieved at the cost of a physical basis (Schmid, 2002). They are restricted to horizontally homogeneous flow conditions, and within canopy flow characteristics and the influence of alongwind turbulent diffusion are neglected. Consequently, analytical models tend to underestimate the contribution of sources near the measurement point, and downwind to the flux. They are especially erroneous when measurements are carried out close to the canopy top over high vegetation like forests, or in heterogeneous environments.

The analytical footprint model employed in this study, the flux source area model FSAM by Schmid (1994, 1997), is based on the model by Horst and Weil (1992). It employs K-theory and an analytical solution of the Eulerian advection-diffusion equation by van Ulden (1978). For the crosswind and vertical concentration distribution functions, an extended version of the surface layer dispersion model by Gryning et al. (1987) is adopted. Because of the use of this model, the footprint algorithms of FSAM can no longer be solved analytically, instead it is able to include thermal stratifications and a realistic wind profile (Schmid, 1994).

As is common for analytical footprint models (e.g. Schuepp et al., 1990; Horst and Weil, 1992, 1994), FSAM is restricted to surface layer scaling conditions (Schmid, 2002), and assumes a constant flux layer with uniform surface emissions with no other sources or sinks in the layer between measurement height and the surface. Horizontally homogeneous flow with uniform profiles of K and u is assumed. The model employs the inverted plume assumption (e.g. Schmid and Oke, 1990), with mean wind parallel but counter to the x-axis direction. Vertical flux divergence is neglected, while diffusion in the lateral direction is taken to be Gaussian. Lateral crosswind diffusion and vertical diffusion can be treated independently, streamwise diffusion is not considered.

The model requires Obukhov length L, surface roughness length z_0, measurement height z_m, friction velocity u_*, and standard deviation of the lateral wind speed component, σ_v, as input parameters. For this study, L, u_*, σ_v and were taken from eddy-covariance measurements. In order to create uniform conditions for both footprint models applied in this study, L, z_0, and z_m were classified (divided into several classes) to simulate the pre-calculated tables used for the LS model (see next section). The output format of the FSAM program was chosen to be a table of weighting factors indicating the relative flux contributions of quadratic fractions of the surface. The total size of the table was adapted to fit in the 90 percent footprint.

3.2 Lagrangian stochastic footprint model

Lagrangian stochastic models use characteristics of prevailing turbulence to calculate trajectories of individual air parcels. The overall flux footprint consists of the integral contribution of several thousand simulated particles that are carried by turbulent air motion along their individual paths between the position where they are released from and the observation point. This technique allows the consideration of horizontally heterogeneous flow conditions, effects of canopy flow on the measured fluxes, and a more realistic treatment of diffusion.

In this study, the Thomson (1987) three dimensional LS trajectory model of Langevin type (e.g. Wilson et al., 1983; Wilson and Sawford, 1996) was used for estimation of the flux footprint functions. The simulations were performed releasing $5 \cdot 10^4$ particles from the height equal to roughness length, and they were followed until the upwind distance accounting approximately 90 percent of the total flux. Due to the stochastic nature of the model, the precise source area of certain percentage could not be defined. In addition to being carried downwind by horizontal advection, the particles were dispersed by turbulent diffusion in vertical, along mean wind and cross mean wind directions. The particles tending downwards near to the surface were perfectly reflected at the height z_0. The parameterization of the flow statistics and the effect of stability on the profiles followed those used in Rannik et al. (2003) except for the roughness sublayer effect which was not taken into account. Consequently, the profiles of the mean wind speed u, the wind fluctuations (σ_u; σ_v; σ_w) and the dissipation rate of turbulent kinetic energy ε followed those of the atmospheric surface layer.

A table of weighting factors, similar to that used with the analytical FSAM as described above, was chosen as output format. These tables were calculated separately for 21 stability classes, 20 roughness lengths and 28 observation heights. The grid sizes of those output tables were adapted to the stability class, although roughness length and measurement height also have an influence on the dimensions of the footprint. For each measurement, the pre-calculated table that was closest to the measured values of all those three characteristics was chosen. Since the model neglected the within canopy flow, the difference between actual measurement height and displacement height was used as the observation height for the model.

3.3 *Footprint calculation for scintillometer measurements*

Both footprint models used for this study have been developed to determine the source area for measurements carried out at a single point in space. To modify them for use on line measurements such as scintillometers, a superposition of multiple model runs was tested and implemented in a software package especially for this study. To define the measurement path, the cells of the land use map containing the transmitter and the receiver, respectively, had to be given as an input. The software approximated the scintillometer path by identifying the cells of the map that are crossed by the laser beam between these two positions. Thus, the total number of cells depends on path length and map resolution. In case of the STINHO-2 experiment, the map resolution for the footprint calculations was set to 2 m, resulting in 71 matrix cells for the approximation of the scintillometer paths 1 and 3, and 43 cells for scintillometer path 2. Tests on the influence of the matrix resolution, using a matrix with a resolution of 1 m as a reference, (data not shown) revealed strongly deviating results with a resolution of 10 m, while a resolution of 5 m in the measurement setup produced differences of up to only 5 percent. For the employed 2 m matrix, the deviations did not exceed 1.5 percent, and thus are negligible.

With a procedure described by Göckede et al. (2004) a footprint-averaged roughness length was determined for every fifth of the cells representing the scintillometer path, while the z_0-values for the cells in between were interpolated linearly. Using these as input values, an individual footprint calculation was subsequently performed for each cell along the scintillometer path. The meteorological parameters needed in the footprint model were taken from the eddy-covariance measurement position for which the most similar land use composition in the source area had been determined. This procedure had to be performed iteratively, as the land use composition of the actual position was not known a priori. In order to take into account that the centre part of the path has the highest influence on the scintillometer measurements (e.g. Thiermann and Grassl, 1992), each source area was normalized with a weighting factor obtained by a bell shaped weighting function (V. Thiermann, personal communication),

$$W(x) = A \cdot x^{11/6} \cdot (P - x)^{11/6}$$

where W(x) is the weighting factor [-] for position x [m] along the measurement path with a total length P [m]. A as a scaling factor is of no importance for the footprint studies.

Finally, the addition of all individual normalized source areas along the scintillometer path yielded the source weight function for the line measurement. As already demonstrated by Meijninger et al. (2002), both the total size and the form of the source area for scintillometer measurements are highly dependent on the relationship between wind direction and path orientation. With the wind blowing perpendicular to the path, a very broad source area is computed, with the width mostly dependent on the path length. For a wind direction parallel to the path orientation, the width of the source area is much smaller and mostly dependent on the standard deviation of the crosswind component, while the peak of the source weight function is much more pronounced.

3.4 *Calculation of the flux contribution from different types of land use*

Both footprint models described above were employed to determine the flux contribution of different types of land use to the total flux measured. These results were obtained by implementing the footprint algorithms into a software package that was originally designed to perform quality assessment studies for complex flux measurement sites (Göckede et al., 2004, 2005). For both point and line measurements, the computed source areas are projected onto a discrete map representing the horizontal

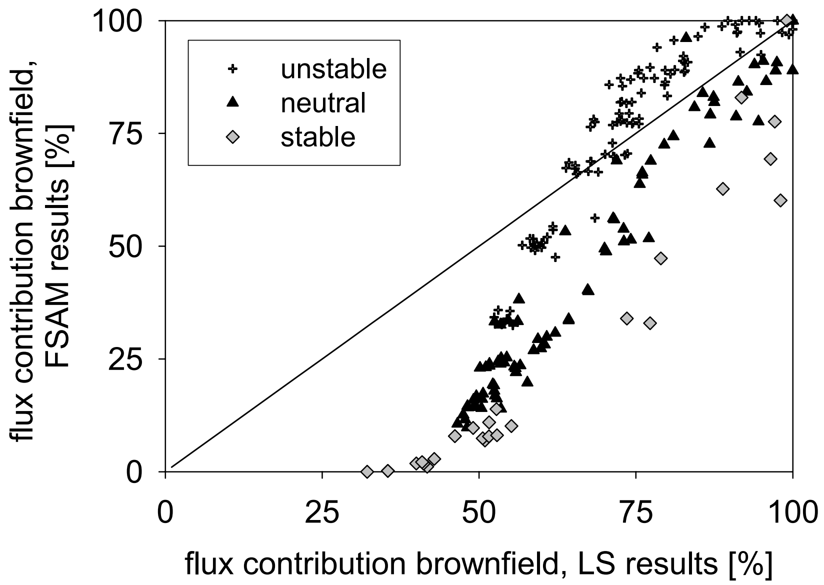

Fig. 2. Comparison of the footprint results of the analytic and LS footprint model for the percentage flux contribution of the brownfield area at eddy-covariance measurement position D.

structure of the land use types in the area surrounding the sensor, assigning a weighting factor to each cell of the map. These weighting factors are sorted by land use type and subsequently summarized, yielding the contribution of each type to the total flux. In this context, each land use type was assumed to be a homogeneous source for the quantity observed, the sensible heat flux.

Prior to the evaluation of the footprint models with flux data, the results for the flux contribution of a specific land use type were compared to demonstrate the differences between the two models. Figure 2 shows the flux contributions of the brownfield area predicted by the two footprint models plotted against each other for the eddy-covariance position D, which is located in the centre of the brownfield.

This example demonstrates that even at measurement heights of only a few meters above ground level and without the consideration of within-canopy flow effects analytical and LS footprint models can produce results that differ significantly. Especially during stable and neutral stratification, the flux contribution from the brownfield area calculated by the LS model may exceed that of the FSAM by up to 45 percent, while during unstable stratification, the flux contribution calculated by FSAM is frequently slightly higher than the LS model results. The difference is mostly due to different treatment of alongwind diffusion, which the LS model takes into account, while the analytical FSAM neglects it completely. Thus, for the stochastic model the peak of the source weight function is closer to the measurement point than for the analytical model, and it also includes contributions from sources downwind from the observation point (e.g. Rannik et al., 2000; Kljun et al., 2002). Furthermore, due to the different treatment of the alongwind diffusion the peak of the source weight function is very pronounced for the LS model and much higher than that of FSAM. With increasing upwind distance from the peak position, the crosswind integrated flux contribution decreases quickly, but had a lengthy extension due to stochastic noise, while for the analytical model the crosswind integrated flux contributions are higher in the region upwind of the peak, but do not extend so far into the upwind direction (e.g. Rannik et al., 2000; Kljun et al., 2002).

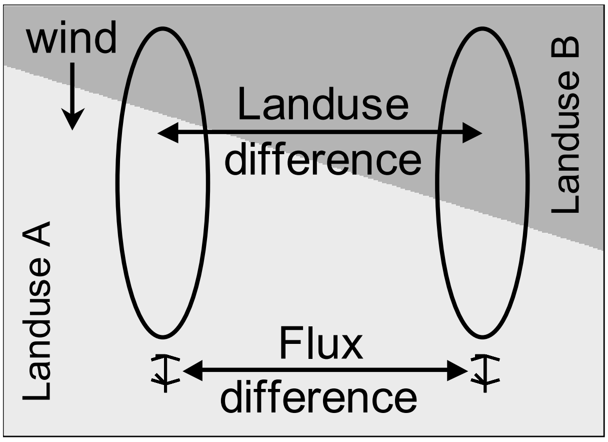

Fig. 3. Sketch of the first footprint validation approach comparing the measured differences of the observed parameter between two sensor positions with the differences in the composition of their source areas as determined by a footprint model.

4 Evaluation approach 1: Comparison of measured flux differences and modeled land use differences for pairs of measurement positions

In the first footprint evaluation approach with natural tracers, results from two measurement positions in heterogeneous terrain without using additional reference measurements to define the exact source strength for each type of land use were compared. In this comparison, knowledge of the exact source strengths and their variations was not necessary as both positions were influenced in the same way by changes. Thus, the minimum sensor requirement for this approach consisted of two measurement positions for the quantity under consideration.

This approach was based on the assumption that changing flux contributions of different types of land use in the source area of a sensor result in changes of the measured quantity, providing that the source strengths of the different land use types are significantly different. Thus, for the comparison study, the two sensor positions had to be chosen such that changing wind directions and stability regimes induce a wide range of differences between the source area compositions (Figure 3). It was expected that, ideally, there would be a distinct functional dependence between measured differences of the quantity and modeled flux contribution differences of the land use types. Thus, this approach aimed at identifying correlations between these two sets of differences, which could serve as a measure for the performance of the employed footprint model.

Using the approach described above and the sensible heat flux as the measured quantity, comparison studies were conducted for the six possible pair combinations of eddy-covariance complexes, and three pair combinations of scintillometer measurement paths. However, the desired wide range of computed flux contribution differences together with a large enough high-quality data set for a sound evaluation could only be obtained for a comparison between eddy-covariance positions A and D, and between the scintillometer paths S_1 and S_2. As both analyses produced the same trends, for reasons of brevity only the results of the scintillometer comparison, that were slightly less scattered, are shown here. In Figure 4, the relative differences of the sensible heat flux measured by the scintillometers S_1 and S_2 are plotted against the differences of the flux contributions of the brownfield area as computed by the analytical or LS footprint model.

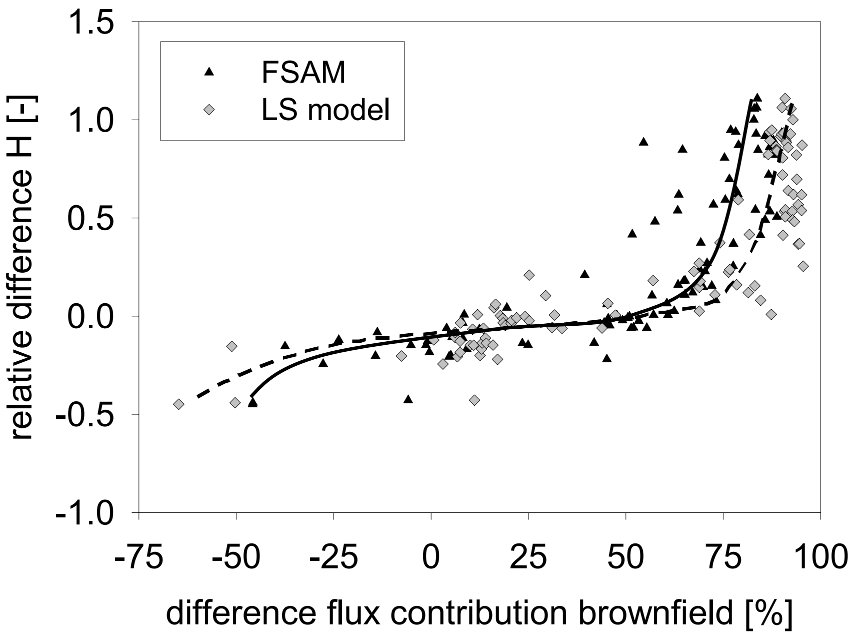

Fig. 4. Results for the first footprint evaluation approach, the comparison of measured flux differences and modeled land use differences for pairs of measurement positions. For the scintillometer positions 1 and 2, the measured flux differences of the sensible heat flux H [K m s^{-1}] are plotted against the flux contribution differences of the brownfield area as computed by the footprint models. The sensible heat flux differences were normalized with the mean value [K m s^{-1}] measured at both positions, and are thus displayed dimensionless. The lines (solid: analytic FSAM; dashed: LS model) are included as visual guides and do not follow any function.

The visualization of the results for the two scintillometer paths 1 and 2 reveals that high differences in the measured fluxes corresponded with high differences in the computed flux contribution of the brownfield area, whereas for a similar source area composition the flux differences approached zero. Although the results for both footprint models tested were considerably scattered, the general relationship between measurement data and model results could clearly be demonstrated with the employed evaluation approach. However, a definite equation for a correlation analysis between flux measurements and source area composition could not be identified. The lines shown in Figure 4 are only included as visual guides and do not follow any specific function. As a consequence, a quantitative evaluation of the results was not possible with this comparison approach. The results indicate that both footprint models produced source areas that generally corresponded with the characteristics of the measurement data, whereas no information could be obtained as to which of the footprint models produced the better results.

5 Evaluation approach 2: Correlation analysis between measured and modeled quantities using reference measurements

The second footprint evaluation approach made use of additional reference measurements to determine the source strength of the land use types in the observation area. This information allowed direct analysis as to whether or not the fluxes measured at a position with inhomogeneous source area corresponded to the fluxes emitted within the modeled source area. In the simplest version at an experimental site composed of two types of land use, this approach requires at least three measurement positions, one with a mixed fetch position and two as reference measurements for each type of land use.

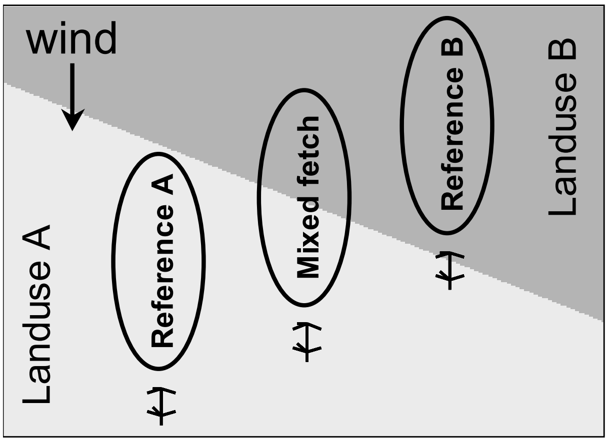

Fig. 5. Sketch of the second footprint validation approach analyzing the correlation between measured fluxes at a mixed fetch position and modeled fluxes, which are composed of reference measurements using footprint model results.

The basic idea of this second comparison approach was that a modeled value of a quantity for the measurement position with mixed source area could be composed of reference values for each type of land use weighted with footprint results. The first two sensors were placed at positions with mostly homogeneous source areas for one type of land use. The third sensor was set up so that the source area was usually inhomogeneous, with the composition of land use types changing with varying atmospheric conditions (Figure 5). To obtain a modeled value of the quantity to be observed, as a first step the flux percentages of both land use types had to be determined for the mixed fetch position. According to this ratio the measurement data of the two reference positions subsequently were mixed, yielding a weighted average value based on the actual source strengths within the source area. This comparison approach was based on the assumption that these average values correspond with the values directly measured at the position with inhomogeneous source area. Accordingly, in the absence of any additional factors, deviations between both data sets indicated an incorrect computation of the source area. Thus, the coefficient of determination of a linear regression between measured and modeled quantities could be used as a measure for the performance of the footprint model.

Again using the sensible heat flux as the quantity under consideration, this footprint evaluation approach was tested using the data of the four eddy-covariance measurement complexes A to D, with the results shown in Figure 6. The scintillometer measurements could not be used in this case because of the arrangement of the paths; only in very few cases could two of them serve as reference measurements. For this analysis, both the position with the mixed source area and the two reference positions were not fixed, but were chosen according to the footprint results for the actual atmospheric conditions. As a reference position for the grassland area either position B or C was chosen, according to which of them had higher flux contribution from grassland. For the brownfield area, the same choice was made between positions A and D; however, in this case the position with the lower flux contribution from brownfield was chosen to serve as the position with mixed source area. Only data sets with both reference positions having a flux contribution of more than 85 percent from grassland or brownfield, respectively, were considered in the analysis.

The results of this study displayed in Figure 6 indicate a close correlation between measured and modeled values of the sensible heat flux. For both the analytical and the LS footprint model, coefficients of determination r^2

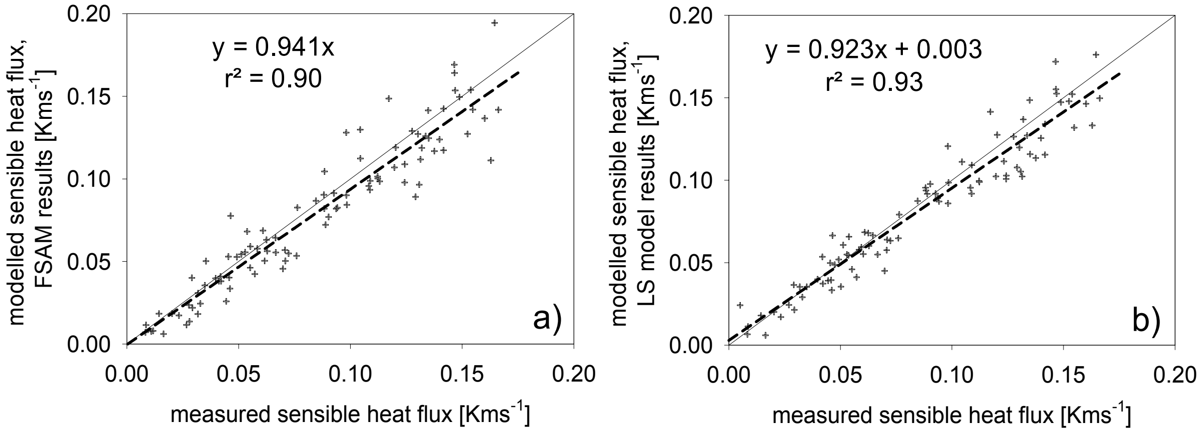

Fig. 6. Test of the second footprint evaluation approach using natural tracers with sensible heat flux data measured by the eddy-covariance complexes during the STINHO-2 experiment. The correlation analysis between measured fluxes and fluxes modeled using reference data and footprint results was performed with a) the analytic FSAM model, and b) the LS model.

were close to 0.9, indicating the high quality of the modeled source area compositions. The slightly higher r^2 values obtained for the LS model suggest that this model provided better results than the analytic FSAM; however, the differences between the models are clearly not significant. To interpret these results, keep in mind that a r^2 value of 0.88 can also be obtained for a regression analysis between H measurements at the brownfield reference and at the mixed fetch position, even without any footprint weighted averaging, because these measurements were driven by the same incoming radiation.

The principle advantage of the second comparison approach was that the functional relationship between measured and modeled quantities is clearly linear. Assuming that a) the reference measurements are truly representative for the specific type of land use, b) effects disturbing the flow such as internal boundary layers can be neglected, and c) there is no additional uncertainty because of measurement errors or instrumental effects, the data scatter could be attributed to the imperfection of footprint modeling. In fact, all three disturbing effects listed above contributed to the scatter of the data, as will be discussed in the following Section 6. Of the two validation methods tested here, this second approach comparing measured and modeled parameters is suggested for future studies because the calculation of the coefficient of determination r^2 enables a quantitative evaluation of the accuracy of the footprint model, and a more objective footprint model comparison.

6 Discussion and Conclusions

The test of the two different footprint validation approaches using natural tracers demonstrated that simple field scale experiments with basic eddy-covariance or scintillometer instrumentation can provide valuable information for footprint evaluations. However, the approaches could be further improved by using a more suitable data set. As the STINHO-2 experiment was not originally designed for footprint evaluation purposes, but was chosen for this study as a low-cost data source of high quality, experimental deficits reduced the significance of the findings. For example, the land use types were not completely homogeneous, and therefore point measurements of the source strength might not have been representative for the experimental area in whole. Especially the brownfield part was affected by the presence of a small underground well. As a consequence, soil moisture and soil temperature were slightly inhomogeneous as could be seen by infrared aerial photographs, with the effect of horizontally varying source strength for the sensible heat flux. Secondly, the instrumentation of the four eddy-covariance measurement complexes was not uniform (Table 1). As a consequence, an instrument comparison experiment using measurement complex A as a reference, which was conducted with standardized fetch conditions for all sensors before the STINHO-2 experiment, revealed mean flux deviations between different pairs of instruments by a factor of 0.93 to 0.83. Furthermore, a longer measurement period would have provided an option to differentiate between stability classes, and also enabled the use of a threshold higher than 85 percent to consider a source area as homogeneous and thus representative for one type of land use. All the influencing factors listed above created some additional scatter to the data, so that the differences in the comparison between measured and modeled sensible heat fluxes in Section 5 could not be solely attributed to incorrect footprint calculations. These uncertainties partly exceeded the deviations induced by the use of different footprint models, and thus a comparison between the two models on a quantitative basis did not provide significant differences. In addition, in some cases the source strengths of the different land use types were so close to each other that even significant differences in the footprint results as shown in Figure 2 did not generate significant deviations in the modeled fluxes.

Disturbing effects of the turbulent flow conditions such as internal boundary layers can also produce additional scatter; however, this cannot be avoided as both footprint validation approaches are based on measurements in heterogeneous terrain. Furthermore, the performance of the validation approaches tested could be improved by analyzing quantities such as the CO_2 flux that can be regarded as passive tracers, instead of using the sensible heat flux H that has considerable influence on the flow conditions.

Scintillometer measurements proved to be valuable for footprint evaluation studies based on natural tracers. Although some of the main advantages of these instruments such as the ability to measure very close to the ground, or the small averaging times were irrelevant here, (e.g. DeBruin, 2002), the small random errors allowed for a more accurate footprint comparison than using the eddy-covariance data. However, the technique relies on stability functions that are still not well established for scintillometers (e.g. DeBruin et al., 2002). The problematic influence of horizontal heterogeneity on the applicability of the scintillometer equations was tested in several studies (e.g. Chehbouni et al., 2000; Beyrich et al., 2002; Meijninger et al., 2002) for large aperture scintillometers with the result that scintillometer methods may also be applied over moderately inhomogeneous terrain. These findings could not be supported by the study presented here for the DBSAS technique applied, as no direct comparison between scintillometer measurements and e.g. eddy-covariance data was performed. Such a comparison was not performed because of the systematic differences between these measurement techniques found e.g. by DeBruin et al. (2002) or Hartogensis et al. (2002); however, for the comparisons among the scintillometers themselves these differences were not important.

According to our analysis the two footprint models used for this study, the analytic FSAM model (Schmid, 1994, 1997) and the LS trajectory model by Rannik et al. (2000, 2003), both produce satisfactory results of the land use composition within the source areas under the conditions chosen. Quantitatively, the second footprint evaluation approach tested revealed a slightly better performance of the LS footprint model in comparison to FSAM. However, due to the additional scatter induced by the non-ideal experimental setup, the differences found between the two footprint models were not significant. As a consequence, the deviating results between these two models found in the footprint comparison study of Kljun et al. (2002) could not be confirmed here.

Overall, our findings demonstrate that natural tracer experiments can serve as a low-cost and practical alternative to artificial tracer experiments for footprint validation purposes as suggested by Foken and Leclerc (2004), but the accuracy of the results depends strongly on the experimental setup. The easiest option of using existing data sets, as in the study presented, usually implies compromises in the measurement setup, and probably introduces additional scatter and a reduced significance of the results. However, the first footprint validation approach, which compares measured flux differences with modeled land use differences for a pair of measurement positions, proved its suitability as a qualitative test for the performance of a footprint model in inhomogeneous conditions. It can be accomplished with simple instrumental setup to detect general relationships between measurements and footprint results. Nevertheless, the lack of a precise functional form of the correlation function does not enable a footprint model comparison on a quantitative basis. The second validation approach, the correlation analysis between measured and modeled quantities using reference measurements, enabled a quantitative footprint model evaluation based on the obtained coefficient of determination. Although a more sophisticated instrumental setup with at least three measurement positions is required, this approach is clearly to be preferred because it allows for a direct comparison of the performance of different models.

The results could be further improved by the use of natural tracer experiments that are especially designed for footprint validation purposes. Such experiments, which are still cheaper and less complicated than artificial tracer studies, should make use of a uniform experimental setup that also monitors passive tracers such as the CO_2-flux and the individual land use classes in the experimental area should be homogeneous sources or sinks for the quantity observed. The measurements should be performed in a heterogeneous terrain with a clearly defined and simple structure, while aerodynamic step changes should be avoided as far as possible. Additional sensors monitoring the source strengths at several positions within one type of land use, or operating at several measurement heights at the mixed fetch position in order to allow for several simultaneous evaluations, could further improve the results.

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References

Andreas, E.L., 1992. Uncertainty in a path-averaged measurement of the friction velocity u_*. J. Appl. Meteorol. 31: 1312-1321.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. and Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Adv. Ecol. Res. 30: 113-175.

Baldocchi, D.D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Fuentes, J.D., Goldstein, A., Katul, G., Law, B.E., Lee, X., Malhi, Y., Meyers, T., Munger, J.W., Oechel, W., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K. and Wofsy, S., 2001. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapour and energy flux densities. Bull. Amer. Meteorol. Soc. 82: 2415-2435.

Beyrich, F., De Bruin, H.A.R., Meijninger, W.M.L., Schipper, J.W. and Lohse, H., 2002a. Results from one-year continuous operation of a large aperture scintillometer over a heterogeneous land surface. Boundary-Layer Meteorol. 105: 85-97.

Beyrich, F., Herzog, H.J. and Neisser, J., 2002b. The LITFASS project of DWD and the LITFASS-98 experiment: The project strategy and the experimental setup. Theor. Appl. Climatol. 73: 3-18.

Chehbouni, A., Watts, C., Lagouarde, J.-P., Kerr, Y.H., Rodriguez, J.-C., Bonnefond, J.-M., Santiago, F., Dedieu, G., Goodrich, D.C. and Unkrich, C., 2000. Estimation of heat and momentum fluxes over complex terrain using a large aperture scintillometer. Agric. For. Meteorol. 105: 215-226.

Cooper, D.I., Eichinger, W.E., Archuleta, J., Hipps, L., Kao, J., Leclerc, M.Y., Neale, C.M. and Prueger, J., 2003. Spatial source-area analysis of three-dimensional moisture fields from lidar, eddy covariance, and a footprint model. Agric. For. Meteorol. 114: 213-234.

DeBruin, H.A.R., 2002. Introduction: Renaissance of scintillometry. Boundary-Layer Meteorol. 105: 1-4.

DeBruin, H.A.R., Meijninger, W.M.L., Smedman, A.-S. and Magnusson, M., 2002. Displaced-Beam Small Aperture Scintillometer Test. Part I: The Wintex Data-Set. Boundary-Layer Meteorol. 105: 129-148.

Finn, D., Lamb, B., Leclerc, M.Y. and Horst, T.W., 1996. Experimental evaluation of analytical and Lagrangian surface-layer flux footprint models. Boundary-Layer Meteorol. 80: 283-308.

Flesch, T.K., Wilson, J.D. and Yee, E., 1995. Backward-time Lagrangian stochastic dispersion models and their application to estimate gaseous emissions. J. Appl. Meteorol. 34: 1320-1332.

Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B.D. and Munger, J.W., 2004. Post-field data quality control. In: Lee, X., Massman, W.J. and Law, B.E. (eds), Handbook of Micrometeorology: A guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp. 181-208.

Foken, T. and Leclerc, M.Y., 2004. Methods and limitations in validation of footprint models. Agric. For. Meteorol. 127: 223-234.

Foken, T., Mangold, A., Hierteis, M., Wichura, B. and Rebmann, C., 1999. Characterization of the heterogeneity of the terrain by normalized turbulence characteristics. In: Proceedings of the 13th Symposium on Boundary Layer and Turbulence, Dallas, TX, American Meteorological Society, pp. 26-27.

Foken, T., Mangold, A., Rebmann, C. and Wichura, B., 2000. Characterization of a complex measuring site for flux measurements. In: Proceedings of the 14th Symposium on Boundary Layer and Turbulence, Aspen, CO, American Meteorological Society, pp. 388-389.

Foken, T. and Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. Agric. For. Meteorol. 78: 83-105.

Göckede, M., Markkanen, T., Hasager, C.B. and Foken, T., 2005. Use of footprint modelling for the characterisation of complex measurement sites. Boundary-Layer Meteorol. (submitted).

Göckede, M., Rebmann, C. and Foken, T., 2004. A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. Agric. For. Meteorol. 127: 175-188.

Gryning, S.-E., Holtslag, A.A.M., Irwin, J.S. and Sivertsen, B., 1987. Applied dispersion modelling based on meteorological scaling parameters. Atmos. Environ. 21: 79-89.

Haenel, H.D. and Grünhage, L., 1999. Footprint analysis: A closed analytical solution based on height-dependent profiles of wind speed and eddy viscosity. Boundary-Layer Meteorol. 93: 395-409.

Horst, T.W. and Weil, J.C., 1992. Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary-Layer Meteorol. 59: 279-296.

Horst, T.W. and Weil, J.C., 1994. How far is far enough - the fetch requirements for micrometeorological measurement of surface fluxes. J. Atmos. Ocean. Technol. 11: 1018-1025.

Horst, T.W. and Weil, J.C., 1995. Corrigenda: How far is far enough - the fetch requirements for micrometeorological measurements of surface fluxes. J. Atmos. Ocean. Technol. 12: 447.

Kljun, N., Rotach, M.W. and Schmid, H.P., 2002. A three-dimensional backward lagrangian footprint model for a wide range of boundary-layer stratifications. Boundary-Layer Meteorol. 103: 205-226.

Leclerc, M.Y., Karipot, A., Prabha, T., Allwine, G., Lamb, B. and Gholz, H.L., 2003a. Impact of non-local advection on flux footprints over a tall forest canopy: a tracer flux experiment. Agric. For. Meteorol. 115: 19-30.

Leclerc, M.Y., Meskhidze, N. and Finn, D., 2003b. Comparison between measured tracer fluxes and footprint model predictions over a homogeneous canopy of intermediate roughness. Agric. For. Meteorol. 117: 145-158.

Leclerc, M.Y., Shen, S. and Lamb, B., 1997. Observations and large-eddy simulation modeling of footprints in the lower convective boundary layer. J. Geophys. Res.-Atmos. 102: 9323-9334.

Leclerc, M.Y. and Thurtell, G.W., 1990. Footprint prediction of scalar fluxes using a Markovian analysis. Boundary-Layer Meteorol. 52: 247-258.

Liu, H.P., Peters, G. and Foken, T., 2001. New equations for sonic temperature variance and buoyancy heat flux with an omnidirectional sonic anemometer. Boundary-Layer Meteorol. 100: 459-468.

Meijninger, W.M.L., Hartogensis, O.K., Kohsiek, W., Hoedjes, J.C.B., Zuurbier, R.M. and De Bruin, H.A.R., 2002. Determination of area-averaged sensible heat fluxes with a large aperture scintillometer over a heterogeneous surface - Flevoland field experiment. Boundary-Layer Meteorol. 105: 37-62.

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorol. 37: 17-35.

Rannik, Ü., Aubinet, M., Kurbanmuradov, O., Sabelfeld, K.K., Markkanen, T. and Vesala, T., 2000. Footprint analysis for measurements over a heterogeneous forest. Boundary-Layer Meteorol. 97: 137-166.

Rannik, Ü., Markkanen, T., Raittila, J., Hari, P. and Vesala, T., 2003. Turbulence statistics inside and over forest: Influence on footprint prediction. Boundary-Layer Meteorol. 109: 163-189.

Schmid, H.P., 1994. Source areas for scalars and scalar fluxes. Boundary-Layer Meteorol. 67: 293-318.

Schmid, H.P., 1997. Experimental design for flux measurements: matching scales of observations and fluxes. Agric. For. Meteorol. 87: 179-200.

Schmid, H.P., 2002. Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. Agric. For. Meteorol. 113: 159-183.

Schmid, H.P. and Oke, T.R., 1990. A model to estimate the source area contributing to turbulent exchange in the surface layer over patchy terrain. Quart. J. Roy. Meteorol. Soc. 116: 965-988.

Schuepp, P.H., Leclerc, M.Y., MacPherson, J.I. and Desjardins, R.L., 1990. Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation. Boundary-Layer Meteorol. 50: 355-373.

Thiermann, V., 1992. A displaced-beam scintillometer for line-averaged measurements of surface turbulence. In: 10th Symposium on Turbulence and Diffusion, Portland, OR, American Meteorological Society, pp. 244-247.

Thiermann, V. and Grassl, H., 1992. The measurement of turbulent surface layer fluxes by use of bichromatic scintillation. Boundary-Layer Meteorol. 58: 367-391.

Thomson, D.J., 1987. Criteria for the selection of stochastic models of particle trajectories in turbulent flows. J. Fluid Mech. 180: 529-556.

van Ulden, A.P., 1978. Simple estimates for the vertical diffusion from sources near the ground. Atmos. Environ. 12: 2125-2129.

Webb, E.K., Pearman, G.I. and Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quart. J. Roy. Meteorol. Soc. 106: 85-100.

Wilczak, J.M., Oncley, S.P. and Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol. 99: 127-150.

Wilson, J.D., Legg, B.J. and Thomson, D.J., 1983. Calculation of particle trajectories in the presence of a gradient in turbulent-velocity variance. Boundary-Layer Meteorol. 27: 163-169.

Wilson, J.D. and Sawford, B.L., 1996. Review of Lagrangian stochastic models for trajectories in the turbulent atmosphere. Boundary-Layer Meteorol. 78: 191-210.

Appendix H: CO_2 efflux from agricultural soils in Eastern Germany – comparison of a closed chamber system with eddy covariance measurements

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With 5 Figures

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Summary

In order to quantify the effects of temperature and soil water content on soil respiration, during June and July 2002 CO_2 soil efflux was measured with a closed chamber (non-steady state, flow through) system in the field. The amount of CO_2 emission was highly dependent on the land-use in the observation area, which consisted of meadow soil and brownfield. The CO_2 emission from the brownfield ranged from 0.9 to 5.5 µmol CO_2 m^{-2} s^{-1}, and that for meadow soil from 1.1 to 12.6 µmol CO_2 m^{-2} s^{-1}. Soil respiration, as a function of soil temperature (T_{soil}), relative soil water content (RSWC), soil pH, and the soil carbon / nitrogen ratio (C/N), was analysed by a modified closed non-linear regression model. Between 63 % and 81 % of the variation of soil CO_2 emission could be explained with changes of T_{soil}, RSWC, pH, and C/N for the individual chambers on the brownfield.

Subsequent analysis involved a comparison of the soil chamber results with eddy covariance (EC) measurements of one week, and included a footprint analysis to account for the influence of the different land use types on the measurements. For this, EC data (143 measurements after quality check) were restricted to those originating from the brownfield area with more than 90 % of the flux. For a second comparison, the net ecosystem exchange (NEE) was calculated for different parts of the meadow using the SVAT model PROXEL. Together with the respiration from the brownfield, a weighted average of model NEE was produced using the flux contribution determined by the footprint model. Acceptable agreement (r^2 = 0.69) was found between the modelled data and individual EC measurements, except during situations where the performance of the footprint model was disturbed by internal boundary layer effects.

1 Introduction

The increase of CO_2 in the atmosphere plays a prominent role in global warming. The problem is caused by anthropogenic activities like industrial processes (Koch et al., 2000) and burning of fossil fuels (Roulet, 2000; Sims and Bradford, 2001). Crop and tillage management can also increase atmospheric CO_2 (Kessavalou et al., 1998). Land use changes are responsible for 20 % of global CO_2 emissions (Schulze et al., 2002). In particular, CO_2 flux from the soil surface to the atmosphere is the

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major source of CO_2 in terrestrial ecosystems (Schwartz and Bazzaz, 1973; Nakadai et al., 2002). Agricultural fallow acts as a carbon emitter (Soegaard, 1999; Soegaard et al., 2003), whereas forests constitute as a carbon sink (Hollinger et al., 1998; Schulze et al., 1999; Kelliher et al., 1999).

Several studies exist on CO_2 efflux of meadow soils (e.g. Hunt et al., 2002; Maljanen et al., 2001b; Kelliher et al., 2002) and agricultural soils (e.g. Ball et al., 1999; Prieme and Christensen, 2001; Nakadai et al., 2002; Maljanen et al., 2001a). The differences between tillage and no-tillage effects on CO_2 fluxes are well documented (Chan and Heeman, 1996; Ball et al., 1999; Chan et al., 2002). In the case of tillage, respiration is often stimulated (Roberts and Chan, 1990).

Soil respiration depends on numerous factors. A positive correlation between soil temperature and soil respiration is well described by several authors (Singh and Gupta, 1977; Reich and Schlesinger, 1992). Also, soil moisture affects the CO_2 soil efflux (Brunnell et al., 1977; Gupta and Singh, 1981). Models were elaborated to describe the impacts of such factors based on linear regression analysis (Witkamp, 1966), Q_{10} (Reich and Schlesinger, 1992) or power relationship (Kucera and Kirkham, 1971), as well as relationships based on the Arrhenius form (Howard and Howard, 1979). Root respiration (Law et al., 1999; Kutsch et al., 2001), heterotrophic respiration (Goulden et al., 1996; Hollinger et al., 1998), substrate amount (Zak et al., 2000), and autotrophic respiration (Curtis et al., 2002) also have an effect on soil respiration. Because the existing models cannot explain the variation of the CO_2 soil efflux measurements well (see Table 1) modelled, there is a need to include additional factors for the modelling of soil respiration.

Comparisons of CO_2 data measured with eddy covariance and soil chambers, respectively, can be used to cross-validate the methods. While both systems are widely applied, they still have individual disadvantages. On the one hand, the eddy covariance method is based on a number of theoretical assumptions, for example steady state conditions of the flow, horizontal homogeneity, or no advection. In principle, these requirements cannot be fulfilled completely during field experiments, and large deviations from the assumed ideal conditions may occur, especially under stable conditions, i.e. calm nights (Baldocchi, 1997; Lee, 1998; Rayment and Jarvis, 2000; Schulze et al., 2002). For this reason, extensive quality checks (see e.g. Foken and Wichura, 1996; Foken et al., 2004) have to be performed to verify that the measured eddy covariance data accords with the theoretical assumptions, and to assign quality flags to separate high quality data from measurements, which have to be discarded. On the other hand when using chambers to determine the CO_2 efflux, chamber effects such as rising temperature or inhibition of turbulent air flow may lead to bias (Norman et al., 1997; Pumpanen et al., 2004). Chambers may also cause disturbance of the air pressure and alteration of CO_2 concentra-

Table 1. Comparison of the results of different soil respiration models for the data of this study.

	Tsoil	RSWC	pH	C/N	meadow r^2	brownfield r^2
Wittkamp (1966)	X				0	0.43
Reich and Schlesinger (1992)	X				0.12	0.41
Janssens et al. (2001)	X	X			0.19	0.39
Reichstein et al. (2002)	X	X			0.51	0.52
this study	X	X	X	X	0.59	0.70

tion in the soil (Healy et al., 1996; Davidson et al., 2002). Several studies revealed that the eddy covariance technique produces CO_2 fluxes, which are between 30 % and 50 % (30 % Subke, 2002; 33 % Norman et al., 1997; 36 % Janssens et al., 2001; 39 % Matteucci et al., 2000; 50 % Law et al., 1999) smaller than the corresponding closed chambers measurements. This divergence was found to be partly due to different target areas of the measurement techniques. Whereas chamber systems quantify fluxes of small surfaces (up to 1 m^2), eddy covariance systems detect fluxes from larger areas and include – particularly in a forest – additional influencing factors including moss photosynthesis and bole respiration (Janssens et al., 2001). The situation is similar for grassland, when all plant material is removed from the interior of the chamber systems to perform the measurements, but eddy covariance instruments sample CO_2 fluxes which are affected by a variety of processes (autotrophic and heterotrophic respiration, photosynthesis). If the plant material is left in the chamber, a direct comparison of he results with eddy covariance is possible, but it is not possible to separate the contribution of soil respiration and plant photosynthesis, respectively. Accordingly, soil CO_2 emissions measured by chambers, in which the aboveground vegetation was removed, can only be compared with eddy covariance methods when the latter are not influenced by photosynthesis, or - for vegetated surfaces - when the chamber data are supplemented with simultaneous estimates of plant photosynthesis. The latter depend on a representative sample of all existing species inside the investigated area and the correct weighting of the fraction of each species.

The study presented here describes in three parts an approach to monitor the net ecosystem exchange of CO_2 (NEE) with a closed chamber system and eddy covariance measurements, and compares both methods considering footprint aspects. The study focuses on CO_2 fluxes from a brownfield surrounded by vegetated areas. Part one deals exclusively with data from the closed chamber system to parameterise the dependency of the soil CO_2 efflux on various parameters. In part two, soil respiration measured with the closed chamber system is compared with eddy covariance measurements. To ensure that both systems are influenced by the same type of CO_2 sources, a footprint analysis using the analytic FSAM (Schmid, 1994, 1997) is performed. Finally, part three of the study includes both the footprint analysis for the eddy covariance measurements and estimates for the plant photosynthesis with the intention to quantify NEE as a combination of soil respiration and leaf gas exchange measurements.

2 Methods

2.1 Site description and experimental setup

The measurements used in this study were carried out in the course of the special observation period STINHO2 of the VERTIKO (Vertical transport under complex natural conditions) project, which is part of the AFO 2000 (German Atmospheric Research 2000) programme. The experiment took place in June and July 2002 at the Falkenberg Boundary-Layer measurement site of the German Meteorological Service, at the Lindenberg observatory (52°10'01"N, 14°07'27"E, 73 m a.s.l.). The landscape in this region was formed by inland glaciers of the last ice age, with a slightly undulating orography and a heterogeneous land use structure (see e.g. Beyrich et al., 2002). The Falkenberg site itself is flat and consists of about 18 ha of managed meadow with short grass. The annual mean air temperature is 8.6°C and the annual precipitation 560 mm.

Dominating meadow species were *Lolium perenne*, *Bromus hordeaceus*, and *Taraxacum officinalis*. For this study, the meadow was optically separated into a stripe pattern, according to species composition and develop-

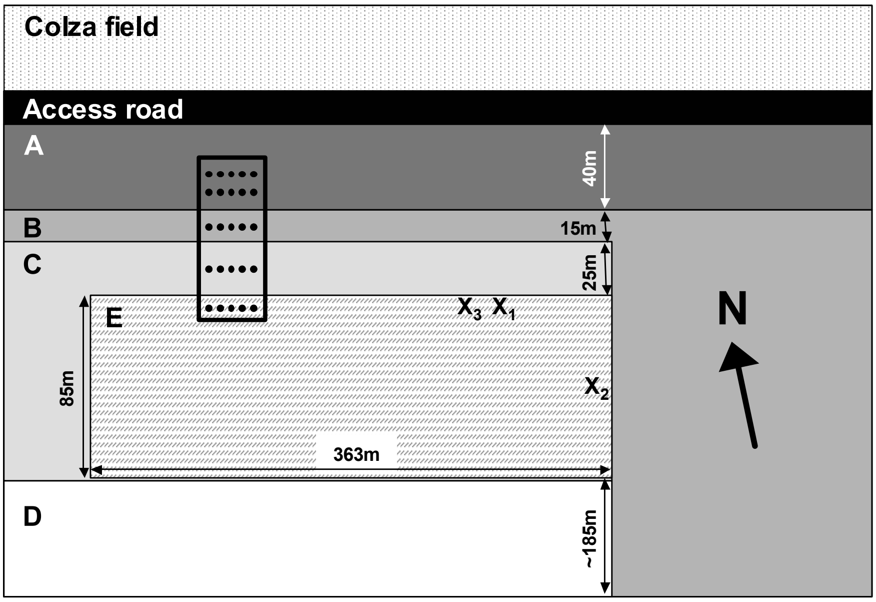


Fig. 1. Experimental setup and site description. The differentiated stripes of meadow as described in the text are labelled with the letters A to D. The brownfield area, which was generated by ploughing a part of area C in the middle of the experiment period, is labelled with E. Chamber measurements were carried out 16 days before ploughing in areas A, B and C. After ploughing area E, measurements were performed on three days in areas C and E. X_i: Eddy covariance tower positions for the different measurement periods (1: 02.07.-04.07., 19:30 UTC; 2: 04.07., 19:30 UTC – 05.07., 8:00 UTC; 3: 05.07., 8:00 UTC – 10.07.).

mental stage, with four stripes orientated approximately from east to west. These stripes were differentiated according to their leaf area indices (LAI) and root dry weight (RDW) in the upper 10 cm of the soil, and thus have a different width. They have been labelled with letters from A (northernmost) to D (southernmost), as shown in Fig. 1.

The experiment was carried out from June 4 to July 10, 2002. On June 20, a part of area C in the centre of the observation area was ploughed, separating the field campaign into two periods: period one (June 4 to June 20) with just four stripes of meadow, and period two (June 20 to July 10) with an additional brownfield. This brownfield (LAI = 0) has been labelled as area E in Fig. 1. Soil chamber measurements in the field were performed during 20 days in June and July of 2002, separated into the two periods mentioned. In the first period, soil CO_2 efflux was measured simultaneously with 5 chambers at different positions of the meadow stripes, as indicated in Fig. 1. During period two, starting at July 1, chamber measurements were carried out additionally at the brownfield.

2.2 Measurements

2.2.1 Soil efflux

The chamber method (non-steady-state flow-through chambers system) has been described in detail by Velthof and Oenema (1995) and Velthof et al. (2000). The system consists of cylindrical steel chambers (height 80 mm and diameter 197 mm) with plexiglass lids attached during the measurement. No fan was used in the system. Overheating could be avoided because single measurements were completed within 12 minutes, and soil temperatures inside and outside the chamber remained similar. The chambers were inserted 2 cm into the soil and all plant material was removed from the chambers' interiors.

The air was pumped in a closed loop from the chamber to the analyser (Photoacoustic Multi-gas Monitor, INNOVA 1312) and back to the chamber. The concentrations of CO_2 and water (for control) were determined from the air stream. Five chambers were measured alternately. Magnetic valves controlled the flow of the different chambers. The CO_2 efflux was determined from the slope of the concentration increase within the chamber using four concentrations measured at 238 s intervals. The system was tested against other measurement systems in a calibration experiment, revealing an underestimation of approximately 4 % for the system employed (see Pumpanen et al., 2004). Measurements were carried out with an offset of 2 hours between the landuse types.

2.2.2 Eddy covariance measurements

The eddy covariance tower was set up from July 2, 2002, 15UTC to July 10, 2002, 05UTC to monitor the turbulent exchange fluxes above the brownfield for the STINHO2 campaign. To maximise the fetch over this area, the tower position was changed twice to agree with the predicted wind direction for the hours to follow, as indicated by Fig. 1. However, due to both the limited extension of the ploughed area, especially in the north-south direction, and the strong rotating character of the wind direction, especially during nighttime, the measured fluxes were often affected by the brownfield as well as the surrounding meadow stripes.

Eddy covariance measurements were carried out at a frequency of 20 Hz with a Campbell CSAT3 ultrasonic anemometer and a LiCor 7500 open path gas analyser to measure water vapour and CO_2 concentrations. The measurement height was 2.0 m. Except for minor modifications, the determination of the fluxes from the raw data follows the concept proposed by Aubinet et al. (2000). Turbulent raw data were rotated according to the planar fit method (Wilczak, 2001), and subsequently the Moore- (Moore, 1986), Schotanus- (Liu et al., 2001), and WPL-corrections (Webb et al., 1980) were performed. The corrected fluxes were checked for their quality according to a scheme proposed by Foken and Wichura (1996) as presented by Foken (2003), which assigns quality flags to the specific fluxes. For the comparison of the CO_2-fluxes with the chamber measurements, only data which had a very high quality (quality check classes 1-3) for both CO_2 flux and friction velocity u_* were chosen. In addition, measurements with a mean horizontal wind speed of lower than 1 m s^{-1} were excluded because of missing turbulent exchange during wind regimes with such low speed. As a result of this quality check procedure, out of 365 possible 30-minute averages for the measurement period, only 143 (39.2 %) proved suitable for the comparison study.

2.2.3 Soil meteorological measurements and soil analysis

Soil temperature (Thermistor, Siemens M841) was recorded at 2 cm depth inside each chamber and outside the chambers every 5 minutes. Soil moisture (Theta Probe, ML2) was measured half hourly.

An analysis of the relation of total carbon to total nitrogen and pH of soil samples of each chamber were performed after finishing the flux measurements. Soil cores with a diameter of 5 cm and a depth of 10 cm were taken in the field, and soil and roots were separated manually. The remaining soil was sieved to remove stones. The root biomass and the soil were dried for three days at 105 °C. The dry mass of the roots was expressed per unit dry mass of the oven-dry soil. A part of the soil was ground with a pebble mill and the ratio of total carbon to total nitrogen in the soil was analysed by an Element Analyzer (Heraeus). The pH-value was determined from fresh soil slurry using a glass electrode (Scheffer and Schachtschabel, 2002). Incubation time of 20 g soil was 1 h in 50 g distilled water.

Measurements of canopy structural characteristics took place at the same place and time as the soil efflux measurements in a representative part of each of the four meadow types B to E as described above.

2.2.4 Leaf physiology and vegetation indices

Leaf physiological parameters (Table 3a) were obtained with LI6400 measurements of leaves, stems, flowers, and fruits of the vegetation by adjusting key parameters to reproduce the measured gas exchange. LAI was determined from biomass harvests (3 replicates) in the meadow stripes at begin and end of the campaign, and shortly before the meadow was cut. Randomly selected plots of 0.25 m^2 were cut, and biomass separated in leaves (grasses and herbaceous), stems and flowers, and necromass. Subsample leaf area was determined with a CI-202 scanner (CID inc USA) and scaled to LAI by specific leaf area (m^2 g^{-1} d.w.). For area determination of stems and inflorescences calliper, ruler, and graph paper were used, and results were scaled to area indices by area-dry weight ratio. All biomass samples were oven-dried at 75 °C. From the north to the south, maximum LAI during the field campaign was 4.7, 3.8, 1.3, and 2.0 m^2 m^{-2} (see Table 3b).

2.3 Model description

2.3.1 Non-linear regression model

The non-linear regression model used in this study Eq. (1) is well described in Reichstein et al. (2002). The model for soil respiration (R_{soil}) includes a function for soil temperature (T_{soil}, Eq. (2)) following an exponential response, and a function of soil water content (RSWC), Eq. (3):

$$R_{soil} = R_{soil,ref} \cdot f(T_{soil}) \cdot g(RSWC) \qquad (1)$$

where $R_{soil,ref}$, a fitted parameter, is the soil respiration under standard conditions (at T_{ref} and non-limiting RSWC)

$$f(T_{soil}) = \exp E_0 \frac{1}{T_{ref} - T_0} \frac{1}{T_{soil} - T_0} \qquad (2)$$

$$g(RSWC) = \frac{RSWC}{RSWC_{1/2} + RSWC} \qquad (3)$$

where E_0 is held constant at 400 [K], T_{ref} is the reference soil temperature and T_0 the lower temperature limit for R_{soil}. T_{ref} was set to 20°C and T_0 at -46.02°C (Lloyd and Taylor, 1994). $RSWC_{1/2}$ represents the RSWC at half-maximum respiration and was a fitted parameter.

In this study $R_{soil,ref}$ of Eq. (1) was extended to include the variability of the ratio of carbon to nitrogen (CN) and the pH value of the soil:

$$R_{soil,ref} = (x + CN \cdot y + pH \cdot z) \qquad (4)$$

where x , y, and z are fitted parameters.

2.3.2 Footprint model

The footprint routine used in this study is the flux source area model FSAM by Schmid (1994, 1997). This algorithm is based on the analytic footprint model by Horst and Weil (1992), and employs an extended version of the surface-layer dispersion model by Gryning et al. (1987) for the determination of the crosswind and vertical concentration distribution functions. While the Gryning model implies that footprint algorithms of FSAM cannot be solved analytically, it facilitates the inclusion of thermal stratifications and a realistic wind profile (Schmid, 1994).

Like other analytical footprint models (e.g. Schuepp et al., 1990; Horst and Weil, 1992; Haenel and Grünhage, 1999; Kormann and Meixner, 2001), FSAM assumes a constant flux layer with sources located only on the ground. The model is restricted to surface layer scaling (Schmid, 2002), in which flow conditions have to be horizontally homogeneous. The algorithms are based on the inverted plume assumption, where the mean wind is parallel but counter to the x-axis direction. Diffusion in the lateral direction is assumed to be Gaussian and vertical flux is constant with height. FSAM neglects alongwind diffusion completely, however lateral crosswind diffusion and vertical diffusion can be treated independently.

FSAM requires Obukhov length L, friction velocity u_*, standard deviation of the lateral wind speed component σ_v, and surface roughness length z_0 as input parameters. The first two parameters were taken from measurements of the eddy covariance complex, while the surface roughness length was read out for each half hourly measurement individually from matrices containing terrain information from a footprint dependent iteration process described by Göckede et al. (2004). The standard deviation of the lateral wind speed component was approximated by a modified version of the equation for the integral turbulence characteristics as proposed by Thomas and Foken (2002). The functions are listed in Table 2. The output format of the FSAM program was chosen to be a table of weighting factors indicating the relative flux contributions of quadratic fractions of the surface to the total flux measured. The side length of each quadratic surface pixel of the source weight function was fixed at 0.5 m, while the total size of the table was adapted to fit in the 90 % effect level ring. This way, in principle, a 90 % footprint is determined, but due to the inclusion of the corners of the weighting factor table, the considered flux contribution is slightly higher than 90 %.

Table 2. Recommended parameterisations of the integral turbulence characteristics of the lateral wind component, $\sigma_v\, u_*^{-1}$. With: σ_v: standard deviation of lateral wind component v, u_*: friction velocity, ζ: stability parameter ($(z-d)/L$), where z is height above the ground, d is displacement height and L is Obukhov length, z_+: normalising factor with a value of 1 m, f: Coriolis parameter. The factor (1.9/2.45) is included to account for the differences between alongwind component u and lateral wind component v (Panofsky and Dutton, 1984).

Stability range	
$-1 < \zeta < -0.2$	$-0.2 < \zeta < 0.4$
$\frac{1.9}{2.45} \cdot 4.15\left(\lvert\zeta\rvert\right)^{1/8}$	$\frac{1.9}{2.45} \cdot 0.44 \ln\left[\frac{z_+ f}{u_*}\right] + 6.3$
by Foken et al. (1991, 1997)	by Thomas and Foken (2002)

To evaluate the contribution of each specific land use class to a measured flux, the resulting source weight function is projected onto a land use matrix, which describes the terrain surrounding the tower in a discrete form. A weighting factor is assigned to each cell of this matrix, and the results are summed up for each of the different classes to yield the specific flux contribution. This procedure is described in more detail by Göckede et al. (2004).

2.3.3 Leaf gas exchange

The SVAT model PROXEL (Tenhunen et al., 1995; Falge et al., 2003) consists of four coupled compartments: atmosphere, canopy, unsaturated soil zone, and ground water table. The atmosphere provides drivers for the meteorological environment. Canopy and soil are both multi-layered. The ground water table acts as a sink for percolating water or as a source for capillary water.

Direct, sky diffuse, reflected, and transmitted radiation are calculated for sunlit and shaded leaves in each canopy layer and on the ground. Vertical profiles of wind speed and air temperature are evaluated and used for an iterative determination of leaf temperature based on leaf energy balance. Leaf photosynthesis is modelled with the Farquhar model (Farquhar and van Caemmerer, 1982; Harley and Tenhunen, 1991). The Ball et al. (1987) equation was implemented for the calculation of stomatal conductance.

The soil water balance is computed using a flexible hybrid between the layered bucket model and the numerical solution of Richards equation (Moldrup et al., 1989). Transpirational demand in the soil layers is distributed in proportion to soil resistance (Moldrup et al., 1991). The reduction of transpiration during soil water depletion is simulated by a linear dependency of leaf physiological parameters on soil water potential in root layers.

Table 3a. Constants and activation energies used for the gas exchange module of the PROXEL-model. Bold values are different for the respective area. For parameter description see Harley and Tenhunen (1991).

Parameter		Values for area A, B, C			Values for area D		Units
		flowers/stems	leaves	herbs	stems	leaves	
Dark	$F(r_d)$	9.74	2.86	2.01	7.54	2.9	-
Respiration	$E_a(r_d)$			64000			J mol^{-1}
	RDFAC			0.5			-
Stomatal	gfac	10	12.1	10.2	10.4	10.15	mmol m^{-2} s^{-1}
Conductance	gmin,	40	27	43	40	50	mmol m^{-2} s^{-1}
	gmax			500			mmol m^{-2} s^{-1}
Electron transport	$C(P_{ml})$	43.46	47.53	55.17	51.905	49.286	-
capacity	$\Delta Ha(P_{ml})$			45000			J mol^{-1}
	$\Delta Hd(P_{ml})$			200000			J mol^{-1}
	$\Delta S(P_{ml})$			640			J K^{-1} mol^{-1}
Carboxylase	$E_a(\tau)$			-28990			J mol^{-1}
kinetics	$f(\tau)$			2339.53			-
	$E_a(K_0)$			36000			J mol^{-1}
	$f(K_0)$			159.597			-
	$E_a(K_C)$			65000			J mol^{-1}
	$f(K_C)$			299.469			-
Carboxylase	$\Delta Hd(VC_{max})$			200000			J mol^{-1}
capacity	$\Delta S(VC_{max})$			660			J K^{-1} mol^{-1}
	$C(VC_{max})$	91.27	99.81	115.85	109	103.5	-
	$\Delta Ha(VC_{max})$			55000			-
Light use efficiency	α	0.049	0.065	0.048	0.065	0.0658	mol CO_2 / mol photons

Table 3b. Plant area index (PAI, m^2·m^{-2}), leaf area index of grasses and herbaceous species (LAI, m^2·m^{-2}), and area index of stems and flowers (SAI, m^2·m^{-2}) for the different areas. For the model runs area indices were linearly interpolated between those dates.

Date	Area A			Area B			Area C			Area D		
	PAI	LAI	SAI	PAI	LAI	SAI	PAI	LAI	SAI	PAI	LAI	SAI
June 4 and 5	3.8	3.4	0.4	2.2	2	0.2	0.7	0.7	0.0	2.0	1.8	0.2
June 22	4.7	4.2	0.5	3.8	3.4	0.4	1.3	1.2	0.1	n.d.	n.d.	n.d.
June 23 (after cut)	0.8	0.7	0.1	0.6	0.5	0.1	0.4	0.4	0.0	n.d.	n.d.	n.d.
July 2 and 3	3.5	3.1	0.4	2.0	1.8	0.2	0.6	0.6	0.0	1.9	1.7	0.2

3 Results and discussion

3.1 Soil respiration model

No differences were found between the soil CO_2 effluxes of the meadow soils before ploughing (Fig. 2). However, data-analyses of the soil after tilling showed lower emissions at the brownfield (Fig. 2). This may be due to the destruction of root mass and consequently a lower respiration in the brownfield areas. A larger microbial respiration, due to degradation of died roots, could have been prevented by the low soil water content at the ploughed field. The amount of the CO_2 efflux was closely linked to soil temperature, as well as to the ratio of carbon to nitrogen and the pH value of the soil (Table 4). Due to the low range of soil water content (<10 %), only a small impact from soil moisture was found both in the brownfield and in the meadow soil. The parameters x, y and z of Equation 4 were fitted to –4.54, 0.32 and 0.78. The soil water content at half-maximum respiration ($RSWC_{1/2}$) was fitted to 0.001 % due to the low range of soil water content in this period. Naganawe et al. (1989) and Kirschbaum (1995) discussed that ecosystems affected by summer drought have lower respiration rates in the summer and would be expected to vary on the basis of soil temperature alone. This corresponds to our results in this study. Temporal effects like the interval between the rain events or spatial heterogeneity of the soil's physical properties and soil microorganism activity may have influenced the high variability in soil emissions. The variations in the measured fluxes are linked to a significant decrease (slope of 0.23, r^2 = 0.98, n=5) of the C/N content in the soil from west to east (Table 4). Marschner et al. (2003) showed significant correlations between the ratio of carbon to nitrogen in the soil and the structure of bacterial and eukaryotic communities in the soil. Analyses of total carbon or total nitrogen in each chamber revealed no significant connection to the CO_2 efflux variation. Together with the C/N ratio, the pH value increased from the west to the east for the investigated field (Table 4). Several studies showed significant effects at different soil pH values (Sitaula et al., 1995; Hall et al., 1997;

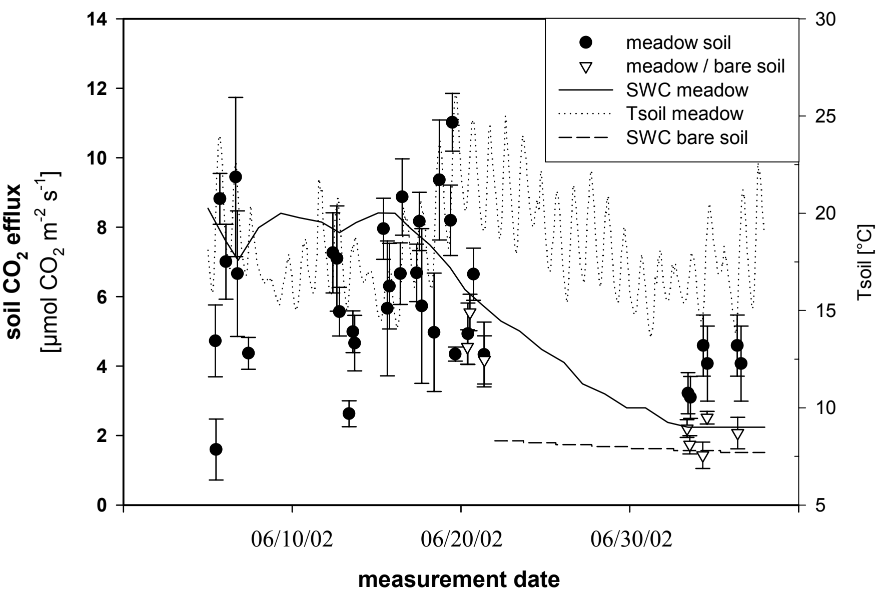


Fig. 2. Overview of the measured CO_2 fluxes, where dots represent meadow soil measurements, triangles represent measurements from the ploughed area (day of ploughing is June 20), the vertical bars represent the standard deviation of 5 simultaneous chamber measurements. The dotted line illustrates the soil temperature, the solid line is soil water content in meadow soil, and the stroked line is soil water content in the brownfield.

Table 4. Mean CO_2 soil effluxes measured with five chambers from the east (chamber 1) to the west (chamber 5) at the brownfield. C/N content and pH value in upper 10 cm of the soil, with samples collected after finishing flux measurements.

	mean CO_2 soil efflux	soil C/N content	soil pH value
chamber 1	1.75 (+/- 0.53)	9.9	5.03
chamber 2	1.96 (+/- 0.49)	10.3	5.04
chamber 3	2.09 (+/- 0.55)	10.9	5.25
chamber 4	2.36 (+/-0.73)	11.0	5.60
chamber 5	2.70 (+/- 0.83)	11.5	5.90

Andersson and Nilsson, 2001). In particular, the activity of microorganism processes increases with rising pH values (Ellis et al., 1998).

Estimates of the CO_2 emissions on the brownfield, using the non-linear regression model, agree reasonably well with the measured mean fluxes (Fig. 3 A). For individual chambers, between 63 % and 81 % of the variation of CO_2 soil emission in the brownfield could be explained by the model through changes of T_{soil}, RSWC, C/N ratio, and pH value (Table 5). Compared with the results of the individual chambers, the model using averaged parameters could explain only 52 % (51 % on meadow soil) of the variation of soil CO_2 (Fig. 4). This result corresponds to the output of the non-linear regression model used by Reichstein et al. (2002) without the expended factors (pH-value and C/N ratio). Due to this fact it is only reasonable to include the new parameters in the model if the data include information on the pH-value and C/N ratio for each place where the soil CO_2 efflux was measured. With an averaged dataset the modified model does not give better results than the original model described by Reichstein et al. (2002).

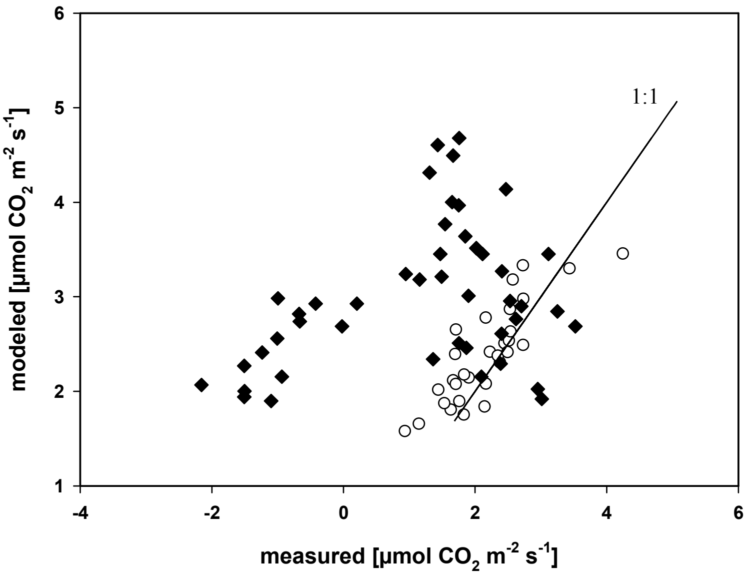
3.2 *Comparison of soil respiration and eddy covariance measurements*

As an intermediate data quality was sufficient for the footprint analysis, out of 365 possible 30-minute intervals in the eddy covariance measurement period, 265 data sets (72.6 %) were chosen to be suitable as input data for this feature after performing the necessary quality checks. Due to numerical instabilities, especially under stable stratification conditions, the footprint could only be calculated for a part of the input data set, leaving 257 results (70.4 %) for further analysis. Of these, 132 (36.2 %) high quality CO_2-flux measurements could be classified with a footprint result. The footprint results indicate that about 65 % of the processed footprint data set, and more than 83 % of the high quality CO_2-flux data are dominated by the influence of the brownfield area (flux contribution brownfield greater than 50 %). Moreover, about 20 % of the total data, and about 45 % of the high quality CO_2-flux data are influenced almost exclusively by brownfield emissions (flux contribution brownfield greater than 90 %).

The first approach for comparing soil efflux data with eddy covariance measurements, concentrates on the respiration process. Concerning the soil data, only the results of the non-linear regression model, which were fitted to the soil chamber measurements of respiration,

Table 5. Coefficients of variation for the univariate analysis of soil respiration influencing parameters during the field measurements.

	T_{soil} r^2	RSWC r^2	C/N r^2	pH r^2
meadow	0.12	0.34	0.23	0.19
brownfield	0.41	0.02	0.26	0.24



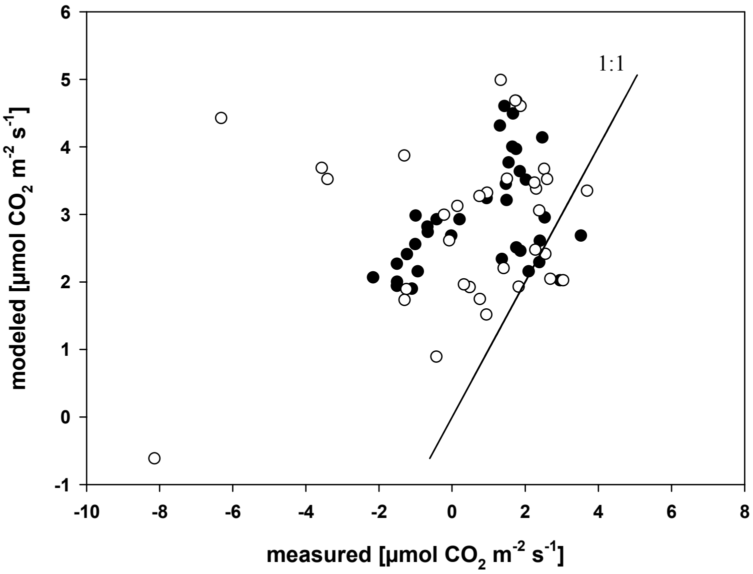
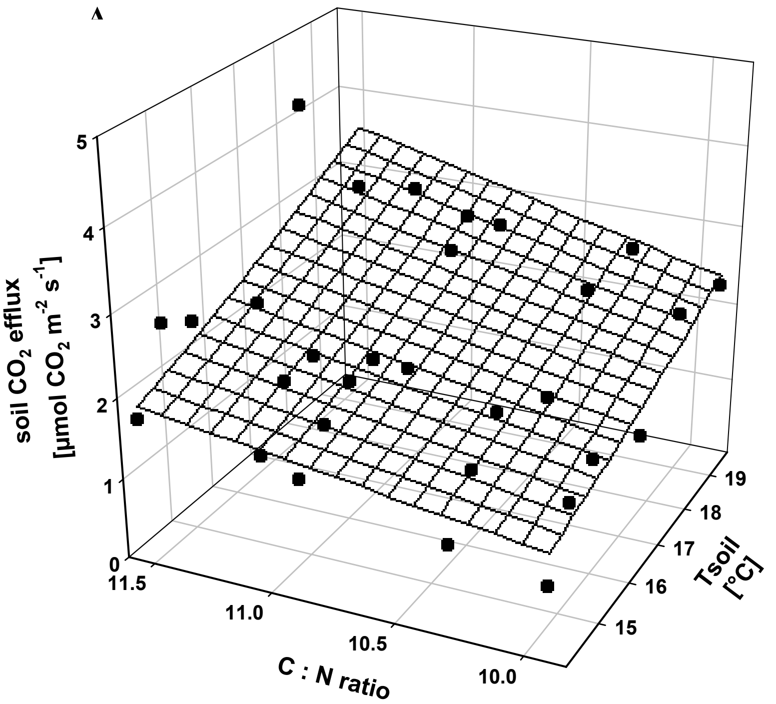


Fig. 3. Comparison A) of the measured soil CO_2 efflux of the brownfield (open dots: soil chambers, $r^2 = 0.70$, slope = 0.64; diamonds: eddy covariance, $r^2 = 0.18$, slope = 0.12) and the modelled CO_2 efflux using the modified non-linear regression model; B) of eddy covariance measurements (closed dots: >90 %, $r^2 = 0.69$, slope = 0.28; open dots: <90 %, $r^2 = 0.10$, slope = 0.16 flux contribution from brownfield) and the footprint weighted results combined with NEE simulated by the SVAT model.

were used. To take into account uncertainties within the soil data due to heterogeneity, the regression model was applied with maximum and minimum values, which had been found in individual measurements for soil pH values and the C/N relationship, respectively. The resulting span of the respiration rates covers a range of 0.6 to 1.5 µmol·m^{-2}·s^{-1}. With the last respiration measurements performed on July 5, an extrapolation of the modelling results was only possible through July 7. Afterwards, the temperature exceeded the domain for which the model had been adjusted. The results of the comparison between measured eddy covariance data and the output of the non-linear regression model are shown in Fig. 3 A.

The high quality CO_2-flux data set from the eddy covariance system was subdivided using the footprint results. Only measurements with a brownfield flux contribution of greater than 90 % were used in order to ensure that the respiration processes would dominate the measured CO_2 signal. In the time interval left



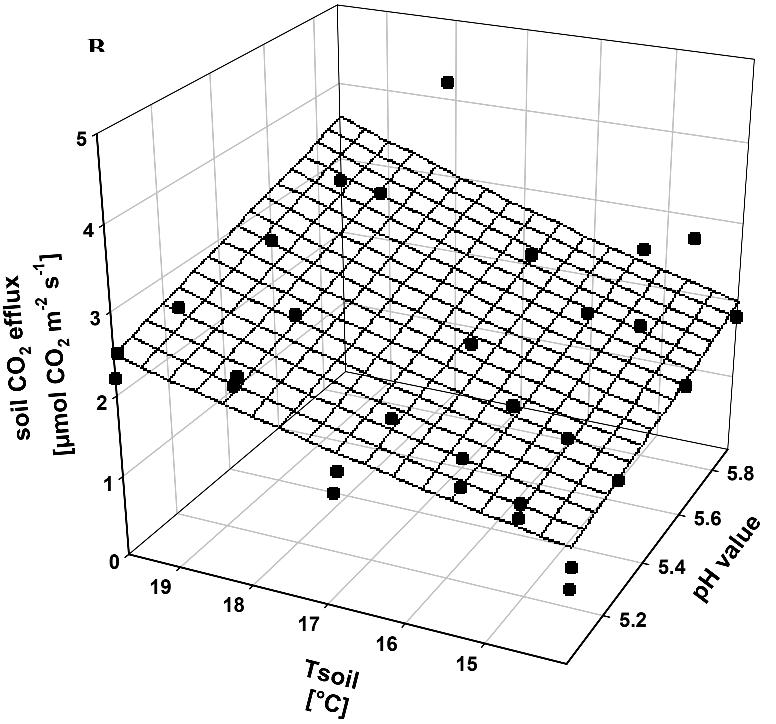


Fig. 4. Soil respiration as a function of soil temperature (T_{soil}) and A) the ratio of carbon to nitrogen; B) the soil pH value. The grid represents the results of the model and the points are the measurements.

for the comparison, 36 out of 87 high quality CO_2-flux measurements (41.4 %) fulfilled this condition.

The results of this first comparison are shown in Fig. 5. General agreement between modelled soil respiration and selected eddy covariance CO_2-fluxes could be observed on July 5 and 7. For these days, 8 out of 18 (44.4 %) of the selected eddy covariance fluxes lie within the indicated soil respiration span, while the remaining measurements are quite

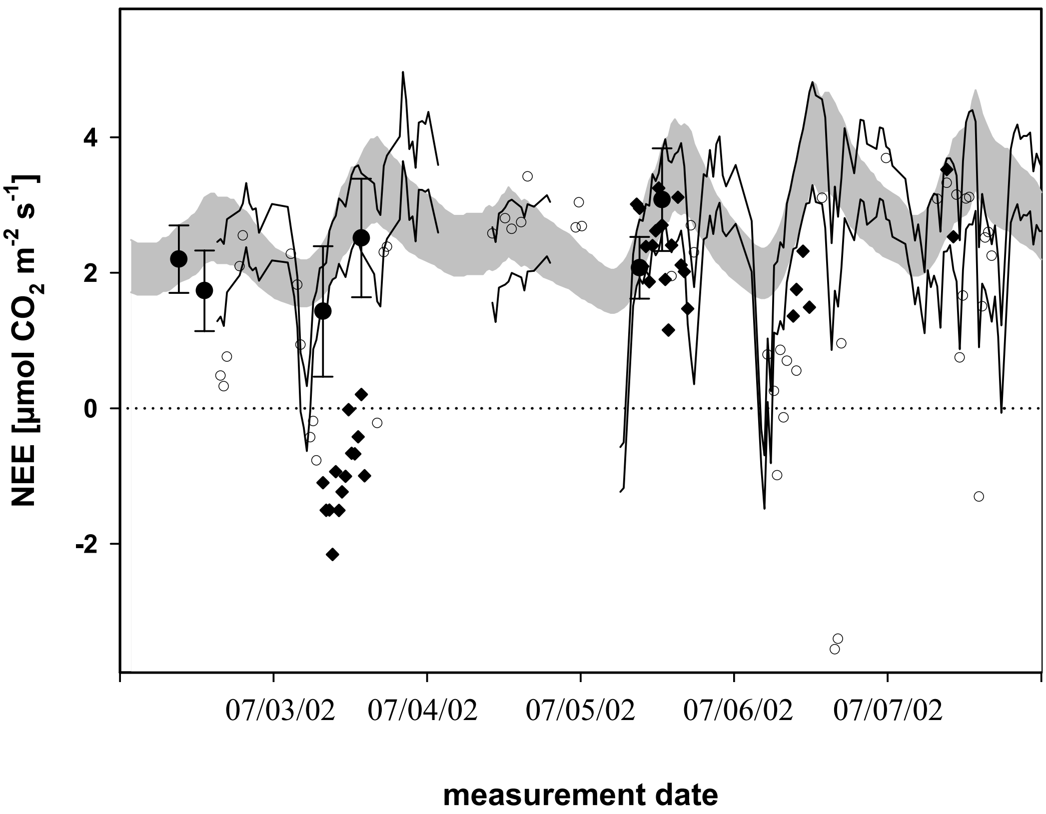


Fig. 5. Time course of CO_2 soil efflux measured with closed chambers, eddy covariance measurements of NEE, and footprint weighted model results. Dots represent the average of five simultaneous measured CO_2 soil emissions measured with closed chambers; diamonds (open dots) are eddy covariance measurements with a flux contribution from the brownfield area of >90 % (<90 %); the grey area is the range of soil CO_2 emission predicted by the non-linear regression model (including effects of changes in T_{soil}, SWC, C/N, and pH); and the solid lines bracket the results of the footprint weighted NEE predicted by the SVAT model (including gas exchange data measured for neighbouring meadow and soil CO_2 efflux).

close to this range. In contrast, the correlation between the systems is only poor for July 6, and for July 3 there seems to be no agreement at all.

The influences responsible for the differences between soil efflux data and the selected eddy covariance measurements can in general be divided into two groups: systemic differences between the measurement techniques, and internal boundary layer effects disturbing the performance of the footprint model. While the former can be attributed to the scatter between both data sets in periods with general agreement, the latter are responsible for larger deviations as observed for example on July 3.

Scatter due to systemic differences between soil efflux and eddy covariance measurements occur because of the deviating time constants of both techniques. Eddy covariance systems detect turbulent structures, which are responsible for the transport of momentum, energy, or any other kind of scalar, and can react immediately to changing boundary conditions. On the other hand, turbulent transport is disturbed by the chamber structure (Norman et al., 1997), if not prevented completely as in closed chamber systems, chamber systems produce fluxes with more or less smooth daily cycles and cannot follow the scattered peaks of the eddy covariance system (Schulze et al., 2002). In general, the resulting differences due to this effect are small and might be removed by applying running mean averaging to the eddy covariance data.

Larger differences between both systems may occur due to internal boundary layer effects, which disturb the performance of the eddy covariance system and cannot be resolved by the footprint model. Internal boundary layers, which occur when air flows over a transition of surface types with different properties, for example roughness or temperature, constitute a region of disturbed turbulence conditions with increasing mean height vertical extension as the distance from the transition increases (see e.g. Garatt, 1992; Stull, 1988). These disturbances cannot be taken into account by the footprint model FSAM that assumes horizontally homogeneous turbulence conditions and an undisturbed flow field to model the diffusion equations. In the study presented, internal boundary layers might affect the eddy covariance measurements, and consequently the footprint results, in two different ways.

The first type of internal boundary layer effects are recorded on July 3. The footprint model computed brownfield flux contributions of more than 99 % for all the eddy covariance measurements between 6 and 14 UTC, thus the measurements should only be affected by respiration. However, negative NEE values are observed, indicating a distinct influence of assimilation processes on the eddy covariance instruments. During this time interval, winds were blowing almost exactly from the south, indicating an influence of the meadow area south of the brownfield (area D in Fig. 1). A possible explanation is the existence of internal boundary layers, which are very low due to the more stable stratification above the vegetated areas with lower Bowen ratios surrounding the brownfield. This is supported by the fact that when driven with input data measured above the meadow, the footprint model produces source areas, which are large enough to cross the transition and also include parts of the southern meadow.

The second type of internal boundary layer effects disturbing the performance of the footprint model occurs when the wind direction shifts around 90° or 270° due to the transition from brownfield to meadow. The computed flux percentages change abruptly with the wind direction, and are also very sensitive to the width of the source area. In FSAM, this width is dependant mainly on the ratio $\sigma_v\, u_*^{-1}$, a growing ratio of which also increases the width of the source area. In these sectors, the internal boundary layer effect might enhance the turbulent exchange and thus also the standard deviation of the crosswind velocity, σ_v. Consequently, the increased width of the source area would result in a smearing effect on the flux contributions, which generally reduces the dominance of the brownfield area to a certain degree.

3.3 NEE prediction

In a second approach to comparing soil efflux data sets with eddy covariance measurements, the assimilation processes of the vegetated part of the experiment area were also taken into account. For each of the four meadow types as described above (see also Fig. 1), the PROXEL model was used to determine the assimilation of CO_2 for each 30-minute mean of the observation period. These results were subtracted from soil respiration measurements performed on area C to yield the net ecosystem exchange of CO_2 for each land use type. For the brownfield area E, assimilation was set to zero so that the respiration results were taken as the NEE. To be able to compare these individual results for each land use type with the eddy covariance measurements, which integrate over several land use types, a footprint weighted averaging was applied (Eq. 5).

$$F_{CO_2}(soil) = \sum_{i=1}^{5} NEE_i \cdot Perc_i \qquad (5)$$

With F_{CO2}(soil) = footprint weighted CO_2-flux, i = index for the land use types A to E, NEE_i = net ecosystem exchange for the specific land use type, and $Perc_i$ = flux percentage for the specific land use type as determined by the footprint model. To account for the uncertainties of the individual NEE results, similar to the comparison of the respiration results as described above, a span was computed for both respiration and assimilation processes. For respiration, the same data as above was used, while for the assimilation minimum or maximum values, respectively, the data was produced according to LAI heterogeneity in the different meadow types. The resulting span of CO_2-fluxes covers a range of 0.6 to 1.7 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

The footprint weighted averaged CO_2-flux was compared with the total number of high quality CO_2-flux measurements from the eddy covariance system. The results of this comparison are shown in Fig. 3 B and Fig. 5. The correlations between the total NEE results of both measurement systems follow those already observed for the comparison of the respiration process as described above. General agreement is to be found for July 4, 5 and 7, where 48.9 % of the eddy covariance measurements are situated within the span of footprint averaged soil chamber based results. The deviations of July 3 and July 6 can be explained again by internal boundary layer effects. As a consequence, during the total period of data comparison, only 33 % fitted into the calculated range of the footprint weighted soil measurements.

In order to check the sensitivity of the approach for measurement errors, three separate test runs of the footprint model were performed with modified wind direction, Obukhov length, and standard deviation of the crosswind velocity. Concerning the wind direction, a variation within the possible range of uncertainty did not result in significant changes. On the other hand, the approach is sensitive to variations of the Obukhov length in situations with a southerly wind direction, when the maximum extension of the source area is close to the transition from brownfield to meadow. The standard deviation of the crosswind velocity is especially important with wind directions around 90° or 270°, when the width of the source area is influencing the land use composition more than its length. Another factor influencing the performance of the approach presented is the heterogeneity of the soil parameters in the study area. Due to the limited number of measurement times and positions, especially in the period used for the comparison between both measurement systems, it is uncertain to which degree the soil chamber data are representative for the area influencing the eddy covariance measurements. This uncertainty is indicated in part by the span of both respiration and NEE as shown in Fig. 5, but it cannot be assured that the whole range of variations is covered.

4 Conclusion

In this study, we developed and tested a basic framework that allows the comparison between up-scaled chamber estimates and EC measurements of net ecosystem exchange (NEE) at a brownfield surrounded by meadows. Modelled NEE is derived from a combination of chamber measurements (i.e., soil, leaves, stems, and fruit) for different land use types, and an analytical footprint model. Given that only a short time period of simultaneous measurements is available for the study, it is satisfying that the different methodologies give comparable results (r^2=0.69). However, the results demonstrate the following:

1) The study shows an approach to combine chamber measurements and eddy covariance data. However, the sensitivity of the derived NEE to an accurate parameterisation of the soil and vegetation CO_2 balance and of the footprint model highlights the value of simultaneous determination of related biological and atmospheric subprocesses. In particular, diurnal and seasonal changes, as well as other potential driving factors, must be carefully examined in the future.
2) The soil emission model must be reviewed from a variety of perspectives. Given its initial structure using temperature, moisture, pH, and C/N ratio as drivers, we must

now address the degree of complexity that is needed for applications on a regional scale, where the above drivers are rarely available.

3) The study compiles an adequate methodological framework, although (a) the footprint model requires further testing for patchy ground cover (development of internal boundary layers due to discontinuities in the source area), (b) dynamical changes in physiological properties of leaves, roots, and micro-organisms are not included, (c) limitations due to soil water availability were strong during the investigated period, and effectiveness under more humid conditions must be evaluated, and (d) the framework has only been tested for the investigated site. Comparisons of observations and modelling results at different sites would be required in order to draw conclusions on a larger scale.

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References*

Andersson S, Nilsson SI (2001) Influence of pH and temperature on microbial activity, substrate availability of soil-solution bacteria and leaching of dissolved organic carbon in a mor humus. Soil Biol Biochem 33: 1181-1191

Aubinet M, Grelle A, Ibrom A, Rannik Ü, Moncrieff J, Foken T, Kowalski AS, Martin PH, Berbigier P, Bernhofer C, Clement R, Elbers J, Granier A, Grünwald T, Morgenstern K, Pilegaard K, Rebmann C, Snijders W, Valentini R, Vesala T (2000) Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Adv Ecol Res 30: 113-175

Baldocchi DD (1997) Measuring and Modeling Carbon Dioxide and Water Vapor Exchange over a Temperate Broad-Leaved Forest during the 1995 Summer Drought. Plant Cell Environ 20: 1108-1122

Ball BC, Scott A, Parker JP (1999) Field N_2O, CO_2 and CH_4 fluxes in relation to tillage,

*references 'in print' were actualised in comparison to the original manuscript

compaction and soil quality in Scotland. Soil Till Res 53: 29-39

Ball JT, Woodrow IE, Berry JA (1987) A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions. In: Biggins I (ed) Progress in Photosynthesis Research IV.5. Proc of the VII International Photosynthesis Congress, pp 221-224

Beyrich F, Herzog HJ, Neisser J (2002) The LITFASS project of DWD and the LITFASS-98 experiment: The project strategy and the experimental setup. Theor Appl Climatol 73: 3-18

Bunnell FL, Tait DEN, Flanagan PW (1977) Microbial respiration and substrate weight loss - II. A model of the influences of chemical composition. Soil Biol Biochem 9: 41-47

Chan KY, Heenan DP (1996) The influence of crop rotation on soil structure and soil physical properties under conventional tillage. Soil Till Res 37: 113-125

Chan KY, Heenan DP, Oates A (2002) Soil carbon fractions and relationship to soil quality under different tillage and stubble management. Soil Till Res 63: 133-139

Curtis PJ, Hanson PJ, Bolstad P, Barford C, Randolph JC, Schmid HP, Wilson KB (2002) Biometric and eddy-covariance based estimates of annual carbon storage in five eastern North American deciduous forests. Agric For Meteorol 113: 3-19

Davidson EA, Savage K, Verchot LV, Navarro R (2002) Minimizing artifacts and biases in chamber-based measurements of soil respiration. Agric For Meteorol 113: 21-37

Ellis S, Howe MT, Goulding KWT, Mugglestone MA, Dendooven L (1998) Carbon and nitrogen dynamics in a grassland soil with varying pH: effect of pH on the denitrification potential and dynamics of the reduction enzymes. Soil Biol Biochem 30: 359-367

Falge E, Tenhunen JD, Aubinet M, Bernhofer C, Clement R, Granier A, Kowalski A, Moors E, Pilegaard K, Rannik Ü, Rebmann C (2003) A model-based study of carbon fluxes at ten European forest sites. In: Valentini R (ed) Fluxes of Carbon, Water and Energy of European Forests, Ecological Studies Series, Vol. 163. Springer, Berlin, Heidelberg, New York, pp 151-177

Farquhar GD, van Caemmerer S (1982) Modelling of photosynthetic response to environment. In: Lange OL, Nobel PS, Osmond CB, Ziegler H (eds) Encyclopedia of plant physiology 12B, Physiological plant ecology II, Water relations and carbon assimilation. Springer, Berlin, Heidelberg, New York, pp 549-587

Foken T (2003) Angewandte Meteorologie, Mikrometeorologische Methoden. Springer, Berlin, Heidelberg, New York, 289 pp

Foken T, Skeib G, Richter SH (1991) Dependence of the integral turbulence characteristics on the stability of stratification and their use for Doppler-Sodar measurements. Z Meteorol 41: 311-315

Foken T, Wichura B (1996) Tools for quality assessment of surface-based flux measurements. Agric For Meteorol 78: 83-105

Foken T, Jegede OO, Weisensee U, Richter SH, Handorf D, Görsdorf U, Vogel G, Schubert U, Kirtzel H-J, Thiermann V (1997) Results of the LINEX-96/2 Experiment. Deutscher Wetterdienst, Forschung und Entwicklung, Arbeitsergebnisse Nr. 48, 75 pp

Foken T, Göckede M, Mauder M, Mahrt L, Amiro BD, Munger JW (2004) Post-field data quality control. In: Lee X, Massman WJ, Law BE (eds) Handbook of Micrometeorology: A guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp 181-208

Garratt JR (1992) The atmospheric boundary layer. Cambridge University Press, Cambridge, 316 pp

Göckede M, Rebmann C, Foken T (2004) A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. Agric For Meteorol 127: 175-188

Goulden ML, Munger JW, Fan F-M, Daube BC, Wofsy SC (1996) Measurements of carbon sequestration by long-term eddy covariance: method and critical evaluation of accuracy. Global Change Biol 2: 159-168

Gryning S-E, Holtslag AAM, Irwin JS, Sivertsen B (1987) Applied dispersion modelling based on meteorological scaling parameters. Atmos Environ 21: 79-89

Gupta SR, Singh JS (1981) Soil respiration in a tropical grassland. Soil Biol Biochem 13: 261-268

Haenel HD, Grünhage L (1999) Footprint analysis: A closed analytical solution based on height-dependent profiles of wind speed and eddy viscosity. Boundary-Layer Meteorol 93: 395-409

Hall JM, Paterson E, Killham K (1998) The effect of elevated CO_2 concentration and soil pH on the relationship between plant growth and rhizosphere denitrification potential. Global Change Biol 4: 209-216

Harley PC, Tenhunen JD (1991) Modeling the photosynthetic response of C3 leaves to environmental factors. In: Boote KJ, Loomis RS (eds) Proceedings of ASA (American Society of Agronomy and Crop Science Society of America) Symposium on Modeling Crop Photosynthesis - From Biochemistry to Canopy. pp 17-39

Healy RW, Striegel RG, Russell TF, Hutchinson GL, Livingston GP (1996) Numerical evaluation of static-chamber measurements of soil-atmosphere gas exchange: identification of physical processes. Soil Sci Soc Amer J 60: 740-747

Hollinger DY, Kelliher FM, Schulze E-D, Bauer G, Arneth A, Byers JN, Hunt JE, McSeveny TM, Kobak KI, Milukova I (1998) Forest-atmosphere carbon dioxide exchange in eastern Siberia. Agric For Meteorol 90: 291-306

Horst TW, Weil JC (1992) Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary-Layer Meteorol 59: 279-296

Howard JA, Howard DM (1979) Respiration of decomposition litter in relation to temperature and moisture. Oikos 33: 457-465

Hunt JE, Kelliher FM, McSeveny TM, Byers JN (2002) Evaporation and carbon dioxide exchange between the atmosphere and a tussock grassland during a summer drought. Agric For Meteorol 111: 65-82

Janssens IA, Kowalski AS, Ceulemans R (2001) Forest floor CO_2 fluxes estimated by eddy covariance and chamber-based model. Agric For Meteorol 106: 61-69

Kelliher FM, Lloyd J, Arneth A, Luhker B, Byers JN, McSeveny TM, Milukova I, Grigoriev S, Panfyorov M, Sogatchev A (1999) Carbon dioxide efflux density from the floor of a central Siberian pine forest. Agric For Meteorol 94: 217-232

Kelliher FM, Reisinger AR, Martin RJ, Harvey MJ, Price SJ, Sherlock RR (2002) Measuring nitrous oxide emission rate from grazed pasture using Fourier-transform infrared spectroscopy in the nocturnal boundary layer. Agric For Meteorol 111: 29-38

Kessavalou A, Doran JW, Mosier AR, Drijber RA (1998) Greenhouse gas fluxes following tillage and wetting in a wheat-fallow cropping system. J Environ Qual 27: 1105-1116

Kirschbaum MUF (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biol Biochem 27: 753-760

Koch J, Dayan U, Mey-Marom A (2000) Inventory of Emissions of Greenhouse Gases in Israel. Water Air Soil Poll 123: 259-271

Kormann R, Meixner FX (2001) An analytical footprint model for non-neutral stratification. Boundary-Layer Meteorol 99: 207-224

Kucera C, Kirkham D (1971) Soil respiration studies in tallgrass prairie in Missouri. Ecology 52: 912-915

Kutsch WL, Staack A, Wotzel J, Middelhoff U, Kappen L (2001) Field measurements of root respiration and total soil respiration in an alder forest. New Phytol 150: 157-168

Law BE, Baldocchi DD, Anthoni PM (1999) Below-canopy and soil CO_2 fluxes in a ponderosa pine forest. Agric For Meteorol 94: 171-188

Lee X (1998) On micrometeorological observations of surface-air exchange over tall vegetation. Agric For Meteorol 91: 39-49

Liu HP, Peters G, Foken T (2001) New equations for sonic temperature variance and buoyancy heat flux with an omnidirectional sonic anemometer. Boundary-Layer Meteorol 100: 459-468

Lloyd J, Taylor JA (1994) On the temperature dependence of soil respiration. Funct Ecol 8: 315-323

Maljanen M, Hytonen J, Martikainen PJ (2001a) Fluxes of N_2O, CH_4 and CO_2 on afforested boreal agricultural soils. Plant Soil 231: 113-121

Maljanen M, Martikainen PJ, Walden J, Silvola J (2001b) CO_2 exchange in an organic field growing barley or grass in eastern Finland. Global Change Biol 7: 679-692

Marschner P, Kandeler E, Marschner B (2003) Structure and function of the soil microbial community in a long-term fertilizer experiment. Soil Biol Biochem 35: 453-461

Matteucci G, Dore S, Stivanello S, Rebmann C, Buchmann N (2000) Soil respiration in Beech and Spruce forests in Europe: Trends, controlling factors, annual budgets and implications for the ecosystem carbon balance. In: Schulze E-D (ed) Carbon and Nitrogen Cycling in European Forest Ecosystems. Ecological studies, Vol. 142. Springer, Berlin, Heidelberg, New York, pp 217-236

Moldrup P, Rolston DE, Hansen AA (1989) Rapid and numerically stable simulation of one dimensional, transient water flow in unsaturated, layered soils. Soil Sci 148: 219-226

Moldrup P, Rolston DE, Hansen AA, Yamaguchi T (1991) A simple, mechanistic model for soil resistance to plant water uptake. Soil Sci 151

Moore CJ (1986) Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorol 37: 17-35

Naganawe T, Kyuma K, Yamamoto H, Yamamote Y, Yokoi H, Tatsuyama K (1989) Measurements of soil respiration in the field: influence of temperature, moisture level, and application of sewage sludge compost and agro-chemicals. Soil Sci Plant Nutrition 35: 509-516

Nakadai T, Yokozawa M, Ikeda H, Koizumi H (2002) Diurnal changes of carbon dioxide flux from bare soil in agricultural field in Japan. Appl Soil Ecol 19: 161-171

Norman JM, Kucharik CJ, Gower ST, Baldocchi DD, Crill PM, Rayment M, Savage K, Striegl RG (1997) A comparison of six methods for measuring soil-surface carbon dioxide fluxes. J Geophys Res-Atmos 102: 28771-28777

Panofsky HA, Dutton JA (1984) Atmospheric Turbulence - Models and methods for engineering applications. John Wiley and Sons, Inc., New York, 397 pp

Prieme A, Christensen S (2001) Natural perturbations, drying-wetting and freezing-thawing cycles, and the emission of nitrous oxide, carbon dioxide and methane from farmed organic soils. Soil Biol Biochem 33: 2083-2091

Pumpanen J, Kolari P, Ilvesniemi H, Minkkinen K, Vesala T, Niinisto S, Lohila A, Larmola T, Morero M, Pihlatie M, Janssens I, Yuste JC, Grünzweig JM, Reth S, Subke J-A, Savage K, Kutsch WL, Östreng G, Ziegler W, Anthoni P, Lindroth A, Hari P (2004) Comparison of different chamber techniques for measuring soil CO_2 efflux. Agric For Meteorol 123: 159-176

Rayment MB, Jarvis PG (2000) Temporal and spatial variation of soil CO_2 efflux in a Canadian boreal forest. Soil Biol Biochem 32: 35-45

Reich JW, Schlesinger WH (1992) The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44 B: 81-99

Reichstein M, Tenhunen JD, Roupsard O, Ourcival J-M, Rambal S, Miglietta F, Peressotti A, Pecchiari M, Tirone G, Valentini R (2002) Severe drought effects on ecosystem CO_2 and H_2O fluxes at three Mediterranean evergreen sites: revision of current hypotheses? Global Change Biol 8: 999-1017

Roberts WP, Chan KY (1990) Tillage-induced increases in carbon dioxide from the soil. Soil Till Res 17: 143-151

Roulet NT (2000) Peatlands, carbon storage, greenhouse gases, and the Kyoto Protocol: Prospects and significance for Canada. Wetlands 20: 605-615

Scheffer F, Schachtschabel P (2002) Lehrbuch der Bodenkunde. Spektrum, Akademischer Verlag, Heidelberg, 607 pp

Schmid HP (1994) Source areas for scalars and scalar fluxes. Boundary-Layer Meteorol 67: 293-318

Schmid HP (1997) Experimental design for flux measurements: matching scales of observations and fluxes. Agric For Meteorol 87: 179-200

Schmid HP (2002) Footprint modeling for vegetation atmosphere exchange studies: a review and perspective. Agric For Meteorol 113: 159-183

Schuepp PH, Leclerc MY, MacPherson JI, Desjardins RL (1990) Footprint prediction of scalar fluxes from analytical solutions of the diffusion equation. Boundary-Layer Meteorol 50: 355-373

Schulze E-D, Beck E, Müller-Hohenstein K (2002) Pflanzenökologie. Spektrum, Akademischer Verlag, Heidelberg, 846 pp

Schulze E-D, Lloyd J, Kelliher FM, Wirth C, Rebmann C, Luhker B, Mund M, Knohl A, Milyukova IM, Schulze W, Ziegler W, Varlagin A, Sogachev AF, Valentini R, Dore S, Grigoriev S, Kolle O, Panfyorov MI, Tchebakova N, Vygodskaya N (1999) Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink - a synthesis. Global Change Biol 5: 703-722

Schwartz DM, Bazzaz FA (1973) In situ measurements of carbon dioxide gradients in a soil-plant-atmosphere system. Oecologia 12: 161-167

Sims PL, Bradford JA (2001) Carbon dioxide fluxes in a southern plains prairie. Agric For Meteorol 109: 117-134

Singh JS, Gupta SR (1977) Plant decomposition and soil respiration in terrestrial ecosystems. Bot Rev 43: 449-528

Sitaula BK, Bakken LR, Abrahamsen G (1995) N-fertilization and soil acidification effects on N_2O and CO_2 emission from temperate pine forest soil. Soil Biol Biochem 27: 1401-1408

Soegaard H (1999) Fluxes of carbon dioxide, water vapour and sensible heat in a boreal agricultural area of Sweden - scaled from canopy to landscape level. Agric For Meteorol 98-99: 463-478

Soegaard H, Jensen NO, Boegh E, Hasager CB, Schelde K, Thomsen A (2003) Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modelling. Agric For Meteorol 114: 153-173

Stull RB (1988) An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers, Dordrecht, Boston, London, 666 pp

Subke J-A (2002) Forest floor CO_2 fluxes in temperate forest ecosystems - An investigation of spatial and temporal patterns and abiotic controls. Bayreuther Forum Ökologie 96: 1-131

Tenhunen JD, Siegwolf RA, Oberbauer SF (1995) Effects of phenology, physiology, and gradients in community composition, structure, and microclimate on tundra ecosystem CO_2 exchange. In: Schulze E-D, Caldwell MM (eds) Ecophysiology of photosynthesis. Springer, Berlin, Heidelberg, New York, pp 431-460

Thomas C, Foken T (2002) Re-evaluation of Integral Turbulence Characteristics and their Parameterisations. 15th Symposium on Boundary Layers and Turbulence, Wageningen, The Netherlands, American Meteorological Society, pp 129-132

Velthof GL, Oenema O (1995) Nitrous oxide fluxes from grassland in the Netherlands: Statistical analysis of flux chamber measurements. Eur J Soil Sci 46: 533-540

Velthof GL, van Groenigen JW, Gebauer G, Pietrzak S, Jarvis SC, Pinto M, Corre W, Oenema O (2000) Temporal stability of spatial patterns of nitrous oxide fluxes from sloping grassland. J Environ Qual 29: 1397-1407

Webb EK, Pearman GI, Leuning R (1980) Correction of flux measurements for density effects due to heat and water vapour transfer. Quart J Roy Meteorol Soc 106: 85-100

Wilczak JM, Oncley SP, Stage SA (2001) Sonic anemometer tilt correction algorithms. Boundary-Layer Meteorol 99: 127-150

Witkamp M (1966) Decomposition of leaf litter in relation to environment, microflora and microbial respiration. Ecology 47: 194-201

Zak DR, Pregitzer KS, King JS, Holmes WE (2000) Elevated atmospheric CO_2, fine roots and the response of soil microorganisms: a review and hypothesis. New Phytol 147: 201-222

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Hiermit erkläre ich, dass ich die Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

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