Quality Assurance for Eddy Covariance Measurements of Turbulent Fluxes and its Influence on the Energy Balance Closure Problem

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QUALITY ASSURANCE FOR EDDY COVARIANCE MEASUREMENTS OF TURBULENT FLUXES AND ITS INFLUENCE ON THE ENERGY BALANCE CLOSURE PROBLEM

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Contents

List of manuscripts

The dissertation is presented in cumulative form. It consists of five individual manuscripts. Two manuscripts have been reviewed and were proposed for publication if the suggested amendments are implemented in a revised version. The other manuscripts are still in the review process or will be submitted for publication soon.

Revised manuscripts

Mauder, M., Liebethal, C., Göckede, M., Leps, J.-P., Beyrich, F., and Foken, T.: 2005, 'Processing and quality control of flux data during LITFASS-2003', *Boundary-Layer Meteorol.*, revised.

Ruppert, J., Mauder, M., Thomas, C., and Lüers, J.: 2005, 'Innovative gap-filling strategy for annual sums of CO_2 net ecosystem exchange', *Agric. For. Meteorol.*, revised.

Submitted manuscripts

Mauder, M., and Foken, T.: 2006, 'Impacts of post-field data processing methods on eddy covariance flux estimates, *Meteorol. Z.*, submitted.

Manuscripts to be submitted

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Mauder, M., Jegede, O. O., Okogbue, E. C., Wimmer, F., and Foken, T.: 2006, 'Surface energy flux measurements at a tropical site in West Africa during the transition from dry to wet season', *Theor. Appl. Climatol.*, to be submitted.

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Summary

The eddy covariance method enables direct measurements of turbulent fluxes at the earth's surface. Such measurements are required to study the surface energy balance and the exchange of gaseous air constituents. Due to improvements in the construction of adequate sensors and the progress in computer technology during the last decades this method is now well-established. However, a general failure to close the energy balance equation has been reported for many micrometeorological field experiments. This unresolved problem motivated this dissertation, which aims at the quality assurance for eddy covariance measurements. The presented concept for quality assurance comprises investigations on the accuracy of the deployed sensors and on the impact of the data analysis for such measurements. A specific focus is set on possible implications for the determination of reliable CO_2 flux estimates, since this issue gained importance during the last years for studies on the global carbon cycle related to global warming due to the green house effect. Data from several field experiments in Germany, California and Nigeria form the experimental basis for these investigations.

A software package was developed to perform the necessary post processing for all eddy covariance measurements presented in this thesis. The results of sensor intercomparison experiments show a typical random error of eddy covariance measurements of 5% for the sensible heat flux and 10% for the latent heat flux, if sensors are well-calibrated and maintained and the assumptions for this method are fulfilled. The applicability of an objective quality assessment scheme of flux data was demonstrated for large datasets from a field campaign comprising 14 measuring systems. The energy balance closure problem has been studied at two exemplary sites. The energy balance could not be closed for measurements over an agricultural area in Germany. For this experiment the sum of turbulent heat fluxes was 30% smaller than the available energy at the surface. In contrast, no systematic bias of the energy balance could be found for measurements over fallow bush-land in Nigeria, although the measures of quality assurance were similar. Neither differences in instrumentation nor in the post-field data processing between both experiments can explain these findings. A further analysis of the dataset from the agricultural area in Germany showed that additional flux contributions can be found when extending the averaging time of covariances beyond the conventional 30 minute interval. The energy balance can even be closed for this site when applying an averaging time of 24 hours. Longwave flux contributions seem to be generated here by the much stronger heterogeneity of the surrounding terrain compared to the more or less homogeneous environment of the Nigerian site. The filtering of heterogeneity induced flux contributions from very low frequency covariances through the commonly used averaging times of less than 30 minutes is identified as major reason of the energy balance closure problem. To improve the understanding of the processes leading to low frequency flux contributions a more detailed analysis of further experiments in combination with large eddy simulation modelling are required. The impact of post-field data

processing was not only evaluated for energy flux estimates but also for fluxes of CO_2, which showed similar additional flux contributions for extended averaging times. Finally, it was demonstrated that the quality assessment scheme presented in this thesis provides a fundamental and robust rejection criterion for a successful gap-filling strategy to determine annual sums of CO_2 net ecosystem exchange.

Zusammenfassung

Die Eddy-Kovarianz Methode ermöglicht direkte Messungen turbulenter Austauschströme an der Erdoberfläche. Diese werden benötigt für Untersuchungen zur Oberflächenenergiebilanz und zum Austausch gasförmiger Bestandteile der Luft. Durch Verbesserungen in der Konstruktion geeigneter Messgeräte und den Fortschritt in der Computertechnologie während der letzten Jahrzehnte ist diese Methode heute gut etabliert. Allerdings gelingt es häufig nicht, die Energiebilanzgleichung für mikrometeorologische Feldexperimente zu schließen. Dieses ungelöste Problem war die Motivation für die vorliegende Dissertation, deren Ziel die Qualitätssicherung für Eddy-Kovarianz Messungen ist. Das hier vorgestellte Konzept zur Qualitätssicherung umfasst Untersuchungen zur Genauigkeit der eingesetzten Messgeräte und zum Einfluss der Datenbearbeitung solcher Messungen. Ein besonderer Schwerpunkt wird auf mögliche Auswirkungen für die Bestimmung verlässlicher CO_2-Flussschätzungen gesetzt, da dieses Thema während der letzten Jahre für Untersuchungen zum globalen Kohlenstoffkreislauf im Zusammenhang mit weltweiter, durch den Treibhauseffekt verursachter, Klimaänderung Bedeutung gewonnen hat. Daten von mehreren Feldexperimenten in Deutschland, Kalifornien und Nigeria bilden die experimentelle Grundlage für diese Forschungen.

Ein Softwarepaket wurde gemäß dem aktuellen Stand der Wissenschaft entwickelt, um die notwendige Nachbearbeitung für alle in dieser Arbeit gezeigten Eddy-Kovarianz Messungen durchzuführen. Die Ergebnisse von Messgerätevergleichsexperimenten zeigen einen typischen zufälligen Fehler von Eddy-Kovarianz Messungen von 5% für den fühlbaren Wärmestrom und 10% für den latenten Wärmestrom, vorausgesetzt die Geräte sind gut kalibriert und gewartet und die dieser Methode zugrunde liegenden Annahmen sind erfüllt. Die Anwendbarkeit eines objektiven Schemas zur Qualitätsbewertung von Flussdaten wurde für umfangreiche Datensätze einer 14 Messsysteme umfassenden Feldkampagne demonstriert. Das Problem der Energiebilanzschließung wird an zwei exemplarischen Standorten untersucht. Für Messungen über einer landwirtschaftlich genutzten Fläche in Deutschland konnte die Energiebilanz nicht geschlossen werden. Für dieses Experiment war die Summe der turbulenten Wärmeströme um 30% kleiner als die an der Oberfläche verfügbare Energie. Im Gegensatz dazu konnte keine systematische Nichtschließung der Energiebilanz für Messungen über brachliegendem Buschland in Nigeria festgestellt werden, obwohl die Maßnahmen zur Qualitätssicherung ähnlich waren. Weder Unterschiede bei der Instrumentierung noch bei der Datennachbearbeitung zwischen beiden Experimenten können diesen Befund erklären. Eine weitere Analyse des Datensatzes für die landwirtschaftlich genutzte Fläche in Deutschland zeigte, dass zusätzliche Flussbeiträge gefunden werden können, wenn man die Mittelungszeit der Kovarianzen über das klassische 30-Minuten-Interval hinaus ausdehnt. Die Energiebilanz kann für diesen Standort sogar geschlossen werden, wenn man eine Mittelungszeit von 24 Stunden verwendet. Langwellige Flussbeiträge scheinen hier durch die

deutlich stärkere Heterogenität der Umgebung generiert zu werden im Vergleich zu dem mehr oder weniger homogenen Umland des Nigerianischen Standorts. Das Filtern von heterogenitätsinduzierten Flussanteilen in sehr niederfrequenten Kovarianzen durch die üblicherweise verwendeten Mittelungszeiten von weniger als 30 Minuten wird als Hauptgrund für das Energiebilanzschließungsproblem angesehen. Um das Verständnis der Prozesse zu verbessern, die zu niedrigfrequenten Flussbeiträgen führen, ist eine detailliertere Analyse weiterer Experimente notwendig in Kombination mit Large Eddy Simulation Modellierung. Der Einfluss der Datennachbearbeitung wurde nicht nur für Energieflüsse bewertet sondern auch für Flüsse von CO_2, die ähnliche zusätzliche Flussbeiträge für erweiterte Mittelungszeiten aufwiesen. Schließlich wurde gezeigt, dass die in dieser Arbeit vorgestellte Qualitätsbewertung ein fundamentales und robustes Auswahlkriterium bietet für eine erfolgreiche Strategie zum Füllen von Datenlücken, um Jahressummen der CO_2-Bilanz eines Ökosystems zu bestimmen.

1 Introduction

Turbulent transport is the main process to exchange energy and gas at the land-atmosphere interface. The eddy covariance method enables the most direct measurement of these interactions, without disturbing the environment under study. This technique requires measurements at frequencies, which are significantly higher than those of turbulent fluctuations in the atmospheric surface layer. Since the large amount of high frequency data allows no visual screening and in view of the susceptibility of the measurement itself it is essential to take elaborate measures of quality assurance to obtain reliable flux estimates from eddy covariance measurements, which enable studies on the surface energy balance and the exchange of gaseous air constituents between ecosystems and the atmosphere.

1.1 The surface energy balance

The conservation of energy is a fundamental concept of physics. If we apply this concept to the processes at the earth's surface we can write it in form of the following equation, the surface energy balance.

$$-Q_s^* = Q_H + Q_E + Q_G + \Delta Q_S , \qquad (1)$$

where

Q^*_s = net radiation,

Q_H = sensible heat flux,

Q_E = latent heat flux,

Q_G = ground heat flux,

ΔQ_S = heat storage.

Fluxes contributing energy to the surface are defined as negative, and fluxes transporting energy away from the surface have a positive sign.

The net radiation together with the ground heat flux supplies the energy available for heating of the air and evapotranspiration of water from the surface into the air. In other words, this available energy is converted into energy in form of sensible heat and latent heat. The transport of this energy into the air occurs by turbulent movement of the air. This turbulent transport is 10^5 times more efficient than molecular conduction of heat, water or other air constituents in the atmosphere.

1.2 The eddy covariance method

Swinbank (1951) and simultaneously Obukhov (1951) proposed and tested the fundamental concepts of eddy covariance to measure turbulent fluxes in the atmospheric surface layer. This method requires measurements with fast response sensors in order to record the full spectrum of turbulent fluctuations. It is necessary to measure fluctuations of wind, temperature, humidity and other gas constituents at a frequency of 10 to 20 Hz. The eddy covariance method is based on the Navier-Stokes equation for momentum and similar equations for temperature or gaseous air constituents by the use of the Reynolds' postulates (e.g. Stull, 1988; Arya, 2001; Foken, 2003). According to Reynolds' decomposition of time series a certain quantity x (or y) can be described as the sum of its average $\overline{x}$ (or $\overline{y}$) and the deviation from this average x' (or y'):

$$x = \overline{x} + x', \tag{2}$$

which leads to the formulation of the following Reynolds' postulates

$$\overline{x'} = 0 \ , \tag{3}$$

$$\overline{xy} = \overline{x}\,\overline{y} + \overline{x'y'}, \tag{4}$$

The equations for the determination of turbulent fluxes are obtained by simplifications of the Navier-Stokes equation, which are listed by Foken and Wichura (1996). Stationarity and homogeneity have to be assumed, such that derivatives with respect to time and space coordinates vanish. Hence, the total flux F of a scalar s in the surface layer under stationary conditions without advection in homogeneous terrain can be expressed as

$$F = \overline{ws} = \overline{w}\,\overline{s} + \overline{w's'} \ . \tag{5}$$

With the average vertical wind component $\overline{w} = 0$, this equation can be simplified to

$$F = \overline{w's'} \ . \tag{6}$$

Thus, the vertical turbulent flux of a scalar quantity s can be approximated by the determination of its covariance with the vertical wind component w, if w and s are measured at the same point in space and time.

1.3 Quality assurance for the eddy covariance method

1.3.1 Instrumentation

Before setting up any sensor an adequate measuring site has to be selected. This site has to represent the area under investigation. Its area must be large enough to provide a sufficient fetch, so that the eddy covariance system can be deployed below a potential internal boundary layer (e.g. Raabe, 1983; Jegede and Foken, 1999; Savelyev and Taylor, 2005). A second well-established approach to relate eddy covariance measurements at a single point to an effective upwind source area of the flux is the footprint analysis (e.g. Leclerc and Thurtell, 1990; Schuepp et al., 1990), which is especially important in complex non-homogeneous terrain. Such footprints can either be determined from analytic dispersion models or from Lagrangian stochastic dispersion models (e.g. Thomson, 1987; Horst and Weil, 1992; Schmid, 1997). Footprint models can be validated through tracer field experiments with a complex set-up of eddy covariance measurement systems (e.g. Göckede et al., 2005).

The sensor height should be larger than 20 times the pathlength of a sonic anemometer in order to capture the full turbulent spectrum (Kaimal, 1975). Eddy covariance measurements often require the deployment of two separate sensors, one sonic anemometer to determine the wind fluctuation and another sensor to measure the scalar to be transported. Kristensen et al. (1997) answer this question “How close is close enough when measuring scalar fluxes with displaced sensors?”. According to this analysis more than 90% of the flux is recovered if the ratio of displacement D to the sensor height z is less than 1/10. A vertical displacement is reported to be favourable to reduce spectral loss in the high frequency part. On the other hand, problems of flow distortion and crosstalk error can be minimized by a horizontal displacement of sensors (Wyngaard, 1988). As a compromise, Foken (2003) recommends a placement of an additional sensor for scalar measurements downwind of the sonic anemometer slightly below the centre of its measuring path.

Table 1: Participation of recent types of sonic anemometers in selected intercomparison experiments; the reference sonic anemometer type is indicated. LINEX-96/2: **Lin**denberg **Ex**periment; LITFASS-98: **L**indenberg **I**nhomogeneous **T**errain – **F**luxes between **A**tmosphere and **S**urface: a long term **S**tudy; MAP-Riviera-99: **M**esoscale **A**lpine **P**rogramme in the Riviera valley; VOITEX-99: **Voit**sumra **Ex**periment; EBEX-2000: **E**nergy **B**alance **Ex**periment. (Table taken from Mauder et al., 2006b, Appendix C, Table 1)

experiment	**LINEX-96/2**	**LITFASS-98**	**MAP-Riviera-99**	**VOITEX-99**	**EBEX-2000**
literature	(Foken et al., 1997b)	(Beyrich et al., 2002)	(Christen et al., 2000)	(Foken, 1999)	(Mauder et al., 2006b, Appendix C)
Campbell CSAT 3	X	X	X(reference)	X(reference)	X(reference)
Kaijo-Denki 310/A	X(reference)	X(reference)	-	-	-
Kaijo-Denki 310/B	-	X	-	-	-
Kaijo-Denki TR90-AH	-	-	-	-	X
Solent HS	-	-	X	-	X
Solent R2/R3	X	-	X	X	-
Metek USA-1	X	-	X	X	X
R. M. Young 81000	-	-	-	X	X
ATI K Probe	-	-	-	-	X
UW Sonic	-	-	-	-	X

The development of sonic anemometers in the 1960s (Bovscheverov and Voronov, 1960; Kaimal and Businger, 1963; Mitsuta, 1966) enabled micrometeorologists to measure turbulent fluctuations in the atmospheric surface layer fast enough to determine turbulent flux. Sonic anemometer field intercomparison experiments were carried out in order to evaluate the accuracy of the data obtained by those early prototypes (Miyake et al., 1971; Tsvang et al., 1973; Dyer, 1981; Dyer et al., 1982; Tsvang et al., 1985).

During the last decade more and more sonic anemometers have become commercially available. Most of the sonic intercomparisons which deal with instruments currently deployed for energy balance measurements are not published. Nevertheless, many of the important micrometeorological field campaigns included a comparison phase, although the results were reported only in a few cases (Table 1). It is a shortcoming of intercomparison experiments previous to this thesis that only sonic anemometers/thermometers were used. Other sensors for scalar measurements like fast-response hygrometers should also be deployed for intercomparison, in order to examine not only the results for the turbulent flux of sensible heat but also for turbulent fluxes of latent heat and also other air constituents (Mauder et al., 2005, Appendix B; Mauder et al., 2006b, Appendix C).

1.3.2 Post-field data processing

The advances in computer technology in the 1980s enabled micrometeorologists to develop systems to process the large amount of data which is necessary for the eddy covariance method. A number of such systems have been documented (e.g. Lloyd et al., 1984; Businger, 1986; McMillen, 1988). Most of the necessary processing steps and flux corrections are well-described in the literature (e.g. Webb et al., 1980; Schotanus et al., 1983; Moore, 1986; Højstrup, 1993; Tanner et al., 1993; Wilczak et al., 2001). Intensive efforts regarding a standardisation of the eddy covariance methodology were made within the worldwide FLUXNET project (Baldocchi et al., 2001), which attempts to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapour, and energy flux densities in the context of global warming. Aubinet et al. (2000) integrates the descriptions of single measuring systems and single processing steps into a general methodology for eddy covariance measurements. As a result of an workshop on methodological aspects of eddy covariance measurements Lee et al. (2004) provide a comprehensive overview on the current state of science regarding micrometeorological issues and methods and give recommendations related to the eddy covariance technique for estimating turbulent mass and energy exchange between the terrestrial biosphere and the atmosphere. Based on these recommendations it is desirable to develop a software package, which implements all processing steps, which are currently considered to be necessary, together with an objective quality assessment in order to demonstrate the practical applicability of such a post-field quality assurance concept (Mauder and Foken, 2004).

1.4 The energy balance closure problem

Measurements of all components of the energy balance (equation 1) make it possible to verify this budget equation for a specific location at a specific time. The results of many field experiments (e.g. Tsvang et al., 1991; Kanemasu et al., 1992; Foken et al., 1997a; Foken, 1998) indicate that the amount of energy which is transported by the turbulent fluxes Q_H and Q_E is not equivalent to the available energy at the surface, which sums up net radiation Q^*_s and ground heat flux Q_G at the surface including soil heat storage. The difference between the turbulent energy fluxes and the available energy is called residual or imbalance. The problem of the experimental energy balance closure was brought to awareness at the end of the eighties and was discussed for the first time during a workshop on instrumental and methodical problems of land surface flux measurements (Foken and Oncley, 1995), which resulted in the organisation of a field experiment. Wilson et al. (2002) gives a first comprehensive overview on the energy balance closure problem, which demonstrates that there is a general lack of energy balance closure for several FLUXNET sites, with the turbulent fluxes of sensible and latent heat being underestimated and/or available energy being overestimated. A mean imbalance on the order of 20% is reported for these sites.

The energy balance closure problem is explicated thoroughly in Culf et al. (2004), where possible reasons for obtaining poor energy balance closure are discussed, ranging from measurement errors associated with the individual instruments to the inability of the methods used to measure certain physical phenomena. Amongst other reasons, which will not be considered in this thesis, since they are not related to measurements of turbulent fluxes, uncertainties in the post-field data processing of eddy covariance measurements are suspected to be crucial (Massman and Lee, 2002). Their impact on the energy balance closure is investigated by Mauder and Foken (2006, Appendix D).

1.5 Application of eddy covariance to study the global carbon cycle

Rising levels of atmospheric CO_2 and other greenhouse gases are of concern to scientists and policy makers because they trap infrared radiation that is emitted by the earth's surface. Therefore, the large-scale, multi-investigator project FLUXNET (Baldocchi et al., 2001) was created to investigate the carbon balance of terrestrial ecosystems. In this context the determination of carbon dioxide net ecosystem exchange (NEE) with the eddy covariance method has become a fundamental quantitative tool to estimate CO_2 exchange rates. Since NEE estimates integrate positive and negative CO_2 fluxes over relatively long periods like a month or a year, it is possible that relatively small systematic errors in single flux values have a relatively large cumulative effect. Therefore, quality assurance must be especially important for CO_2 flux measurements to determine defensible NEE estimates. Uninterrupted time series are required to calculate such budgets. It is the intent of the micrometeorological community to collect eddy covariance data 24 hours a day and 365 days a year. However, missing data in the archived records is a common feature, due to several instrumental or meteorological reasons. Usually, parameterisations are deduced from the remaining flux data to fill data gaps with reasonable modelled CO_2 flux values. Therefore, it is important to define objective criteria to decide which data should be rejected and which data can be considered as high quality data for parameterisations (Ruppert et al., 2005, Appendix F).

1.6 Objectives of the thesis

The aim of this dissertation is the quality assurance for measurements of turbulent fluxes. This comprises all actions necessary to provide adequate confidence that flux estimates obtained by the eddy covariance method are of the type and quality needed and expected by the user of flux data. This includes measures of quality control, quality assessment and quality improvement for flux estimates of sensible heat, water vapour and CO_2. An important question is to which extent issues related to the eddy covariance technique can be a reason for problems to close the surface energy balance in field experiments.

The first objective of this thesis is the presentation of a quality assurance concept for surface energy flux measurements and its application to field experiments. It is addressed by Mauder et al. (2005, Appendix B) and Mauder et al. (2006b, Appendix C), which report the results of the eddy covariance sensor comparisons during EVA-GRIPS 2002 and EBEX-2000. All common types of sonic anemometers and fast-response open-path hygrometers are treated in these two field studies under different environmental conditions. Deficiencies of some of the tested instruments are exposed and analysed in order to suggest options for corrections and a possible use of data of such imperfect sensors. Furthermore, recommendations regarding adequate sensor set-ups for eddy covariance measurements are presented based on the intercomparison results. The accuracy of eddy covariance measurements can be quantitatively determined depending on the sensor type and a post-field data quality assessment. An objective quality assessment scheme is presented by Mauder et al. (2005, Appendix B). This study analyses surface flux measurements of 14 eddy covariance systems of LITFASS-2003 and presents an overview on the availability of high quality data for this field campaign.

The second objective is the investigation of the impact of post-field data processing on eddy covariance flux estimates and energy balance closure. To that end, Mauder et al. (2006b, Appendix C) analyses the results of a comparison study for post-field data processing methods. This comparison demonstrates to which extent the results of eddy covariance measurements can differ for one and the same raw dataset between commonly used processing algorithms. Another study (Mauder and Foken, 2006, Appendix D) focuses on the single processing steps and their impact on eddy covariance flux estimates and energy balance closure.

The third objective is the application of the quality assurance concept to eddy covariance measurements to determine net ecosystem exchange of CO_2. It is addressed by Mauder and Foken (2006, Appendix D) and Ruppert et al. (2005, Appendix F). The first paper describes the impact of post-field data processing on the CO_2 flux estimates. Special attention is paid to alternative approaches for the correction of density effects caused by heat and water vapour transfer, which are reported to alter NEE estimates significantly (Liu, 2005). Ruppert et al. (2005, Appendix F) defines objective data rejection criteria, which form the innovative basis of a new gap-filling strategy. This strategy is tested for the FLUXNET station Waldstein-Weidenbrunnen by applying the quality assessment scheme to a one year dataset of eddy covariance measurements from this site.

A principal requisite to address all three objectives is the development of a software package to perform the entire post-field data processing of eddy covariance measurements. Such a software was developed in preparation for this thesis, called TK2 (Mauder and Foken, 2004). It is based on experiences in this field at the University of Bayreuth. It implements the state of science guidelines according to Lee et al. (2004) and makes them applicable to practice. Thanks to improvements in automation and usability of this software large datasets from different measurement sites can be analysed with a standardised routine.

2 Experiments and data

The results presented in this thesis are based on large datasets either obtained by the author's own experiments under supervision of Th. Foken, or provided by project partners in close cooperation within the specific studies. The data presented in the publication listed in the Appendices B and D were collected during the extensive field campaign LITFASS-2003 conducted in summer 2003 and during a pre-experiment of the EVA-GRIPS project at the same location one year before. Two measurement systems during both experiments were deployed by the author (Mauder et al., 2003a; Mauder et al., 2003b), whereas several other measurement systems were operated by project partners within the EVA_GRIPS and the VERTIKO framework (Beyrich et al., 2004). The paper presented in Appendix C uses data obtained from the EBEX-2000 experiment in 2000 (Oncley et al., 2002), which was coordinated by the American National Center for Atmospheric Research and the University of Bayreuth. Three of the EBEX-2000 flux stations were deployed by the University of Bayreuth under supervision of Th. Foken supported by the author (Bruckmeier et al., 2001). The measurements during NIMEX-1 presented in the manuscript of Appendix E were carried out in close cooperation with the Obafemi Awolowo University Ile-Ife, Nigeria in 2004 (Jegede et al., 2004). The dataset for the study by Ruppert et al. (2005, Appendix F) was collected in 2003 during the WALDATEM-2003 experiment by Thomas et al. (2004).

2.1 EBEX-2000

The **E**nergy **B**alance **Ex**periment EBEX-2000 was designed to study possible reasons for the energy balance closure problem (Oncley et al., 2002). One major goal was the investigation of instrument related problems. Therefore, EBEX-2000 featured many side-by-side eddy covariance sensor intercomparisons, which are analysed by Mauder et al. (2006b, Appendix C). The EBEX-2000 experiment was carried out in the San Joaquin Valley of California on an irrigated cotton field of half a square mile size near Fresno, CA (36°06' N, 119°56' W, 67 m a.s.l.). The measurement systems were operated from June 20 to August 24, 2000. The weather was characterised by clear skies. Air temperatures typically ranged from 15° C during the night to maxima up to 35° C during daytime (Oncley et al., 2005).

The first ten days of the field campaign were reserved for the eddy covariance sensor intercomparison. During the remainder of the experiment, several other pair-wise comparisons were possible with sensor types that could not be deployed in the main intercomparison. Altogether, data from ten eddy covariance systems could be compared for the study presented in Mauder et al. (2006b, Appendix C). These systems comprised all common sensor types, i.e. seven different types of sonic anemometers and two different types of fast-response hygrometers:

- CSAT3 sonic anemometer by Campbell Scientific, Inc., USA,
- UW sonic anemometer by NCAR, USA,
- Solent HS sonic anemometer by Gill Instruments Ltd., UK,
- K-Probe sonic anemometer by ATI Electronics Inc., USA,
- TR90-AH sonic anemometer by Kaijo-Denki, Japan,
- USA-1 sonic anemometer by Metek GmbH, Germany,
- Model 81000 sonic anemometer by R.M. Young, USA,
- KH20 krypton hygrometer by Campbell Scientific, Inc., USA,
- LI-7500 open-path CO_2/H_2O gas analyser LI-COR Biosciences, USA.

A combination of a Campbell CSAT3 sonic anemometer and a Campbell KH20 krypton hygrometer from the University of Bayreuth served as reference system. The comparison eddy covariance systems was performed for periods when they were deployed sufficiently close to the reference, such that one can assume the measured turbulence statistics and fluxes coincide due to a common source or footprint area. The results of this sensor intercomparison are presented in Mauder et al. (2006b, Appendix C), where detailed description of the entire experimental set-up and the applied measurement devices can be found.

2.2 EVA-GRIPS 2002

Sonic anemometers and hygrometers from institutes within the EVA-GRIPS framework (Regional **Eva**poration at **Gri**d/**P**ixel Scale over Heterogeneous Land Surfaces) were compared during an experiment in May and June 2002 at the boundary-layer field site (in German: Grenzschichtmessfeld = GM) Falkenberg of the German Meteorological Service (52°10'01" N, 14°07'27" E, 73 m a.s.l.). Seven eddy covariance systems were deployed along a line of north-south orientation. The statistical analysis of this intercomparison presented in Mauder et al. (2005, Appendix B) focuses on three days' data from May 30 to June 1, 2002, as westerly winds prevailed during this period. As reference system served a combination of a Campbell CSAT3 together with a LI-COR LI-7500 from the University of Bayreuth. The same sensor combination was part of the intercomparison of EBEX-2000 and was compared to other eddy covariance systems from several international institutions (Mauder et al., 2006b, Appendix C).

2.3 LITFASS-2003

The LITFASS-2003 (**L**indenberg **I**nhomogeneous **T**errain – **F**luxes between **A**tmosphere and **S**urface: a long term **S**tudy) experiment aimed to investigate horizontal heterogeneity effects on the evapotranspiration as a cooperation of the research networks EVA-GRIPS and VERTIKO (Vertikaltransporte von Energie und Spurenstoffen an Ankerstationen und ihre räumlich/zeitliche Extrapolation unter komplexen natürlichen Bedingungen). The issue of determining the evapotranspiration was addressed by in-situ measurements, satellite data analysis and computer model studies on different scales (Beyrich et al., 2004). This experiment was carried out in the surroundings of the Meteorological Observatory Lindenberg (MOL) of the German Meteorological Service in an area of 20 km x 20 km size (52°05'30" N, 13°54'00" E, 52°16'30" N, 14°12'00" E), since this heterogeneous landscape southeast of Berlin is considered to be typical for European temperate latitudes. The intensive observation period of LITFASS-2003 lasted from May 19, 2003 to June 17, 2003. The weather during this period was hot and dry with daytime temperature maxima up to 35° C most of the time, interrupted by a few thundershower events.

As it was not known in advance how big the differences between different land use types would be, it was of great importance to determine the sensible and latent heat fluxes at the different sites as precisely as possible and to quantify the uncertainty of these measurements. Reduction of flux measurement uncertainties can be achieved by a detailed knowledge of the characteristics of the different sensor systems and by the application of a well-described harmonised data processing algorithm. Therefore, the con-

Table 2: Instrumentation of the micrometeorological stations during LITFASS-2003 (CNR1, NR LITE: net radiometers by Kipp&Zonen, The Netherlands; CM24: pyranometer/albedometer by Kipp&Zonen, The Netherlands; DD-PIR: double direction precision infrared radiometer by Eppley Laboratory, Inc., USA; Q7, Q6: net radiometers by REBS Inc., USA; BDA-065: Schulze–Däke net radiometer by W. Finck, Germany; USA-1: sonic anemometer by METEK GmbH, Germany; CSAT3: sonic anemometer by Campbell Scientific, Inc., USA; KH20: krypton hygrometer by Campbell Scientific, Inc., USA; LI-7500: open-path CO_2/H_2O gas analyser by LI-COR Biosciences, USA; HFP01SC, HP3: heat flux plates by Hukseflux Thermal Sensors, The Netherlands; WS31S: heat flux plates by TNO-TPD, The Netherlands).

site	type of surface	net radiation	sonic anemometer	hygrometer	soil heat flux plate
A1	cereal	CNR-1	USA-1	KH20	Leskowa
A2	rape	CNR-1	CSAT3	KH20	HFP01SC
A3	cereal	NR LITE	CSAT3	KH20	HFP01SC
A4	maize	Q7	CSAT3	KH20	HFP01SC
A5	cereal	CNR-1	USA-1	KH20	HP3
A6	maize	CM24/DD-PIR	CSAT3	LI-7500	HFP01SC
A7	rape	Q6	CSAT3	KH20	HFP01SC
A8	cereal	BDA-065	CSAT3	LI-7500	WS31S
A9	rape	BDA-065	CSAT3	LI-7500	WS31S
NV2	grassland	CM24/DD-PIR	USA-1	LI-7500	HP3
NV4	grassland	CM24/DD-PIR	USA-1	LI-7500	HP3
HV	pine forest	CM24/DD-PIR	USA-1	LI-7500	HP3
FS	lake	CM24/DD-PIR	USA-1	LI-7500	-
SS	lake	-	USA-1	LI-7500	-

cept of quality assurance presented in this thesis was applied here. After a sensor intercomparison phase (see section 2.2) the datasets of 30 days from 14 eddy covariance stations of LITFASS-2003 were analysed to obtain quality-assured estimates of turbulent fluxes as reported by Mauder et al. (2005, Appendix B). Table 2 presents the LITFASS-2003 stations and their instrumentation.

2.4 NIMEX-1

The NIMEX-1 (**Ni**gerian **M**icrometeorological **Ex**periment) was carried out in order to investigate surface energy fluxes at a typical site in tropical West Africa. All components of the energy balance were measured directly including an eddy covariance system consisting of a sonic anemometer (Metek USA-1) and a krypton hygrometer (Campbell KH20). The measurement systems were deployed on the territory of the Obafemi Awolowo University, Ile-Ife, Nigeria (7°33' N, 4°33' E, 288 m a.s.l.). The measurement site and its surrounding landscape can be described as fallow bush-land (Jegede et al., 2004). The eddy covariance flux measurements were carried out in the period from February 19, 2004 to March 9, 2004, which corresponds to the transition from the dry to the wet season in this area. Air temperatures ranged from 20° C to 35° C. The general weather conditions were dominated by the interplay between the southwesterly monsoonal winds and northeasterly harmattan winds, which alternately transported very different air masses to the area under study: moist marine air from the Gulf of Guinea and dry dusty air from the Sahara and the Sahel zone. Data of the NIMEX-1 experiment were used for the study presented in Mauder et al. (2006a, Appendix E).

2.5 FLUXNET station Waldstein-Weidenbrunnen

The study by Ruppert et al. (2005, Appendix F) presents a strategy for the processing, subsequent quality control and gap-filling of carbon dioxide eddy covariance flux measurements for the derivation of annual sums of NEE. The complete evaluation scheme was applied to data recorded at the FLUXNET station Waldstein-Weidenbrunnen DE-Wei in the German Fichtelgebirge Mountains (50°08' N, 11°52' E, 775 m a.s.l.) using the TK2 software for the post-field data processing of a one year dataset of 2003. The CO_2 flux measurements were performed on a 33 m tall tower over spruce forest using a sonic anemometer (R2 until May 19, 2003, since then R3-50, Gill Instruments Ltd., UK) and an open-path gas analyser for CO_2 and H_2O (LI-7500, LI-COR Biosciences, USA). The forest has a mean canopy height of 19 m. Understorey vegetation is sparse and consists of small shrubs and grasses. A detailed description of the research site can be found in Gerstberger et al. (2004).

3 Results

3.1 Quality assurance for micrometeorological field experiments

In general quality assurance for eddy covariance measurements of micrometeorological field experiments comprises two major components: Sensor intercomparison studies and quality assessment of the flux data.

3.1.1 Eddy covariance sensor intercomparison

Mauder et al. (2005, Appendix B) and Mauder et al. (2006b, Appendix C) report the results of the eddy covariance sensor comparisons of EVA-GRIPS 2002 and EBEX-2000. The majority of sonic anemometer comparisons during EBEX-2000 have a coefficient of determination $R^2 > 0.95$ and have a regression coefficient close to 1.00. Of immediate concern are the data from sensors where $R^2 < 0.95$ or exceed a 5% threshold in the slopes of the regression lines (regression coefficients 0.95 - 1.05). These are the wind statistics from the Kaijo-Denki TR90-AH and the ATI K-probe, friction velocities u_* from the Metek USA-1 and the R.M. Young 81000 and the temperature statistics from the Gill Solent-HS. After wind-tunnel tests and an additional field intercomparison with the Kaijo-Denki TR90-AH, a correction of -13% is recommended for all vertical eddy covariance fluxes measured by this instrument. In opposition to a study of Kaimal et al. (1990), a single-path correction factor f of 16% is found to be preferable for the ATI K-probe instead of 20% to improve its comparison. Wake effects downstream of a sonic transducer or other supporting structures are suspected as reasons for the problems of the Metek USA-1 and the R.M. Young 81000. A polynomial equation of third degree was proposed for the correction of the raw sonic temperature data of the Solent-HS as a function of an independent slow-response reference temperature measurement (Mauder et al., 2006b, Appendix C). An excellent agreement was found between sonic anemometers of type Campbell CSAT3 and NCAR's UW sonics, which justifies the choice of the first one as reference instrument.

More problems were met regarding the hygrometers that were tested in the intercomparisons. Day to day drifts in the calibration coefficients of some of the KH20 krypton hygrometers were observed during EBEX-2000, which can partly be explained by scaling effects of the optical windows (Tanner and Campbell, 1985). Larger changes in the behaviour of a KH20 were attributed to its sensitivity to condensing humidity inside the sensor's enclosure in combination with corrosion of electrical contacts. From the EVA-GRIPS 2002 comparison one can see that deviations within the group of KH20s are larger than within the group of LI-7500s. However, still unexplained deviations of the water vapour flux measurements on the order of 10% to 20% remain for both instruments, which can probably be reduced through frequent recalibrations as it was done before and after LITFASS-2003 (Mauder et al., 2005, Appendix B).

3.1.2 *Quality assessment of eddy covariance flux estimates*

In order to make a uniform data analysis of the eddy covariance measurements presented in this thesis possible, the comprehensive software package TK2 (Mauder and Foken, 2004) was developed at the University of Bayreuth. It includes quality tests of the raw data and all necessary corrections of the covariances (Lee et al., 2004), as well as quality tests for the resulting turbulent fluxes (Foken and Wichura, 1996; Foken et al., 2004). Most of the processing steps are well described in the literature. They were brought into a reasonable sequence (Figure 1) and some own modifications and adaptations were made (Mauder et al., 2005, Appendix B).

Before the calculation of typically 30 minute covariances the high frequency dataset is screened using the algorithm of Vickers and Mahrt (1997) to eliminate spikes in the time series. An eventual time delay between two time series from two separate instruments, e.g. a sonic anemometer and a hygrometer, is determined automatically by cross-correlation analysis for each averaging interval. Inherent to turbulence measurements are deficiencies which cause more or less important violations of assumptions to the eddy covariance method necessitating a set of corrections to the calculated covariances.

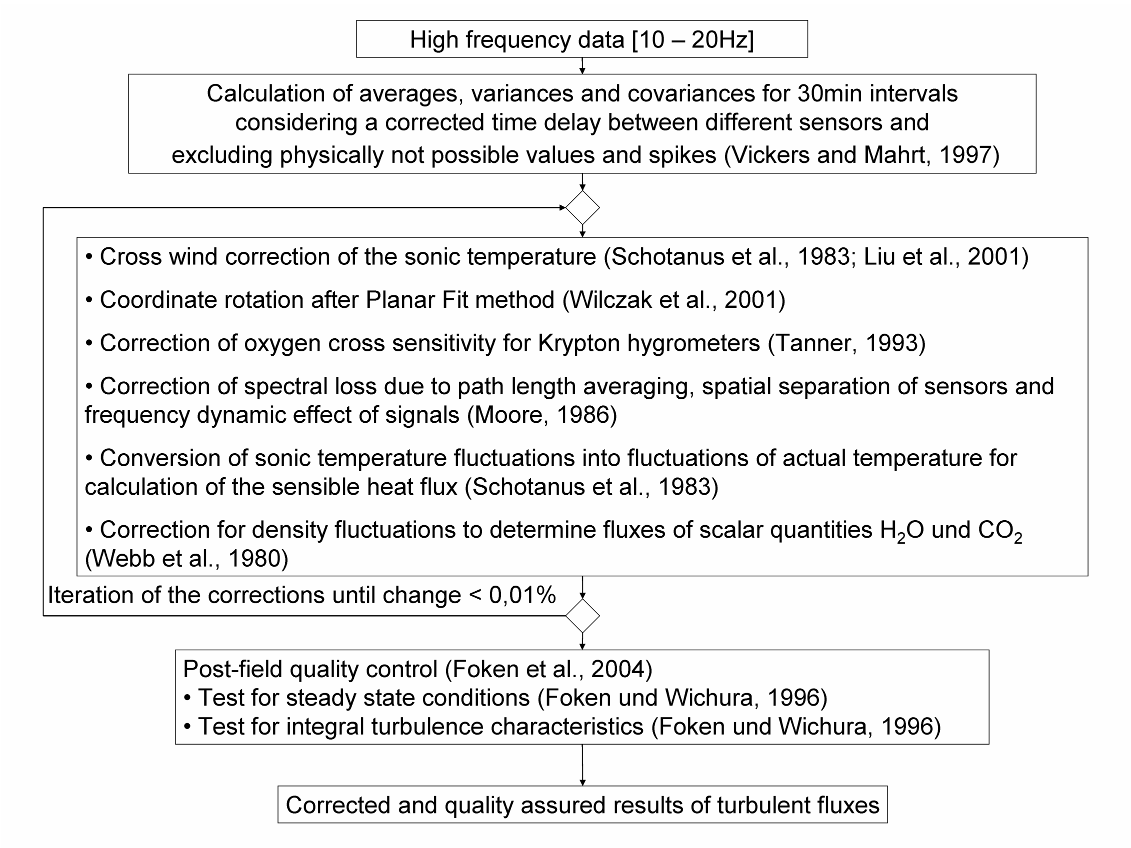


Figure 1: Processing scheme of the software package TK2 developed at the University of Bayreuth (Mauder and Foken, 2004). It performs all post-processing of turbulence measurements and produces quality assured turbulent fluxes. (Figure taken from Mauder et al., 2005, Appendix B, Figure 1)

The first correction to be conducted is the crosswind correction of the sonic temperature (Schotanus et al., 1983) because it has to be applied to data in the sonic anemometer coordinate system (Liu et al., 2001). Then the coordinate system of the sonic measurements is transformed into a coordinate system parallel to the mean stream lines, using the planar fit method (Wilczak et al., 2001) or alternatively using the double rotation method (Kaimal and Finnigan, 1994). The correction according to Tanner et al. (1993) has to be applied to the data obtained by krypton hygrometers due to a cross sensitivity to oxygen of these instruments.

A correction for high frequency spectral loss is necessary for several reasons (Moore, 1986). Turbulent fluxes are corrected for line averaging of sonic anemometers and hygrometers, spatial separation of sonic anemometers, hygrometers and fast response temperature sensors, and dynamic frequency response of fast response temperature sensors. If the longitudinal sensor separation was already corrected by the time delay corrected calculation of the covariance, only the lateral fraction of the sensor separation has to be corrected. Transfer functions are convoluted with parameterised spectra of vector and scalar quantities proposed by Moore (1986) for stable stratification and by Højstrup (1981) for unstable stratification. As the parameterisations of stable cospectra in Moore (1986) are erroneous (Moncrieff et al., 1997), cospectral models by Kaimal et al. (1972) were used instead for the whole stability range.

Since sonic anemometers do not directly measure temperature but the speed of sound, the humidity effect of this parameter was corrected according to the paper of Schotanus et al. (1983). To determine turbulent fluxes of air constituents like H_2O, a correction according to Webb et al. (1980) or Liu (2005) is necessary. This procedure incorporates two aspects. The first is the conversion of the volume-related measurement of the content of a scalar quantity, e.g. absolute humidity [kg m^{-3}], into a mass-related parameter like specific humidity or mixing ratio [kg kg^{-1}]. The second aspect is the correction of a positive vertical mass flow, which results from the mass balance equation, because vertical velocities of ascending parcels have to be different from descending ones due to density differences (Webb et al., 1980; Fuehrer and Friehe, 2002). Since some of the processing steps are interdependent, the whole sequence of flux corrections and conversions is iterated. The resulting flux data are tested on stationarity and development of turbulence according to the procedures proposed by Foken and Wichura (1996) in an updated version of Foken et al. (2004). The output of this entire procedure is quality-assured estimates of turbulent fluxes.

This scheme of quality assessment was applied to the corrected flux estimates of LITFASS-2003. It provides objective criteria to give an overview of the availability of highest quality latent heat flux data during daytime (0600 and 2000 UTC) for the LITFASS-2003 experiment (Figure 2). Most of the stations show an average availability of more than 80% of highest quality latent heat flux data. Significantly lower percentages on May 19, May 23 and June 5, 2003 for all stations are mainly caused by rain events.

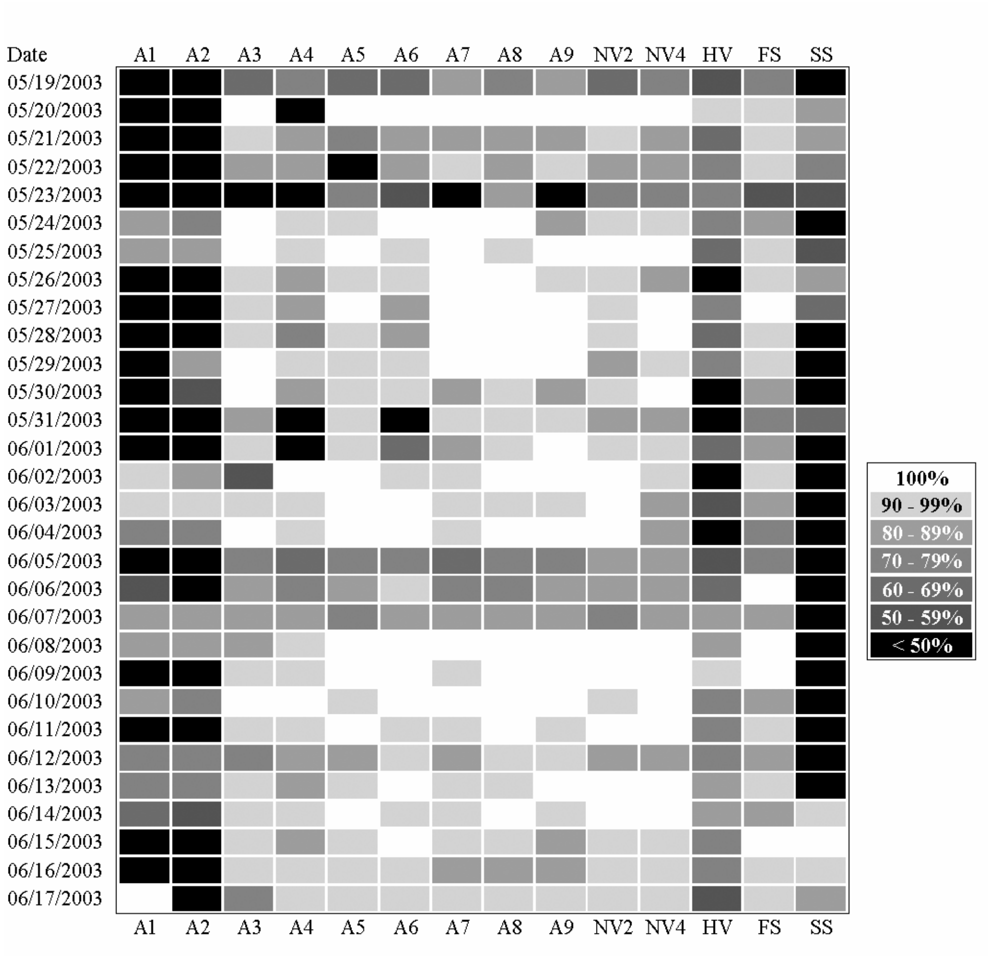


Figure 2: Availability of highest quality latent heat flux data between 0600 and 2000 UTC for the LITFASS-2003 experiment, May 19 to June 17, 2003. Black boxes indicate days of less than 50% availability, including days with instrumental malfunction. (Figure taken from Mauder et al., 2005, Appendix B, Figure 2)

Lower data quality on May 21 and 22, 2003 and on June 6 and 7, 2003 can be attributed to distinct cumulus convection on the back side of a cold front, which causes instationary conditions. Data gaps due to instrumental malfunction are the reason that less than 50% of the latent heat flux data were of highest quality over several days at stations A1, A2, and SS. Partially lower data quality for site HV has to be noticed indicating resolution problems of its data acquisition system.

3.2 Eddy covariance related problems of energy balance closure

All components of the energy balance were determined experimentally at two different exemplary sites. Mauder et al. (2006a, Appendix E) studies the energy balance closure problem for NIMEX-1 in a more or less homogeneous environment in Nigeria. In comparison, data from a maize field of the LITFASS-2003 experiment in Germany serve as example for measurements in heterogeneous terrain (Mauder et al., 2005, Appendix B).

An energy balance residual of approximately 30% was found for the LITFASS-2003 maize field (Figure 3a), although all measures of quality assurance were applied to these measurements, e.g. deployment of highest quality instrumentation, calibrations, application of all corrections for the eddy covariance fluxes, adequate consideration of the soil heat storage (Mauder et al., 2005, Appendix B). In contrast, the energy balance could almost be closed for the measurements during NIMEX-1 for the Nigerian bush-land site (Figure 3b) with similar measures of quality assurance.

To understand the good energy balance closure during NIMEX-1, one should recall the reasons given for non-closure during other experiments in the literature (Culf et al., 2004). Possible differences due to the instrumentation are relatively small compared to the energy balance residual during LITFASS-2003 (see section 3.1.1). The studies of Mauder et al. (2006b, Appendix C) and Mauder and Foken (2006, Appendix D) investigate to which extent uncertainties related to the post-field data processing of eddy covariance measurements can explain these different findings for both experiments. Therefore, the impact of post-field data processing methods on the eddy covariance flux estimates and the energy balance closure is analysed.

The comparison of post-field data processing methods between the EBEX-2000 participants shows differences of up to 10% for the sensible heat flux, and up to 15% for the latent heat flux (Figure 4). About 10% of the difference in latent heat flux values was due to the fact that one group (C) did not adequately for the spatial displacement between the sonic anemometer and the hygrometer. The next biggest difference is

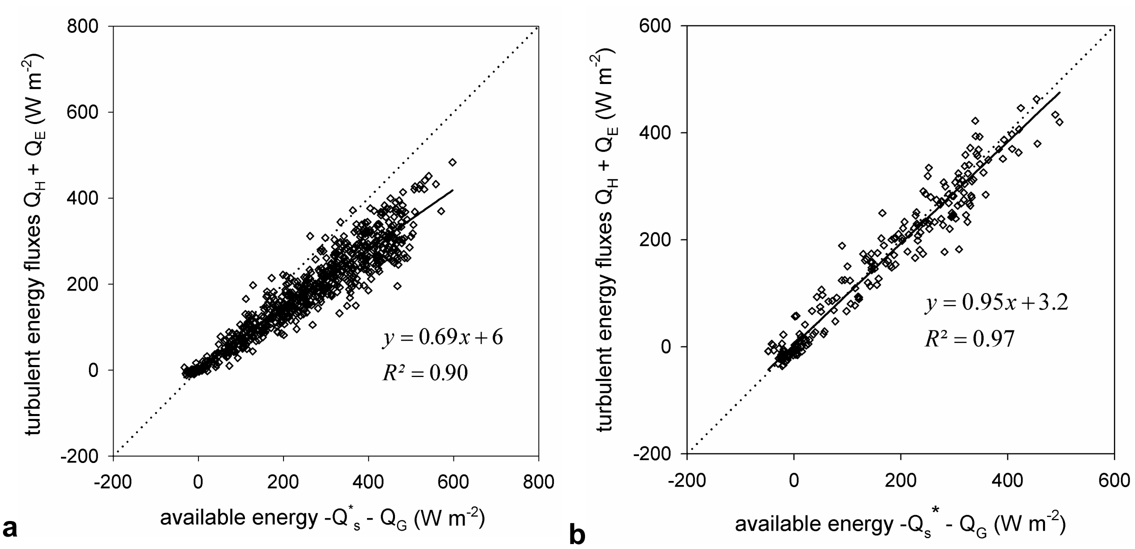


Figure 3a: Sum of the turbulent energy fluxes vs. the available energy (sum of net radiation and ground heat flux) for the whole **LITFASS-2003** measurement period, May 19 to June 17, 2003. The regression equation shows an average imbalance of approx. 30% (Figure taken from Mauder et al., 2005, Appendix B, Figure 4b, modified). **b:** Turbulent energy fluxes versus available energy during **NIMEX-1** and linear regression (Figure taken from Mauder et al., 2006a, Appendix E, Figure 8).

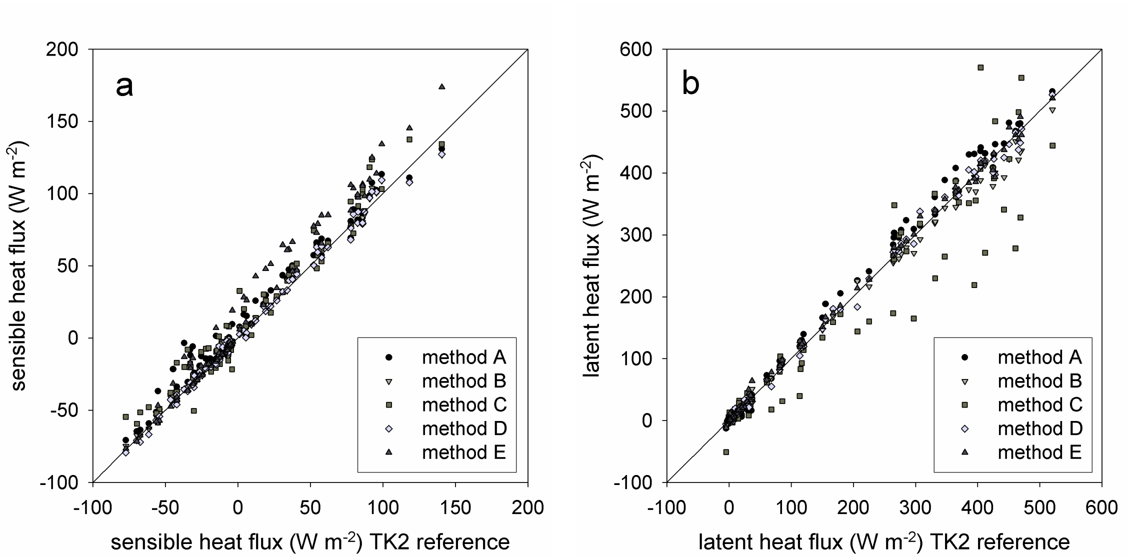


Figure 4: Results for turbulent fluxes calculated from the same time series (measured with the NCAR system at EBEX-2000 site 8, Aug. 9, 2000 1700 UTC – Aug. 11, 2000 1700 UTC) using different post-field data processing methods of the EBEX-2000 participants; sensible heat flux on the left (a), latent heat flux on the right (b). Results of methods A,B,C,D and E are plotted against reference software TK2 (Mauder and Foken, 2004). (Figure taken from Mauder et al., 2006b, Appendix C, Figure 1)

whether linear detrending was applied to the time series or not. Finally, the procedure used to apply the Schotanus (1983) correction for the sensible heat flux can have a significant impact. This can be seen in particular for method E (Figure 4a). All other procedures appear to have a similar impact on the resulting heat flux estimates between the different methods. Most of the methods tend to result in systematically slightly higher sensible heat fluxes than TK2 (Figure 4a), because they do not perform an iteration of all corrections. The latent heat flux estimates obtained by the other processing methods scatter around the TK2 results more or less equally in both directions (Figure 4b).

Mauder and Foken (2006, Appendix D) investigates the impact of post-field data processing on flux estimates and energy balance closure using the TK2 software to analyse a dataset from a selected maize site of LITFASS-2003. This study shows that the entire post-field data processing leads to a reduction of the mean energy balance residual by 16% (Table 3). Its average midday maximum of 133 W m^{-2} is lowered to 118 W m^{-2}. This reduction is caused mainly by an increase of the mean latent heat flux through the post-field data processing (+20%); whereas the overall impact on the sensible heat flux is relatively small (+4%). The biggest impact of all post-field data processing steps was found for the CO_2 flux. Its average value, which is negative corresponding to net CO_2 uptake by this ecosystem, was approximately halved in magnitude compared to raw 30 minute covariances (Table 3) mainly due to the correction according to Webb et al. (1980).

Table 3: Overall impact of the post-field data processing on the turbulent fluxes and the energy balance residual, based on 30 minute averaging time. Dataset from a selected maize site of LITFASS-2003. {Table taken from \Mauder, 2006 #307, Appendix D, Table 1}

overall impact of the post-field data processing	
sensible heat flux	+4%
latent heat flux	+20%
CO_2 flux	+53%
energy balance residual	-16%

The study by Mauder and Foken (2006, Appendix D) also investigates eddy covariance flux estimates for averaging times different from the classic 30 minute interval, since the application of a too-short averaging time can act as spectral high-pass filter (Finnigan et al., 2003). The impact of an extension of the averaging time for the covariance calculations is shown in Figure 5. All flux estimates change significantly in magnitude going from 5 minute covariances over 30 minutes to longer averaging times. The mean sensible heat flux for 5 minutes of 40.1 W m^{-2} increases to 40.8 W m^{-2} for 30 minutes, and to 74.9 W m^{-2} for 1440 minutes (= 24 hours). The mean latent heat flux increases more or less continuously from 73.9 W m^{-2} for 5 minute covariances, over 74.5 W m^{-2} for 30 minutes covariances, to 77.9 W m^{-2} for 360 minutes covariances before it decreases again for longer averaging times ending up at 66.9 W m^{-2} for 1440 minutes. A continuous decrease of the resulting energy balance residual for increasing averaging times can be observed. Its value for the traditional 30 minute interval of 31.8 W m^{-2} in average is reduced to 7.6 W m^{-2} for an averaging interval of 720 minutes

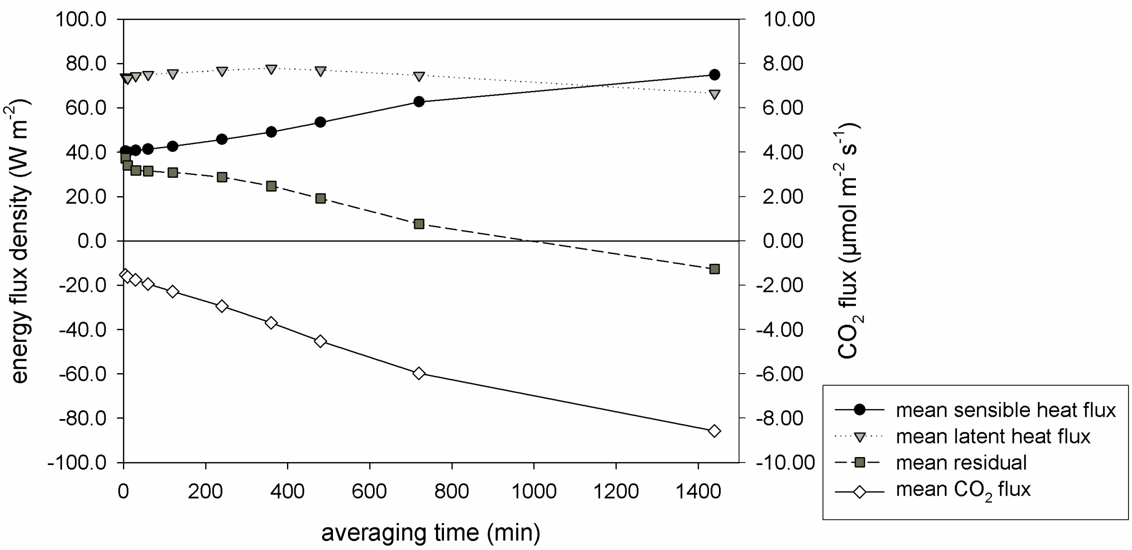


Figure 5: Mean turbulent flux estimates and the resulting energy balance residual for different averaging times. Dataset from a selected maize site of LITFASS-2003. (Figure taken from Mauder and Foken, 2006, Appendix D, Figure 7)

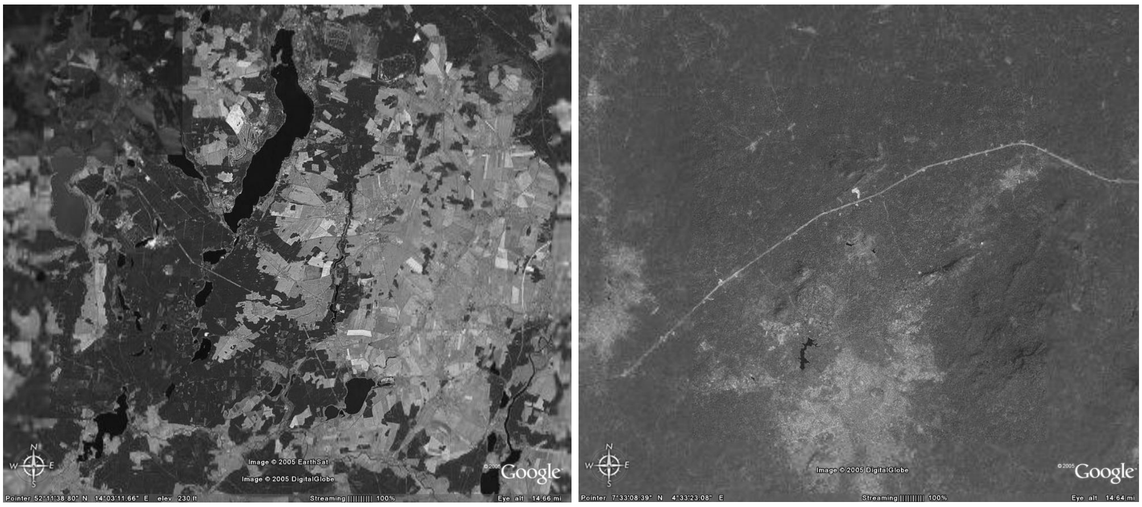
and decreases further to -12.7 W m^{-2} for 1440 minutes. The impact of different averaging times on the CO_2 flux was found to be even higher than for the other two turbulent fluxes. Its mean value calculated from 5 minute covariances of -1.53 µmol m^{-2} s^{-1} decreases to -8.51 µmol m^{-2} s^{-1} when stepping to 1440 minute averaging time, which means a quintuplication of the net assimilation estimate for this maize canopy.

One critical issue regarding the extension of the averaging time up to 24 hours is weather the stationarity criterion is still fulfilled. The definition of weak stationarity, which has to be applied here, requires that mean values and variances are time-invariant. Clearly, the answer to the question if stationarity can be assumed depends on the length of the averaging time. It was argued that for the standard 30 minute interval the stationarity criterion is often fulfilled (e.g. Foken, 2003), because on the one hand it covers the micro-turbulent transport, which is met at frequencies > 10^{-3} Hz, and on the other hand trends of parameters due to their diurnal course usually occur on larger scales than 30 minutes.

However, averages and variances calculated for 24 hours usually show only small variations for relevant parameters such as wind velocity, temperature or humidity. The whole diurnal course is contained completely within a 24 hour interval. Only general weather changes could cause larger differences, e.g. the passage of a frontal system or seasonal differences. Therefore, one can assume that the stationarity criterion is also satisfactorily fulfilled for an averaging time of 24 hours, although an extension of the averaging time implies further complications. It is questionable to which extend the measured eddy covariances fluxes can be related to the other locally measured surface energy balance components or to which extent advection, i.e. transport with the mean vertical wind, has to be considered. However, flux contributions from covariances of longer than 30 minute averaging time seem to be crucial to close the energy balance (Mauder and Foken, 2006, Appendix D).

The same measures of quality assurance regarding instrumentation and post-field data analysis were applied for both experiments, LITFASS-2003 and NIMEX-1. Therefore, one can conclude that the differences in energy balance closure between both sites are related to the different environmental conditions. Another possible reason for a non-closed surface energy balance is the operation of eddy covariance measurements in non-homogeneous terrain (Panin et al., 1998; Culf et al., 2004). Heterogeneous terrain can induce instationarities or long-scale turbulent fluxes, which impair the eddy covariance method.

Figure 6 gives an impression of the two dissimilar landscapes of LITFASS-2003 and NIMEX-1. The satellite image of the NIMEX-1 area shows the city of Ile-Ife in the south surrounded by quite uniform bush-land almost without any distinguishable structuring (Figure 6b). Therefore, this site can serve as an example for measurements in an environment of weak heterogeneity. In contrast, the LITFASS-2003 experiment was located in an area of strong heterogeneity. It is characterised by a large forest area in the



(a) (b)

Figure 6: Visible band satellite images from (a) the LITFASS-2003 area around Lindenberg, Germany, (b) the NIMEX-1 area around Ile-Ife, Nigeria. The experiment sites are located approximately in the centres of the images. The same zoom-factor is applied for all images; they cover an area of approx. 27 x 23 km (Google, 2005). (Figure taken from Mauder et al., 2006a, Appendix E, Figure 9, modified).

west and agricultural land in the east, with several lakes of different size in between (Figure 6a). On a smaller scale, the agricultural land is sub-divided in well-defined patches of different crops. These have clearly defined borders, which generate sudden changes in surface parameters like aerodynamic roughness height, surface temperature and soil moisture. Such sudden changes can hardly be identified in the NIMEX-1 area.

Clearly defined borders as they exist in the LITFASS-2003 area can induce edge effects, which generate very large eddies of wavelengths on the order of a few hours. Such turbulent organised structures (TOS) were analysed in a Large Eddy Simulation (LES) study by Kanda et al. (2004). They reported that the increased presence of TOS patterns under strong inhomogeneity can enhance secondary circulations and resulting large heat transports due to local advection, while less TOS due to weaker inhomogeneity can reduce local advections and low frequency trends at local points. According to Kanda et al. (2004) TOS can be captured by the eddy covariance method when extending the averaging time of usually 30 minutes beyond typical wavelengths of TOS.

For the LITFASS-2003 experiment longwave flux contributions were found (Figure 5), which are able to close the large energy balance residual at this site (Mauder and Foken, 2006, Appendix D). This strongly supports the thesis “that the filtering of this low frequency covariance by the averaging-rotation operations in common use is a large contributory factor to the failure to close the energy balance” (Finnigan et al., 2003). However, longwave flux contributions cannot only be attributed to tall canopies or hilly terrain as in the work of Finnigan et al. (2003), because the LITFASS-2003 maize field had a low canopy height (0.5 m) and was located in a flat surrounding. Rather, the distinct heterogeneity of this terrain with clearly defined anthropogenic borders due to cultivation is likely to be responsible for the generation of very longwave flux contributions and consequently a lack of energy, when eddy covariance flux estimates are calculated for the classic 30 minute averaging time. Probably not only the heterogeneity of the nearest surrounding of the measurement field causes energy balance closure problems like Panin et al. (1998) assume. Rather, a general strong heterogeneity of the entire landscape seems to generate additional energy transport in very low frequency turbulent structures (Mauder and Foken, 2006, Appendix D).

The dependence on the observation height of TOS patterns, which were found in the LES study by Kanda et al. (2004), might also be one reason for significantly different measured flux values between different levels of tall towers (e.g. Beyrich et al., 2002) that were formerly attributed to changing footprint areas for increasing observation height (Foken and Leclerc, 2004). In addition, TOS patterns can be one explanation for discrepancies between aircraft-based and tower-based eddy covariance measurements (e.g. Desjardins et al., 1997).

3.3 Implications for the determination of CO_2 net ecosystem exchange

The study presented by Mauder and Foken (2006, Appendix D) not only evaluates the impact of post-field data processing on energy flux estimates but also on fluxes of CO_2. Alternative methods by Liu (2005) and Webb et al. (Webb et al., 1980) to correct CO_2 flux estimates for effects of heat and water vapour transfer are compared. For a selected maize field of the LITFASS-2003 experiment, the approach of Liu (2005) leads to net CO_2 uptake estimates for this ecosystem which are 26% larger than estimates obtained using the WPL correction. The results for the respiration estimates (positive CO_2 fluxes) are very similar for both methods, whereas the assimilation estimates (negative CO_2 fluxes) are larger when applying the method by Liu (2005) instead of the WPL correction. Liu's approach presumably leads to the more reliable results, since this derivation is based on the conservation equation for the total moist air, whereas only dry air has been considered by Webb et al. (1980).

The paper of Ruppert et al. (2005, Appendix F) addresses another issue of quality assurance for the eddy covariance method, namely the detection and treatment of data gaps for the determination of annual estimates of CO_2 net ecosystem exchange as desired within the FLUXNET framework. A set of criteria used for quality assessment identifies periods with instrumental or methodological failures. These criteria include tests for the methodological assumptions of the eddy covariance method according to Foken and Wichura (1996) in an updated version by Foken et al. (2004). The new evaluation scheme is compared with the commonly used practice of a friction velocity u_* threshold criterion (Goulden et al., 1997; Aubinet et al., 2000; Gu et al., 2005) of 0.3 m s^{-1}. The comparison between both rejection criteria shows that the flux data quality assessment with tests on stationarity of fluxes and on developed turbulence leads to a less systematic distribution of data gaps compared to the commonly used u_* threshold (Figure 7).

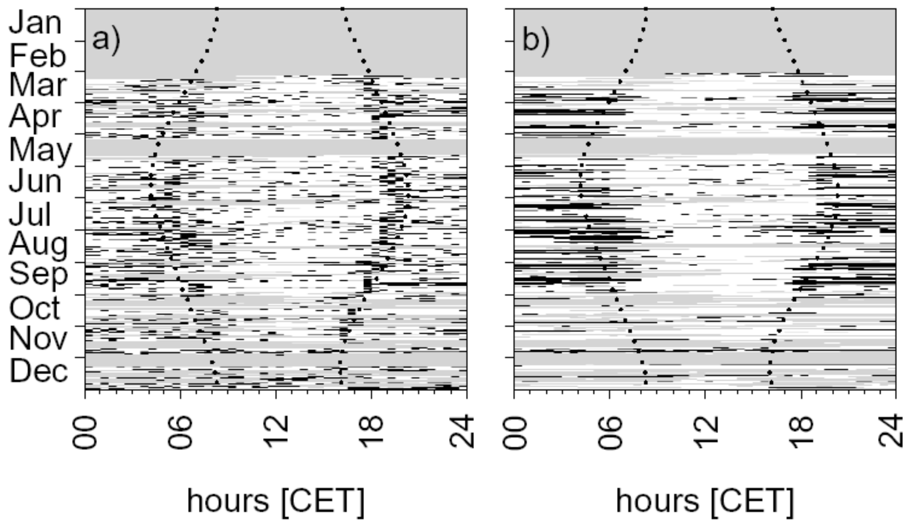


Figure 7: Eddy flux quality assessment at the FLUXNET station Waldstein-Weidenbrunnen for the year 2003 using (a) criteria based on the stationarity test and the test of integral turbulence characteristics in order to check for the validity of the eddy-covariance method and well developed turbulent conditions (criteria 3 and 4). In comparison, the use of $u_* < 0.3$ m s^{-1} (b) as criterion to indicate poor turbulence conditions leads to rejection of a large proportion of the nighttime data especially during the summer. White areas represent accepted and black rejected data. Grey areas indicate missing data due to rain, fog, ice or general instrument failure. The dotted lines indicate astronomical sunrise and sunset (Figure taken from Ruppert et al., 2005, Appendix F, Figure 7)

This new flux data evaluation scheme may therefore help to reduce the risk of selective systematic error in the annual sum of NEE (Moncrieff et al., 1996). At the same time it significantly increases the number of available high quality nighttime measurements (+9% throughout the year), especially during summer (+26%), giving a more robust basis for the parameterisation of respiratory fluxes and for the derivation of the annual sum. Data rated as low quality at higher values of u_* indicate that the u_* criterion is not sufficient for the assessment of the assumptions of the eddy covariance method.

4 Conclusions

The state of science recommendations from an AMERIFLUX workshop (Lee et al., 2004) on the issue of quality assurance and quality control of surface flux measurements were made applicable to a standardised routine: the TK2 software package (Mauder and Foken, 2004). This programme was used to analyse numerous eddy covariance measurements of several national and international micrometeorological experiments in a uniform and standardised way:

- One week data from ten eddy covariance stations for the EBEX-2000 sensor intercomparison (Mauder et al., 2006b, Appendix C)
- 30 days data from 14 eddy covariance stations of LITFASS-2003 (Mauder et al., 2005, Appendix B), with particular interest in latent and sensible heat fluxes over different land use types
- 15 days data from eddy covariance measurements during NIMEX-1 (Mauder et al., 2006a, Appendix E) to investigate surface energy fluxes at a tropical site in West Africa
- One year data from the Waldstein/Weidenbrunnen FLUXNET site (Ruppert et al., 2005), focussed on CO_2 flux and annual NEE over a spruce forest.

The eddy covariance sensor intercomparison experiments of EBEX-2000 and EVA-GRIPS 2002 were analysed to assess the typical uncertainty of eddy covariance flux estimates related to the instrumentation (Mauder et al., 2005, Appendix B; Mauder et al., 2006b, Appendix C). Based on these intercomparison results, highest quality sensors were classified type A (suitable for fundamental research applications), whereas other probes are type B (adequate solution for general flux measurements). To determine the instrument related accuracy of flux measurements, these types as well as the classification according to Foken et al. (2004) into high quality data (flag 1-3) and moderate quality data (flag 4-6) can be used. The result is shown in Table 4 for most of the currently available sonic anemometers. Flags greater than 6 are not listed here. Such data can only serve for rough orientation (flag 7-8) or should be excluded (flag 9).

Table 4: Accuracy of turbulent fluxes based upon the experiences from the EVA_GRIPS Pre-Experiment in 2002 and the EBEX-2000 intercomparison (Table taken from Mauder et al., 2005, Appendix B, Table 8, modified)

anemometer	quality class	sensible heat flux	latent heat flux
Type A, e.g. CSAT3, UW, Solent HS, ATI-K	1-3	5% or 10 W m^{-2}	10% or 20 W m^{-2}
	4-6	10% or 20 W m^{-2}	15% or 30 W m^{-2}
Type B, e.g. USA-1, R.M. Young 81000	1-3	10% or 20 W m^{-2}	15% or 30 W m^{-2}
	4-6	15% or 30 W m^{-2}	20% or 40 W m^{-2}

Table 4 describes a random instrument-related error, which can be partly attributed to a statistical flux sampling error and in some cases additionally to deficiencies in the sensor design and/or probe-induced flow distortion problems. If eddy covariance sensors are well-calibrated and maintained no large systematic errors could be found for any sensor type, which could result in a general over- or underestimation of turbulent energy fluxes. Therefore, problems associated with individual instruments of eddy covariance systems cannot provide an adequate explanation for a systematic lack of turbulent energy transport compared to the available energy at the earth's surface.

An exemplary study (Mauder and Foken, 2006, Appendix D) with a dataset from a selected maize field of the LITFASS-2003 experiment showed that the entire post-field data processing of eddy covariance measurements including all necessary flux corrections, conversions and quality checks reduces the energy balance residual by 16%, when the commonly used averaging interval of 30 minutes is applied for the calculation of covariances. However, the energy balance can completely be closed through an extension of the averaging time up to 24 hours. The presence of flux contributions of longer wavelength than 30 minutes could be explained through the strong surface heterogeneity surrounding this measurement site in accordance with a LES model study by Kanda et al. (2004). In contrast to the heterogeneous LITFASS-2003 area, the energy balance could be closed for the measurements during NIMEX-1 even for 30 minute averaging time. Presumably, less low frequency turbulent structures were generated due to the weaker heterogeneity of the environment (Mauder et al., 2006a, Appendix E).

Therefore, one can conclude that the filtering of flux contributions from very low frequency covariances through the commonly used averaging times of less than 30 minutes explains a major part of the energy balance closure problem (Mauder and Foken, 2006, Appendix D). A strong heterogeneity of the area surrounding a measurement site could be identified as main reason for the generation of such very longwave energy flux contributions (Mauder et al., 2006a, Appendix E). Extending the averaging times may solve energy balance problems but also implies some complications like the separation of the locally meaningful fluxes, which can be attributed to the ecosystem under study, from wider-scale advective transport related to other areas (Mahli et al., 2004). In addition, for many applications of eddy covariance measurements, e.g. the calibration and validation of numerical model simulations or other process studies, a significantly better temporal resolution than 24 hours is required. Further analyses with datasets from several different sites are needed to investigate the relations between heterogeneity, longwave flux contributions and energy balance closure. These investigations dealing with real world measurements should be carried out in close connection with LES model studies in order to improve the understanding of the physical mechanism of the energy imbalance.

An analysis for a selected maize field (Mauder and Foken, 2006, Appendix D) shows that the correction procedure after Liu (2005), which is based on more fundamental assumptions than the WPL correction (Webb et al., 1980), leads to increased estimates of

CO_2 uptake by an ecosystem compared to the WPL correction. This is in accordance with Liu (2005). The study by Ruppert et al. (2005, Appendix F) showed that the tests on stationarity and developed turbulence (Foken and Wichura, 1996; Foken et al., 2004) obtained from the TK2 data analysis provide a fundamental and robust quality assessment of turbulent flux data for a successful gap-filling strategy for annual sums of NEE. Especially above forest sites, these rejection criteria provide more specific information related to the dependence of nighttime NEE on turbulent mixing or decoupling within the canopy than a certain value of u_* measured above the canopy.

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', *Advances in Ecological Research* **30**, 113-175.

Baldocchi, D., Falge, E., Gu, L. H., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X. H., Malhi, Y., Meyers, T., Munger, W., Oechel, W., U, K. T. P., 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 vapor, and energy flux densities', *Bull. Am. Meteorol. Soc.* **82**, 2415-2434.

Beyrich, F., Richter, S. H., Weisensee, U., Kohsiek, W., Lohse, H., DeBruin, H. A. R., Foken, T., Göckede, M., Berger, F. H., Vogt, R., and Batchvarova, E.: 2002, 'Experimental determination of turbulent fluxes over the heterogeneous LITFASS area: Selected results from the LITFASS-98 experiment', *Theor. Appl. Climatol.* **73**, 19-34.

Beyrich, F., Adam, W., Bange, J., Behrens, K., Berger, F. H., Bernhofer, C., Bösenberg, J., Dier, H., Foken, T., Göckede, M., Görsdorf, U., Güldner, J., Hennemuth, B., Heret, C., Huneke, S., Kohsiek, W., Lammert, A., Lehmann, V., Leiterer, U., Leps, J.-P., Liebethal, C., Lohse, H., Lüdi, A., Mauder, M., Meijninger, W. M. L., Mengelkamp, H.-T., Queck, R., Richter, S. H., Spieß, T., Tittebrand, A., Weisensee, U., and Zittel, P.: 2004, Verdunstung über einer heterogener Landoberfläche. Das LITFASS-2003 Experiment. Deutscher Wetterdienst, Forschung und Entwicklung, Offenbach, Arbeitsergebnisse **79**, 100 pp.

Bovscheverov, V., and Voronov, V.: 1960, 'Akustitscheskii fljuger', *Izv AN SSSR, ser Geofiz* **6**, 882-885.

Bruckmeier, C., Foken, T., Gerchau, J., and Mauder, M.: 2001, Documentation of the experiments EBEX-2000, July 20 to August 24, 2000. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **13**, 21 pp. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

Businger, J. A.: 1986, 'Evaluation of the accuracy with which dry deposition can be measured with current micrometeorological techniques', *J. Climate Appl. Meteor.* **25**, 1100-1124.

Christen, A., van Gorsel, E., Andretta, M., Calanca, M., Rotach, M., and Vogt, R.: 2000, 'Intercomparison of ultrasonic anemometers during the MAP-Riviera project', in *9th Conference on Mountain Meteorology*, Aspen, CO, 130-131.

Culf, A. D., Foken, T., and Gash, J. H. C.: 2004, 'The energy balance closure problem', in P. Kabat and M. Claussen (ed.), *Vegetation, Water, Humans and the Climate. A New Perspective on an Interactive System*, Springer, Berlin, Heidelberg, pp. 159-166.

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

Dyer, A. J.: 1981, 'Flow distortion by supporting structures', *Boundary-Layer Meteorol.* **20**, 363-372.

Dyer, A. J., Garratt, J. R., Francey, R. J., McIlroy, I. C., Bacon, N. E., Bradley, E. F., Denmead, O. T., Tsvang, L. R., Volkov, Y. A., Koprov, B. M., Elagina, L. G., Sahashi, K., Monji, N., Hanafusa, T., Tsukamoto, O., Frenzen, P., Hicks, B. B., Wesely, M., Miyake, M., and Shaw, W.: 1982, 'An international turbulence comparison experiment (ITCE-76)', *Boundary-Layer Meteorol.* **24**, 181-209.

Finnigan, J. J., Clement, R., Malhi, Y., Leuning, R., and Cleugh, H. A.: 2003, 'A re-evaluation of long-term flux measurement techniques, Part I: Averaging and co-ordinate rotation', *Boundary-Layer Meteorol.* **107**, 1-48.

Foken, T., and Oncley, S. P.: 1995, 'Workshop on instrumental and methodical problems of land surface flux measurements', *Bull. Am. Meteorol. Soc.* **76**, 1191-1193.

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., Kirzel, H.-J., and Thiermann, V.: 1997a, 'Results of the LINEX-96/2 Experiment', *Deutscher Wetterdienst, Forschung und Entwicklung, Arbeitsergebnisse* **48**, 75 pp.

Foken, T., Weisensee, U., Kirzel, H.-J., and Thiermann, V.: 1997b, 'Comparison of new-type sonic anemometers', in *12th Symposium on Boundary Layer and Turbulence*, Vancouver, BC, Amer. Meteorol. Soc., Boston, 356-357.

Foken, T.: 1998, 'Ergebnisse des LINEX-97/1 Experimentes', *Deutscher Wetterdienst, Forschung und Entwicklung, Arbeitsergebnisse* **53**, 38 pp.

Foken, T.: 1999, Comparison of the sonic anemometer Young Model 81000 during VOITEX-99. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **8**, 12 pp. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

Foken, T.: 2003, *Angewandte Meteorologie. Mikrometeorologische Methoden*, Springer, Heidelberg, 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, 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.

Fuehrer, P. L., and Friehe, C. H.: 2002, 'Flux corrections revisited', *Boundary-Layer Meteorol.* **102**, 415-457.

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: A german case study*, Springer, Heidelberg, pp. 15-41.

Göckede, M., Mauder, M., Markkanen, T., Arnold, K., Leps, J.-P., and Foken, T.: 2005, 'Approaches to validate footprint models using natural tracer measurements from a field experiment', *Agric. For. Meteorol.*, revised.

Google (2005). Google Earth, www.google.com. **2005**.

Goulden, M. L., Daube, B. C., Fan, S.-M., Suttan, D., J., Bazzaz, A., Munger, J. W., and Wofsy, S. C.: 1997, 'Physiological response of a black spruce forest to weather', *J. Geophys. Res.* **102**, 28987-28996.

Gu, L. H., Falge, E. M., Boden, T., Baldocchi, D. D., Black, T., Saleska, S. R., Suni, T., Verma, S. B., Vesala, T., Wofsy, S. C., and Xu, L.: 2005, 'Objective threshold determination for nighttime eddy flux filtering.' *Agric. For. Meteorol.* **128**, 179-197.

Højstrup, J.: 1981, 'A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux', *Boundary-Layer Meteorol.*, 341-356.

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

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.

Jegede, O. O., and Foken, T.: 1999, 'A study of the internal boundary layer due to a roughness change in neutral conditions observed during the LINEX field campaigns', *Theor. Appl. Climatol.* **62**, 31-41.

Jegede, O. O., Mauder, M., Okogbue, E. C., Foken, T., Balogun, E. E., Adedokun, J. A., Oladiran, E. O., Omotosho, J. A., Balogun, A. A., Olandosu, O. R., Sunmonu, L. A., Ayoola, M. A., Aregbesola, T. O., Ogolo, E. O., Nymphas, E. F., Adeniyi, M. O., Olantona, G. I., Lapido, K. O., Ohamobi, S. I., Gbobaniyi, E. O., and Akinlade, G. O.: 2004, 'The Nigerian Micrometeorological Experiment (NIMEX-1): An Overview', *Ife J. Sci.* **6**, 191-202.

Kaimal, J. C., and Businger, J. A.: 1963, 'A continuous wave sonic anemometer-thermometer', *J. Climate Appl. Meteorol.* **2**, 156-164.

Kaimal, J. C., Wyngaard, J. C., Izumi, Y., and Coté, O. R.: 1972, 'Spectral characteristics of surface layer turbulence', *Quart. J. Roy. Meteorol. Soc.* **98**, 563-589.

Kaimal, J. C.: 1975, 'Sensor and techniques for direct measurement of turbulent fluxes and profiles in the atmospheric surface layer', in D. H. Lenschow (ed.), *Atmospheric Technology*, NCAR, pp. 7-23.

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

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

Kanda, M., Inagaki, A., Letzel, M. O., Raasch, S., and Watanabe, T.: 2004, 'LES study of the energy imbalance problem with eddy covariance fluxes', *Boundary-Layer Meteorol.* **110**, 381-404.

Kanemasu, E. T., Verma, S. B., Smith, E. A., Fritschen, L. Y., Wesely, M., Fild, R. T., Kustas, W. P., Weaver, H., Steawart, Y. B., Geney, R., Panin, G. N., and Moncrieff, J. B.: 1992, 'Surface flux measurements in FIFE: An overview', *J. Geophys. Res.* **97**, 18547-18555.

Kristensen, L., Mann, J., Oncley, S. P., and Wyngaard, J. C.: 1997, 'How close is close enough when measuring scalar fluxes with displaced sensors', *J. Atm. Oceanic Tech.* **14**, 814-821.

Leclerc, M. Y., and Thurtell, G. W.: 1990, 'Footprint prediction of a scalar flux using a markovian analysis', *Boundary-Layer Meteorol.* **52**, 247-258.

Lee, X., Massman, W., and Law, B. E. (ed.): 2004, 'Handbook of micrometeorology. A guide for surface flux measurement and analysis', Kluwer Academic Press, Dordrecht, 250 pp.

Liu, H., 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.

Liu, H.: 2005, 'An alternative approach for CO_2 flux correction caused by heat and water vapour transfer', *Boundary-Layer Meteorol.* **115**, 151–168.

Lloyd, C. R., Shuttleworth, W. J., Gash, J. H. C., and Turner, M.: 1984, 'A microprocessor system for eddy-correlation', *Agric. For. Meteorol.* **33**, 67-80.

Mahli, Y., McNoughton, K. G., and von Randow, C.: 2004, 'Low frequency atmospheric transport and surface flux measurements', in X. Lee, W. J. Massman and B. Law (ed.), *Handbook of Micrometeorology. A Guide for Surface Flux Measurement and Analysis*, Kluwer, Dordrecht, pp. 101-118.

Massman, W. J., and Lee, X.: 2002, 'Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges', *Agric. For. Meteorol.* **113**, 121-144.

Mauder, M., Foken, T., and Göckede, M.: 2003a, Dokumentation des Experiments EVA_GRIPS,27.05.2002 bis 10.06.2002. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **22**, 22 pp. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

Mauder, M., Foken, T., Göckede, M., Liebethal, C., Ruppert, J., and Bertolini, T.: 2003b, Dokumentation des Experiments LITFASS-2003, 19.05.2003 bis 20.06.2003, Dokumentation des Experimentes GRASATEM-2003, 14.05.2003 bis 01.06.2003. Universität Bayreuth, Abt. Mikrometeorologie. Print, ISSN 1614-8916., Arbeitsergebnisse **23**, 47 pp.

Mauder, M., and Foken, T.: 2004, Documentation and instruction manual of the eddy covariance software package TK2. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **26**, 44 pp. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

Mauder, M., Liebethal, C., Göckede, M., Leps, J.-P., Beyrich, F., and Foken, T.: 2005, 'Processing and quality control of flux data during LITFASS-2003', *Boundary-Layer Meteorol.*, revised.

Mauder, M., and Foken, T.: 2006, 'Impact of post-field data processing on eddy covariance flux estimates and energy balance closure', *Meteorol. Z.*, submitted.

Mauder, M., Jegede, O. O., Okogbue, E. C., Wimmer, F., and Foken, T.: 2006a, 'Surface energy flux measurements at a tropical site in West Africa during the transition from dry to wet season', *Theor. Appl. Climatol.*, to be submitted.

Mauder, M., Oncley, S. P., Vogt, R., Weidinger, T., Ribeiro, L., Bernhofer, C., Foken, T., Kohsiek, W., de Bruin, H. A. R., and Liu, H.: 2006b, 'The Energy Balance Experiment EBEX-2000. Part II: Intercomparison of eddy covariance sensors and post-field data processing methods', *Boundary-Layer Meteorol.*, to be submitted.

McMillen, R. T.: 1988, 'An eddy correlation technique with extended applicability to non-simple terrain', *Boundary-Layer Meteorol.* **43**, 231-245.

Mitsuta, Y.: 1966, 'Sonic anemometer-thermometer for general use', *Journal of the Meteorological Society of Japan* **Ser. II, 44**, 12-24.

Miyake, M., Stewart, R. W., Burling, H. W., Tsvang, L. R., Koprov, B. M., and Kuznetsov, O. A.: 1971, 'Comparison of acoustic instruments in an atmospheric turbulent flow over water', *Boundary-Layer Meteorol.* **2**, 228-245.

Moncrieff, J., Mahli, Y., and Leuning, R.: 1996, 'The propagation of errors in long-term measurements of land-atmosphere fluxes of carbon and water', *Global Change Biology* **2**, 231-240.

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

Moore, C. J.: 1986, 'Frequency response corrections for eddy correlation systems', *Boundary-Layer Meteorol.* **37**, 17-35.

Obukhov, A. M.: 1951, 'Investigation of the micro-structure of the wind in the near-surface layer of the atmosphere (in Russian)', *Izvestia AN SSSR, seria Geofizika* **3**, 49.

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

Oncley, S. P., Foken, T., Vogt, R., Kohsiek, W., de Bruin, H., Bernhofer, C., Christen, A., Grantz, D., Lehner, E., Liebethal, C., Liu, H., Mauder, M., Pitacco, A., Ribeiro, L., and Weidinger, T.: 2005, 'The Energy Balance Experiment EBEX-2000. Part I: Overview and energy balance', *Boundary-Layer Meteorol.*, to be submitted.

Panin, G. N., Raabe, A., and Tetzlaff, G.: 1998, 'Inhomogeneity of the land surface and problems in parametrization of surface fluxes in natural conditions', *Theor. Appl. Climatol.* **60**, 163-178.

Raabe, A.: 1983, 'On the relation between the drag coefficient and fetch above the sea in the case of off-shore wind in the near shore zone', *Z. Meteorol.* **33**, 363-367.

Ruppert, J., Mauder, M., Thomas, C., and Lüers, J.: 2005, 'Innovative gap-filling strategy for annual sums of CO_2 net ecosystem exchange', *Agric. For. Meteorol.*, revised.

Savelyev, S. A., and Taylor, P. A.: 2005, 'Internal Boundary Layers: I. Height Formulae for Neutral and Diabatic Flows', *Boundary-Layer Meteorol.* **115**, 1-25.

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

Schotanus, P., Nieuwstadt, F. T. M., and DeBruin, H. A. R.: 1983, 'Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations', *Boundary-Layer Meteorol.* **26**, 81-93.

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.

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

Swinbank, W. C.: 1951, 'The measurement of vertical transfer of heat and water vapour by eddies in the lower atmosphere', *J. Meteorol.* **8**, 135–145.

Tanner, B. D., and Campbell, G. S.: 1985, 'A krypton hygrometer for measurement of atmospheric water vapor concentration', in *Moisture and Humidity*, Instrument Society of America, Research Triangle Park, NC, 609-612.

Tanner, B. D., Swiatek, E., and Greene, J. P.: 1993, 'Density fluctuations and use of the krypton hygrometer in surface flux measurements', in R. G. Allen (ed.), *Management of irrigation and drainage systems: integrated perspectives*, American Society of Civil Engineers, New York, NY, pp. 945-952.

Thomas, C., Ruppert, J., Lüers, J., Schröter, J., Mayer, J. C., and Bertolini, T.: 2004, Documentation of the WALDATEM-2003 Experiment, 28.4.-3.8.2003. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **24**, 59 pp. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

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

Tsvang, L. R., Koprov, B. M., Zubkovskii, S. L., Dyer, A. J., Hicks, B., Miyake, M., Stewart, R. W., and McDonald, J. W.: 1973, 'A comparison of turbulence measurements by different instruments; Tsimlyansk field experiment 1970', *Boundary-Layer Meteorol.* **3**, 499-521.

Tsvang, L. R., Zubkovskij, S. L., Kader, B. A., Kallistratova, M. A., Foken, T., Gerstmann, W., Przandka, Z., Pretel, J., Zelený, J., and Keder, J.: 1985, 'International turbulence comparison experiment (ITCE-81)', *Boundary-Layer Meteorol.* **31**, 325-348.

Tsvang, L. R., Fedorov, M. M., Kader, B. A., Zubkovskii, S. L., Foken, T., Richter, S. H., and Zelený, J.: 1991, 'Turbulent exchange over a surface with chessboard-type inhomogeneities', *Boundary-Layer Meteorol.* **55**, 141-160.

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

Webb, E. K., Pearman, G. I., and Leuning, R.: 1980, 'Correction of the 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, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., and Field, C.: 2002, 'Energy balance closure at FLUXNET sites', *Agric. For. Meteorol.* **113**, 223-243.

Wyngaard, J. C.: 1988, 'Flow-distortion effects on scalar flux measurements in the surface layer: Implications for sensor design', *Boundary-Layer Meteorology (Historical Archive)* **42**, 19-26.

List of appendices

Appendix A: Individual contributions on the joint publications

The publications of which this cumulative thesis consists were composed in close cooperation with other researchers. Hence, many authors contributed to the publications listed in Appendices B to F in many different ways. This section specifies my own contributions to the individual manuscripts.

Appendix B

Mauder, M.*, Liebethal, C., Göckede, M., Leps, J.-P., Beyrich, F., and Foken, T.: 2005, 'Processing and quality control of flux data during LITFASS-2003', *Boundary-Layer Meteorol.*, revised.

I was responsible for two eddy covariance stations during EVA-GRIPS 2002 and LITFASS-2003. I analysed the eddy covariance sensor intercomparison of EVA-GRIPS 2002. The software for the processing of eddy covariance data was developed by me. I processed all eddy covariance data from LITFASS-2003. The text of this manuscript was mainly written by me except of section 4.3, section 5 and section 6.

C. Liebethal was responsible for the analysis of the soil and radiation fluxes. She wrote the text passages regarding these issues (section 5 and section 6). M. Göckede performed the footprint based characterisation of the measuring sites (section 4.3). The work profited from extensive discussions with J.-P. Leps and F. Beyrich.

T. Foken encouraged the composition of this manuscript as my supervisor and contributed to it through helpful discussions and editorial work. He also contributed concluding text passages.

Appendix C

Mauder, M.*, Oncley, S. P., Vogt, R., Weidinger, T., Ribeiro, L., Bernhofer, C., Foken, T., Kohsiek, W., de Bruin, H. A. R., and Liu, H.: 2006, 'The Energy Balance Experiment EBEX-2000. Part II: Intercomparison of eddy covariance sensors and post-field data processing methods', *Boundary-Layer Meteorol.*, to be submitted.

I analysed the intercomparison of eddy covariance sensors. I applied all necessary corrections and quality tests to the eddy covariance flux data. I wrote major parts of the manuscript. I was also involved in the operation of three eddy covariance stations during EBEX-2000 under supervision of T. Foken.

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* *Corresponding author*

S. P. Oncley coordinated the EBEX-2000 experiment. The data acquisition and the calculation of raw statistics of the eddy covariance measurements were organised by him. He essentially contributed to this manuscript through extensive text passages regarding the sensor descriptions, editorial comments and sharing his thoughts and experience in many discussions.

The data for the sensor intercomparison were provided by S. P. Oncley, R. Vogt, C. Bernhofer, W. Kohsiek, H. A. R. de Bruin, and H. Liu. T. Weidinger was responsible for the analysis of comparison of post-field data processing methods.

Appendix D

Mauder, M.*, and Foken, T.: 2006, 'Impact of post-field data processing on eddy covariance flux estimates and energy balance closure', *Meteorol. Z.*, submitted.

I developed the software required for this analysis and conducted the entire data processing. I was responsible for the eddy covariance measurements presented in this publication. I wrote the entire text of this manuscript.

T. Foken encouraged this manuscript as my supervisor and essentially contributed to its progress through sharing his critical thoughts and helpful comments.

Appendix E

Mauder, M.*, Jegede, O. O., Okogbue, E. C., Wimmer, F., and Foken, T.: 2006, 'Surface energy flux measurements at a tropical site in West Africa during the transition from dry to wet season', *Theor. Appl. Climatol.*, to be submitted.

I conducted the entire post-field data processing for the eddy covariance measurements of NIMEX-1. I took part at field experiment in Nigeria deploying instrumentation from the University of Bayreuth. I wrote the entire text of this manuscript.

O.O. Jegede organised the NIMEX-1 field experiment. E. C. Okogbue also participated in the experiment and supported this work through helpful suggestions in several discussions. F. Wimmer conducted the analysis of ogives for this study.

This work profited from the long-time good cooperation of my supervisor T. Foken with Nigerian scientists at the University of Ile-Ife. This manuscript was improved by fruitful discussions with T. Foken who also contributed through editorial work.

* *Corresponding author*

Appendix F

Ruppert, J.*, Mauder, M., Thomas, C., and Lüers, J.: 2006, 'Innovative gap-filling strategy for annual sums of CO2 net ecosystem exchange', *Agric. For. Meteorol.*, revised.

As the first author, J. Ruppert was responsible for the composition of a draft for this manuscript. He contributed to the measurements at the Waldstein/Weidenbrunnen site. He developed the parameterisations for the gap-filling of the CO_2-flux data and part of the empirical criteria for the quality assessment. The main part of this manuscript was written by him.

My contributions to this manuscript were to perform the post-field data processing of the eddy covariance measurements and to participate in the overall interpretation of all results. I also wrote the part of the text related to the data processing and the justification of the quality assessment criteria and performed editorial work for the entire text.

C. Thomas was mainly responsible for the measurements at the Waldstein/Weidenbrunnen site. J. Lüers was also supported these measurements and contributed the text passage about objective segregation between seasonal stages. As supervisor he contributed to the progress of this work in many fruitful discussions.

* *Corresponding author*

Appendix B

PROCESSING AND QUALITY CONTROL OF FLUX DATA DURING LITFASS-2003

MATTHIAS MAUDER[1*], CLAUDIA LIEBETHAL[1], MATHIAS GÖCKEDE[1], JENS-PETER LEPS[2], FRANK BEYRICH[2], THOMAS FOKEN[1]

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Abstract. Different aspects of the quality assurance and quality control (QA/QC) of micrometeorological measurements were combined to create a comprehensive concept which was then applied to the data from the experiment LITFASS-2003 (**L**indenberg **I**nhomogeneous **T**errain – **F**luxes between **A**tmosphere and **S**urface: a long term **S**tudy). The main focus of the QA/QC efforts was on the eddy covariance measurements of the latent heat flux. The results of a turbulence intercomparison experiment showed deviations between the different eddy covariance systems in the order of 15% or less than 30 W m^{-2} for the latent heat flux and 5% or less than 10 W m^{-2} for the sensible heat flux. In order to avoid uncertainties due to the post-processing of turbulence data, a comprehensive software package was used for the analysis of whole LITFASS-2003 experiment, including all necessary algorithms for corrections and quality control. An overview of the quality tests results shows that for most of the days more than 80% of the available latent heat flux data are of high quality as long as there are no instrumental problems. The representativeness of a flux value for the target land use type was analysed using a stochastic footprint model. Different methods to calculate soil heat fluxes at the surface are discussed and a sensitivity analysis is conducted to select the most robust method for LITFASS-2003. This QA/QC system has been developed for the requirements of LITFASS-2003 but it can also be applied to other experiments dealing with similar objectives.

Keywords: eddy covariance, LITFASS-2003, quality control, radiation, ground heat flux, turbulent fluxes

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1. Introduction

The EVA_GRIPS (Regional **Eva**poration at **Gri**d/**P**ixel **S**cale over Heterogeneous Land Surfaces) project aims to investigate horizontal heterogeneity effects on the evapotranspiration. The issue of determining the evapotranspiration was addressed by in-situ measurements, satellite data analysis and computer model studies (Beyrich et al., 2005b). An important precondition for the success of such a study is a calibration and validation dataset provided by highest quality in-situ flux measurements. The LITFASS-2003 experiment was designed for this purpose in a 20 x 20 km^2 area near the Meteorological Observatory Lindenberg (MOL), Germany, and conducted for a 30 day period in May and June 2003. During LITFASS-2003 turbulent fluxes of momentum, sensible and latent heat were measured at 14 micrometeorological stations to cover every land use type of significant areal proportion. As the project aims to analyse heterogeneity effects and it was not known in advance how big the differences between different land use types would be, it was of great importance to determine the sensible and latent heat fluxes at the different sites as precisely as possible and to quantify the uncertainty of these measurements. Reduction of flux measurement uncertainties can be achieved by a detailed knowledge of the characteristics of the different sensor systems and by the application of well-described harmonised data processing algorithms.

Sensor intercomparison experiments are a valuable tool to characterise the possible errors of the turbulence measurement itself, and therefore they were performed for several decades (Miyake et al., 1971; Tsvang et al., 1973; Dyer et al., 1982; Tsvang et al., 1985; Foken et al., 1997; Beyrich et al., 2002; Mauder, 2002; Oncley et al., 2002). However, new types of instruments became available recently by different manufacturers and some of those were used in the LITFASS-2003 experiment. Besides sonic anemometers that were used in previous intercomparison experiments, fast-response hygrometers should also be deployed for comparison, in order to examine not only the results for the sensible heat flux but also for the latent heat flux.

In addition to instrumental uncertainties, there are several problems in fulfilling all assumptions to the eddy covariance method (Stull, 1988; Kaimal and Finnigan, 1994; Lee et al., 2004). Therefore, it is necessary to apply some corrections, conversions and transformations to the pure result of the covariance in order to obtain the turbulent flux. Algorithms for these procedures are available (Webb et al., 1980; Schotanus et al., 1983; Moore, 1986; Wilczak et al., 2001) and have to be applied during the post-field data analysis (Foken et al., 2004). Furthermore, quality tests are important to sort out data of bad quality. Based on these results of the tests the user of the flux data can decide which data fulfil his specific qualitative requirements. Reasons for a violation of the assumptions to the eddy covariance method and thus objective to test procedures can be flux sampling problems (Vickers and Mahrt, 1997), or the meteorological conditions, such as instationarities or poorly developed turbulence (Foken and Wichura, 1996).

The main focus of the QA/QC efforts lies in the determination of the latent heat flux. But the determination of all other terms of the energy balance at the surface are also objects of quality assurance and quality control, because they are required for the calibration and validation of computer model simulations and satellite data analysis. A comprehensive QA/QC concept for surface energy fluxes was developed. It has to be applicable to a measurement campaign comprising several micrometeorological stations like the LITFASS-2003 experiment. Therefore, the QA/QC concept is intended to work with as many automated procedures as possible. In addition to measurements of the turbulent fluxes, the concept will include measurements of net radiation and the soil heat flux.

2. Experimental Set-up

The LITFASS-2003 study area in the grounds surroundings of the Meteorological Observatory Lindenberg and the boundary-layer field site (in German: Grenzschichtmessfeld = GM) Falkenberg of the German Meteorological Service is located in a region of more or less rural character (Beyrich et al., 2005a). The main land use types are agricultural crops, forests, lakes and small settlements. For the LITFASS-2003 experiment from May 19 to June 17, 2003, the set-up comprised 14 micrometeorological stations operated at 13 sites over the major land use types occurring in the area (Beyrich et al., 2005b). One turbulence station was situated at a height of 30.6 m above ground level over a pine forest of 14 m height, named HV. Four stations (A1, A3, A5, A8) were located on cereal fields, three over rape (A2, A7, A9), two over maize (A4, A6), two over grassland (NV2, NV4) and two stations were over lakes (FS, SS). Their instrumentation regarding the measurement of the energy balance components is given in Table 1.

At each site, all components of the energy balance were measured:

$$-Q_s^* = Q_H + Q_E + Q_G(z=0), \tag{1}$$

where Q^*_s is net radiation, Q_H is sensible heat flux, Q_E is latent heat flux, $Q_G(z=0)$: ground heat flux, i.e. heat entering surface (soil, plants, water).

Fluxes which are contributing energy to the surface are defined as negative, and fluxes which are transporting energy away from the surface are positive. In some situations, when significant amounts of energy are stored in the biomass or within the canopy space of tall vegetation, extra terms may be added on the left site of equation 1.

Table 1: Instrumentation of the micrometeorological stations during LITFASS-2003 (CNR1, NR LITE: net radiometers by Kipp&Zonen, The Netherlands; CM24: pyranometer/albedometer by Kipp&Zonen, The Netherlands; DD-PIR: double direction precision infrared radiometer by Eppley Laboratory, Inc., USA; Q7, Q6: net radiometers by REBS Inc., USA; BDA-065: Schulze–Däke net radiometer by W. Finck, Germany; USA-1: sonic anemometer by METEK GmbH, Germany; CSAT3: sonic anemometer by Campbell Scientific, Inc., USA; KH20: krypton hygrometer by Campbell Scientific, Inc., USA; LI-7500: open-path CO_2/H_2O gas analyser by LI-COR Biosciences, USA; HFP01SC, HP3: heat flux plates by Hukseflux Thermal Sensors, The Netherlands; WS31S: heat flux plates by TNO-TPD, The Netherlands)

site	type of surface	net radiation	sonic anemometer	hygrometer	soil heat flux plate
A1	cereal	CNR-1	USA-1	KH20	Leskowa
A2	rape	CNR-1	CSAT3	KH20	HFP01SC
A3	cereal	NR LITE	CSAT3	KH20	HFP01SC
A4	maize	Q7	CSAT3	KH20	HFP01SC
A5	cereal	CNR-1	USA-1	KH20	HP3
A6	maize	CM24/DD-PIR	CSAT3	LI-7500	HFP01SC
A7	rape	Q6	CSAT3	KH20	HFP01SC
A8	cereal	BDA-065	CSAT3	LI-7500	WS31S
A9	rape	BDA-065	CSAT3	LI-7500	WS31S
NV2	grassland	CM24/DD-PIR	USA-1	LI-7500	HP3
NV4	grassland	CM24/DD-PIR	USA-1	LI-7500	HP3
HV	pine forest	CM24/DD-PIR	USA-1	LI-7500	HP3
FS	lake	CM24/DD-PIR	USA-1	LI-7500	-
SS	lake	-	USA-1	LI-7500	-

3. Intercomparison Pre-Experiments

The intercomparison of the sensors already started one year before the LITFASS-2003 experiment. Radiation sensors, soil sensors, sonic anemometers, and hygrometers of the participating institutes were compared, most of them during a pre-experiment in May and June 2002 at the GM Falkenberg. Of specific interest were the fast response hygrometers. All of them were calibrated in the laboratory and tested during a field intercomparison experiment. The laboratory calibration was performed with the help of a dew point generator (LI-610, LiCor Inc.), creating a sequence of five pre-defined dew point values, first in an increasing and then in a decreasing order. The adjustment time was at least seven minutes for each calibration point, and a precision dew point mirror (EdgeTech DewPrime II) was used for control (Weisensee et al., 2003).

For the side-by-side field intercomparison, seven turbulence complexes consisting of a sonic anemometer and a hygrometer were operated by the participating groups along a line of north-south orientation. The operators of these turbulence complexes were the Meteorological Observatory Lindenberg, (MOL), the University of Hamburg (UHH), the University of Bayreuth (UBT), the Technical University of Dresden (TUDD), and the GKSS Research Centre Geesthacht. The instruments were mounted at a height of 3.25 m above ground on towers, which were separated 9 m from each other. The measurements of statistical moments were only compared for a relatively small wind direction sector of 45° width around west, where the measurements of all turbulence complexes were undisturbed by each other and were equally influenced by a footprint area representing the same canopy: grassland of 0.08 m height. The intercomparison analysis focuses on tree days' data from May 30 to June 1, 2002, as westerly winds prevailed during this period. To evaluate the intercomparison experiment, a regression analysis was performed and the statistical measures of comparability *rmsd* and bias *d* (ISO, 1993) were calculated.

$$d=\frac{1}{n}\sum\left(x_{a,i}-x_{b,i}\right) \tag{2}$$

$$rmsd=\sqrt{\frac{1}{n}\sum\left(x_{a,i}-x_{b,i}\right)^2}\ , \tag{3}$$

where

n = number of observations

$x_{a,i}$ = ith observation of the sensor being evaluated

$x_{b,i}$ = ith observation of the reference instrument

The results of the regression analyses comparing the measurements of sensible and latent heat flux are given in Tables 2 and 3, which are based on the data analysis of the different groups using different software packages. Therefore, the deviations include both instrumental and data analysis uncertainty. We selected as the reference complex the Campbell CSAT3 combined with the LI-7500 (LiCor Inc.) of the University of Bayreuth (UBT#1) because the characteristics of these instruments are well known from former intercomparison experiments (Foken et al., 1997; Foken, 1999; Mauder, 2002). Especially the same sensor combination consisting of this CSAT3 and this LI-7500 took part at the intercomparison of EBEX-2000 (**E**nergy **B**alance **Ex**periment) and was compared to the reference system from NCAR (**N**ational **C**enter for **A**tmospheric **R**esearch).

The regression analysis for the sensible heat flux measured by the different stations shows that the absolute values of the regression lines are smaller than 8 W m^{-2} and the slopes differ less than 6% from 1.00. The comparability values of the tested sonic anemometers are in the order of 15 W m^{-2} and the absolute values of the bias lie around 5 W m^{-2}. Only the USA-1(UHH) instrument deviates more from the reference indicated

Table 2: Comparison of the sensible heat flux during the pre-experiment 2002, reference UBT#1, CSAT3/LI-7500. Results of the regression analysis are given as absolute value of the regression equation, the regression coefficient or slope of the regression line, and R^2. Additional: comparability rmsd (W m^{-2}) and bias (W m^{-2}).

sensor	abs. value (W m^{-2})	regression coefficient	R^2	comparability *rmsd* (W m^{-2})	bias *d* (W m^{-2})
USA-1 (MOL#1)	-0.9	0.96	0.94	14.7	-4.8
USA-1 (MOL#2)	-8.0	1.04	0.94	15.0	-4.3
USA-1 (UHH)	-6.0	0.94	0.92	19.0	-10.8
USA-1 (UBT#2)	-5.5	1.00	0.93	15.5	-5.0
CSAT3 (TUDD)	-0.0	1.04	0.93	15.7	3.4
CSAT3 (GKSS)	-1.7	0.94	0.96	13.0	-6.5

Table 3: Comparison of the latent heat flux during the pre-experiment 2002, reference UBT#1, CSAT3/LI-7500. Results of the regression analysis are given as absolute value of the regression equation, the regression coefficient or slope of the regression line, and R^2. Additional: comparability rmsd (W m^{-2}) and bias (W m^{-2}).

sensor	abs. value (W m^{-2})	regression coefficient	R^2	comparability *rmsd* (W m^{-2})	bias *d* (W m^{-2})
USA-1/KH20 (MOL#1)	28.6	1.08	0.77	46.2	38.9
USA-1/LI-7500 (MOL#2)	18.4	0.87	0.74	24.4	0.7
USA-1/LI-7500 (UHH)	28.5	0.92	0.68	32.9	18.3
USA-1/KH20 (UBT#2)*)	-	-	-	-	-
CSAT3/KH20 (TUDD)	12.6	1.25	0.77	53.6	45.3
CSAT3/KH20 (GKSS)	22.8	0.98	0.82	28.5	19.5

*) Latent fluxes could not be calculated for UBT#2 due to data acquisition problems of the KH20.

by a comparability value of 19 W m^{-2} and a bias of 11 W m^{-2}. Nevertheless, the general agreement of the sensors regarding the sensible heat flux is good, although the instrumentation, the data acquisition and analysis were not exactly the same for each group.

The measurements of the latent heat flux show more significant deviations from the reference measurement. The absolute values of the regression lines are in a range from 10 to 30 W m^{-2}, the slopes differ up to 25% from 1.00. Comparability values for the latent heat flux measurements range from 24 W m^{-2} to 54 W m^{-2}. The bias values go up to 45 W m^{-2}. Extremely large deviations of the measuring system CSAT3/KH20 (TUDD) from the reference (UBT#1) could be partly explained by differences in the data analysis. The generally larger uncertainty in the measurement of the latent heat flux in comparison to the sensible heat flux can be attributed to its dependency on the interaction of two separate sensors. Additionally, the single measurement of humidity fluctuations is afflicted with larger uncertainties. This is confirmed by the results of the regression analysis comparing the variances of the humidity measurements. Looking at all comparison parameters in Table 4, we can see that deviations within the group of KH20s are larger than within the group of LI-7500s.

The quantification of uncertainties in the turbulent flux measurements found in the intercomparison can be transferred to the measurements done during the LITFASS-2003 experiment in the following year under comparable conditions regarding the instrumentation, weather and site characteristics. Nevertheless, the precision of the measurements is still open to improvement. Therefore, we drew the following conclusions from this pre-experiment:

All krypton (KH20) and infrared (LI-7500) hygrometers used at the different micrometeorological stations during LITFASS-2003 had to be obligatorily calibrated both before and after the field campaign in the laboratory. For further data analysis, the coefficients determined at the calibration procedure before the experiment were used. The slopes of the regression lines of the two calibrations before and after the one month measuring period typically differed by less than 2% from each other.

During the intercomparison pre-experiment, each group analysed the data using their own software tool. The investigation for the reasons for the differences between the different instruments in the intercomparison showed that it can be in part attributed to different data processing algorithms, which caused in a software comparison experiment

Table 4: Comparison of the variance of the humidity fluctuations during the pre-experiment 2002, reference UBT#1, LI 7500. Results of the regression analysis are given as absolute value of the regression equation, the regression coefficient or slope of the regression line, and R^2. Additional: comparability rmsd (W m^{-2}) and bias (W m^{-2}).

sensor	**abs. value (g^2 m^{-6})**	**regression coefficient**	R^2	**comparability** *rmsd* **(g^2 m^{-6})**	**bias** *d* **(g^2 m^{-6})**
KH20 (MOL#1)	-0.0139	1.25	0.87	0.0752	0.0554
LI-7500 (MOL#2)	-0.0323	1.02	0.92	0.0411	-0.0274
LI-7500 (UHH)	0.0006	0.90	0.90	0.0459	-0.0262
KH20 (UBT#2)	-0.0022	1.10	0.97	0.0367	0.0273
KH20 (TUDD)	-0.0648	1.59	0.66	0.1413	0.0958
KH20 (GKSS)	0.0134	0.73	0.91	0.0706	-0.0572

up to 10% different fluxes for one and the same test dataset. So, we decided to unify the data analysis of the eddy covariance measurements of the LITFASS-2003 experiment for all micrometeorological stations.

4. Eddy Covariance Data Analysis

4.1 Data Calculation and Correction

In order to make a uniform data analysis of the eddy covariance measurements possible, the comprehensive software package TK2 (Mauder and Foken, 2004) was developed at the University of Bayreuth. It includes quality tests of the raw data and all necessary corrections of the covariances, as well as quality tests for the resulting turbulent fluxes. The major components of this quality control system are shown in Figure 1. Most of the processing steps are well described in the literature. Therefore we will not repeat every detail, but will discuss our own modifications and adaptations.

The first step of the data processing is the conversion of the high frequency raw data into meteorological units. As mentioned above, for all hygrometers the calibration

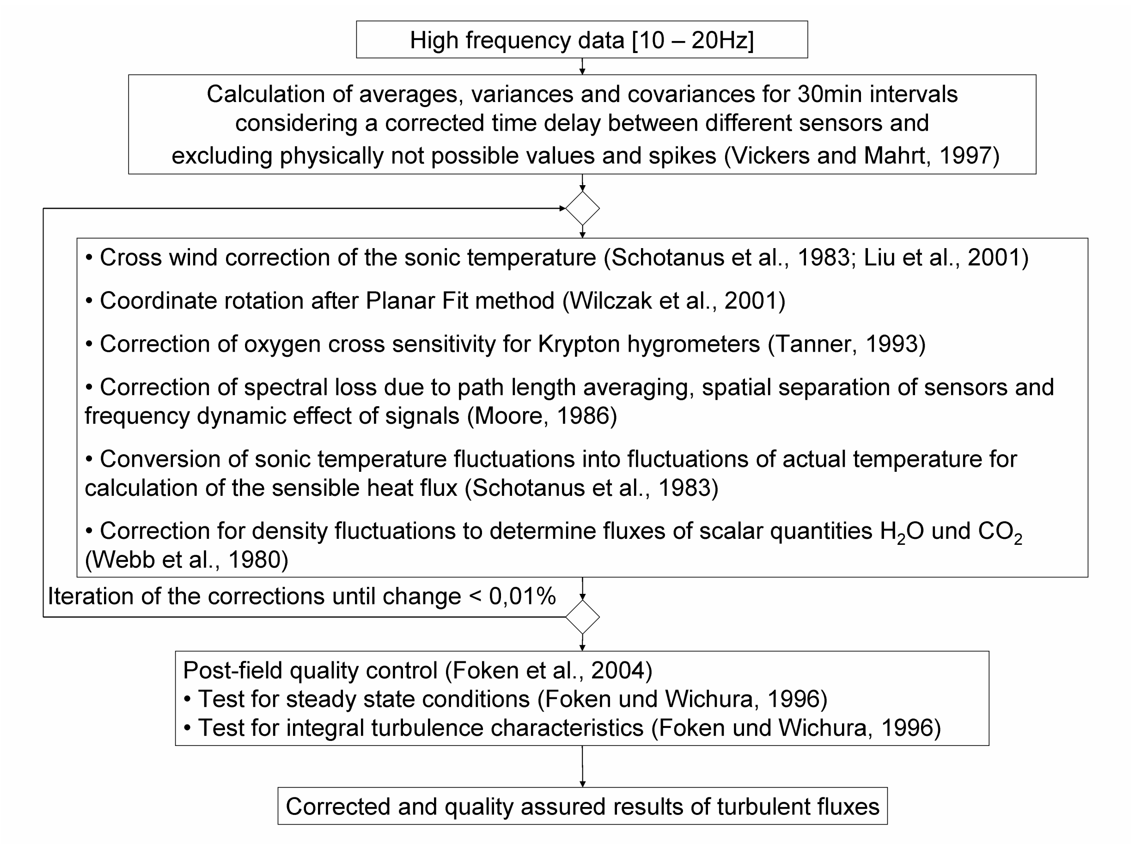

Figure 1: Processing scheme of the software package TK developed at the University of Bayreuth (Mauder and Foken, 2004). It performs all post-processing of turbulence measurements and produces quality assured turbulent fluxes.

measured in the laboratory of the Meteorological Observatory Lindenberg was used. The For METEK USA-1 sonic anemometers a flow distortion correction is necessary, since its transducer heads are too bulky compared to its pathlength (Wyngaard and Zhang, 1985). Therefore the so-called head correction (HC) has been developed by the manufacturer. For this anemometer type there are two correction algorithms available: HC1 is a simple two-dimensional correction, and HC4 is based on a three-dimensional correction matrix. Our studies on simulated datasets showed that HC1 increases the vertical turbulent fluxes by a factor of 1.1 compared to no head correction, and HC4 increases the vertical turbulent fluxes by a factor of 1.2. As we found better agreement with the CSAT3 reference sonic anemometer for the METEK USA-1 when applying HC1, we decided to use this option for LITFASS-2003. Afterwards, the data of all turbulence measurements are tested for electrical and physical plausibility using consistency limits for each measured parameter.

The dataset is then screened using the algorithm from Vickers and Mahrt (1997), which is based on the work of Højstrup (1993), to detect remaining spikes in the high frequency time series and interpolate eventually discarded values. There is the possibility that a time delay occurs between two time series if two separate instruments are used, e.g. a sonic anemometer for wind components and a gas analyser for water vapour. This time delay between the two sensors was determined automatically by cross-correlation analysis for each averaging interval. The automatic determination of the time delay is of special advantage for LI-7500 gas analysers, as their time delay is not known with accuracy because of an internal software problem. In addition, with this method the high frequency spectral loss can be corrected for the along-wind or longitudinal component of the sensor separation (Moore, 1986). After all these steps we obtain the “raw” covariances for calculating turbulent fluxes.

Some data acquisition systems were not capable of collecting the high frequency raw data of turbulence measurements. This was the case for stations A3, A4, A7, A8, A9, HV and FS. Instead they stored online averages, variance and covariances of a certain averaging interval, 5 or 10 minutes. As the calculation of variances and covariances is a nonlinear procedure, they cannot be averaged arithmetically to obtain 30 minute values. A certain number *N* of formerly calculated (co)variances $\left(\overline{w'x'}\right)_j$ and averages for short-term intervals *j* with a number of measurements *U* can be combined in order to calculate the (co)variance for the long-term interval *I* comprising *M* values (Foken, 2003, after Peters, personal communication, 1997):

$$\left(\overline{w'x'}\right)_I = \frac{1}{M-1}\left[(U-1)\sum_{j=1}^{N}\left(\overline{w'x'}\right)_j + U\sum_{j=1}^{N}\overline{w}_j \cdot \overline{x}_j - \frac{U^2}{M}\sum_{j=1}^{N}\overline{w}_j\sum_{j=1}^{N}\overline{x}_j\right] \tag{4}$$

Inherent to turbulence measurements are deficiencies which cause more or less important violations of assumptions to the eddy covariance method necessitating a set of corrections to the calculated covariances. The first correction to be conducted is the crosswind correction of the sonic temperature (Kaimal and Finnigan, 1994) because it has to be applied to data in the sonic anemometer coordinate system, if not already implemented in sensor software as in the Campbell CSAT3. For the METEK USA-1 data, this crosswind correction is necessary. For this purpose, we used the modification by Liu et al. (2001) to the geometry of this omnidirectional type of sonic anemometer. Then the coordinate system of the sonic measurements is transformed into a coordinate system, which is parallel to the mean stream lines, using the Planar Fit method (Wilczak et al., 2001). The required regression coefficients were determined on the basis of the whole 30 day dataset, provided that the position of the sonic anemometer was not moved within this period. Krypton hygrometers are not only sensitive to water vapour, but also, to a smaller degree, to oxygen in the sampling volume. This cross sensitivity can be deduced from the covariance (Tanner et al., 1993). For this correction, the extinction coefficient for oxygen k_o is required. We used a general value of 0.045 for all Krypton hygrometers in LITFASS-2003, which was proposed by Tanner et al. (1993), although recent findings (van Dijk, 2002) indicate that this value might be slightly too high for a path length of 0.013 m. But sensor specific values for k_o were not available for the instruments used.

A correction to the measured covariances for high frequency spectral loss is necessary for several reasons (Moore, 1986). The LITFASS-2003 turbulent fluxes were corrected for line averaging of sonic anemometers and hygrometers, spatial separation of sonic anemometers, hygrometers and fast response temperature sensors, and dynamic frequency response of fast response temperature sensors. If the longitudinal sensor separation was already corrected by the time delay corrected calculation of the covariance, only the lateral fraction of the sensor separation had to be corrected. The transfer functions are folded with parameterised spectra of vector and scalar quantities proposed by Moore (1986) for stable stratification and by Højstrup (1981) for unstable stratification. As the parameterisations of stable cospectra in Moore (1986) are erroneous (Moncrieff et al., 1997), cospectral models by Kaimal et al. (1972) were used instead for the whole stability range. We assume that the spectral loss at the low frequency end is negligibly small, when applying 30 minutes block averaging without detrending in accordance with a recommendation in Lee et al. (2004). Flux contributions in the very longwave part of the spectrum are investigated in a different study.

Sonic anemometers do not really measure temperature but the speed of sound, which depends on the density of the air, which again depends on its temperature and also to a minor degree on its water vapour content. To obtain the fluctuations of the actual temperature T instead of the fluctuations of sonic temperature T_s, the humidity effect was corrected according to the paper by Schotanus et al. (1983).

$$\overline{w'T'} = \overline{w'T_s'} - 0.51\overline{T}\,\overline{w'q'} \tag{5}$$

To determine turbulent fluxes of air constituents like H_2O, the correction after Webb et al. (1980) is necessary. This procedure, called WPL correction, incorporates two aspects. The first is the conversion of the volume related measurement of the content of a scalar quantity, e.g. absolute humidity [kg m^{-3}], into a mass-related parameter like specific humidity or mixing ratio. The second aspect is the correction of a positive vertical mass flow, which results from the mass balance equation, because vertical velocities of ascending parcels have to be different from descending ones due to density differences (Webb et al., 1980; Fuehrer and Friehe, 2002; Liebethal and Foken, 2003; 2004). The correct latent heat flux is calculated after

$$\overline{w'a'} = (1+\mu\sigma)\left(\overline{w'a'}_{measured} + \bar{a}\frac{\overline{w'T'}}{\bar{T}}\right), \text{ where } \mu = \frac{m_{air}}{m_{water}} = 1.6,\ \sigma = \frac{\bar{a}}{\overline{\rho_{air}}}. \qquad (6)$$

It can be seen from equations 3 and 4 that the corresponding corrections are interdependent. This means one completely corrected flux is required for the correction of another and vice versa. Note also that all parameterisations of spectra and cospectra are formulated as a function of the Obukhov length L, which is again a function of the friction velocity u_* and the sensible heat flux $\overline{w'T'}$.

$$L = -\frac{u_*^3}{\kappa \frac{g}{T}\overline{w'T'}} \qquad (7)$$

Therefore, the whole sequence of flux corrections is iterated. A stop criterion of less than 0.001% change for the turbulent fluxes from one loop to the next typically leads to a number of less than 10 iterations. The effect of the iteration on the turbulent fluxes depends on the magnitude of the necessary corrections. For the LITFASS-2003 dataset, the iteration of flux corrections caused an increase to the sensible heat flux by up to 1% or 2% and a decrease of the latent heat flux data by approximately 1%. This is not negligible compared to the total impact of all flux corrections, which is in the order of 5% to 15% of the uncorrected flux estimate (Liu et al., 2001; Liebethal and Foken, 2003; 2004).

4.2 Quality Control

Following a procedure proposed by Foken and Wichura (1996) and further developed by Foken et al. (2004), two quality tests were applied to the latent heat flux data of every micrometeorological station. One test is designed to detect non steady state conditions, which are an assumption of the eddy covariance method. Violations of this assumption can be caused by horizontal heterogeneities or temporal instationarities. This test compares a 30-minute covariance with the arithmetic mean of the six 5-minute covariances in this 30-minute interval. The agreement between both values is a measure of steady state conditions.

The second test is based on the flux-variance similarity, which means that the ratio of the standard deviation of a turbulent parameter and its turbulent flux is nearly constant or a function, e.g. of the stability. These normalised standard deviations are called integral turbulence characteristics. The test compares measured integral turbulence characteristics with modelled ones. The models used are given by Foken et al. (2004). The agreement between both values is a measure of well-developed turbulence. To check the sensible heat flux, models for normalised standard deviations of the vertical wind velocity *w* and temperature *T* were applied. As there are no models for normalised standard deviations of humidity available, we only used the model for *w* to check the latent heat flux. In general, a deviation of measured integral turbulence characteristics from modelled ones can be an indicator for several violations of the assumptions to the eddy covariance method, e.g. internal boundary layers, height of the surface layer, horizontal heterogeneity, gravity waves or no turbulence. Instrumental problems can also be detected by this test, because measurement errors often result in values of the integral turbulence characteristics which do not follow the theoretical model. The results of both tests are added to a quality flag for every 30 minute turbulent flux value on a scale from 1 to 9 (Table 5) following a scheme proposed by Foken et al. (2004).

Flags 1 to 3 represent highest quality data and can be used for fundamental research, such as the development of parameterisations. The flags 4 to 6 can be used for the calculation of monthly or annual sums for continuously running systems. Flags 7 and 8 are used only for orientation. Sometimes it is better to use class 7 or 8 data instead of a gap-filling procedure, but these data should not differ significantly from the data before and after it in the time series. Data of flag 9 should be excluded under all circumstances. Figure 2 shows the percentage of 30-minute averages of the latent heat flux between 0600 and 2000 UTC classified as highest quality data; i.e. flags 1 to 3.

Table 5: Overall flag system after Foken et al. (2004)

steady state (deviation in %)	integral turbulence characteristic (deviation in %)	Final flag
0 – 15	0 – 30	**1**
16 – 30	0 – 30	**2**
0 – 30	31 – 75	**3**
31 – 75	0 – 30	**4**
0 – 75	31 – 100	**5**
76 – 100	0 – 100	**6**
0 – 250	0 – 250	**7**
0 – 1000	0 – 1000	**8**
> 1000	> 1000	**9**

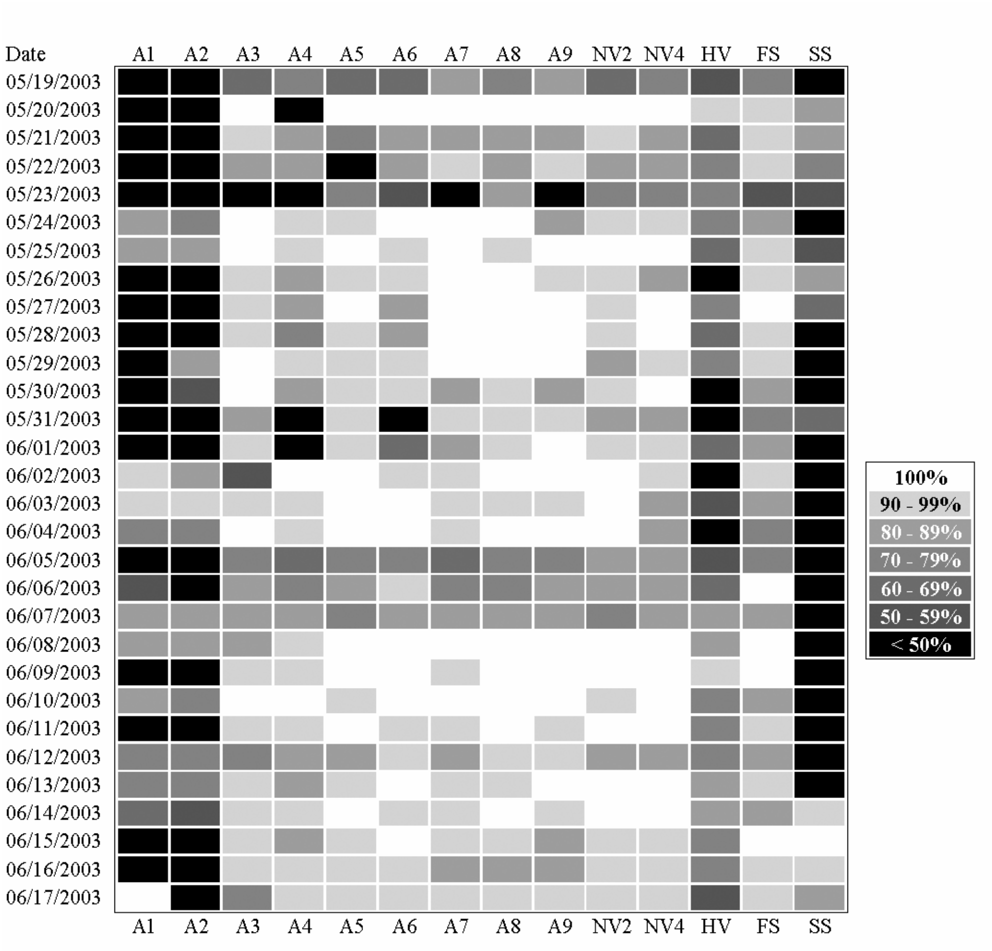

Figure 2: Availability of highest quality latent heat flux data between 0600 and 2000 UTC for the LIT-FASS-2003 experiment, May 19 to June 17, 2003. Black boxes indicate days of less than 50% availability, including days with instrumental malfunction.

Most of the 14 micrometeorological sites have a high average percentage of more than 80% of highest quality latent heat flux data available during daytime. Significantly lower percentages on May 19, May 23 and June 5, 2003 are mainly caused by rain events, when disturbed half hourly values of the latent heat flux were discarded automatically. Partly lower data quality on May 21 and 22, 2003 and on June 6 and 7, 2003 can be attributed a distinct cumulus convection on the back side of a cold front, which causes instationary conditions. It is eye-catching that at stations A1, A2, and SS less than 50% of the latent heat flux data were of highest quality over several days. The reasons are data gaps due to temporary problems with instrumentation at these sites. When data are available at these three sites because the instruments and data acquisition is working, the data quality is not significantly worse than at the other sites. On days without rain, percentages of less than 50% are rare for the rest of the sites. In most cases they are caused by instrumental problems, e.g. on May 31, 2003, at site A6, when the data acquisition was interrupted. At site HV partially lower data quality has to be noticed, mainly because of the results of the steady state test. The test results of that station might be ascribed to the number of relevant digits recorded by this specific data acquisition system, which is partially insufficient for the steady state test procedure, especially for small fluxes. However, it can be sufficient for the computation of a 30 minute covariance. This has to be checked in particular cases.

4.3 Characterisation of the measuring sites

Furthermore, a footprint analysis was performed for all sites, and the existence of possible internal boundary layers was investigated to detect the wind direction for which the data can be used. Concerning the test for internal boundary layers, we had to be assured that the sensor was definitely located below any internal boundary layer that might result from a sudden change of the surface characteristics if the distance to the edges of the field is finite. As a rough estimate, the following equation was used to determine the height of an internal boundary layer (δ) (Raabe, 1983; Jegede and Foken, 1999) neglecting an weak stability dependent effect (Savelyev and Taylor, 2005). The conditions for the sensor height z [m] were formulated:

$$z \leq \delta = 0.3\sqrt{x}\ , \tag{8}$$

where x: fetch [m] (see also Table 6).

Following a concept proposed by Göckede et al. (2004; 2005), the footprint analyses intended to determine the flux contributions from different types of land use to the total fluxes measured, in order to assure the representativeness of the measurement position for the specific target land use type. To identify the land use composition within the source area of each measurement position, the three dimensional forward Lagrangian stochastic trajectory model of Langevin type (Thomson, 1987) was used. The parameterisation of the flow statistics and the effect of stability on the profiles were in line with those used in Rannik et al. (2003). For the present study, the simulations were performed releasing 5 x 10^4 particles from a height close to the ground. The particles were then tracked until the upwind distance accounted for approximately 90% of the total flux. For each measurement site, model runs were performed for a set of combinations

Table 6: Fetch x, height of the new equilibrium layer δ and flux contribution from the target land use type dependent on the wind direction and stability for site A6

	30°	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	**360°**
***x* in m**	29	41	125	360	265	203	211	159	122	81	36	28
***δ* in m**	1.6	1.9	3.4	5.7	4.9	4.3	4.4	3.8	3.3	2.7	1.8	1.6
flux contribution form target land use type in %												
stable	26	37	76	97	93	84	86	81	76	61	37	26
neutral	56	67	100	100	100	100	100	100	100	88	67	56
unstable	76	87	100	100	100	100	100	100	100	98	87	76

of wind direction and atmospheric stability in order to identify all conditions during which the data were not representative for the target land use type, and to subsequently exclude these measurements from the data base. Such an analysis was carried out for all eddy covariance stations within the LITFASS-2003 campaign. As an example, Table 6 shows the results for the calculated flux contributions of the target land use type (here: maize) for the site A6. Only turbulent flux measurement for wind directions with δ higher than the measuring height of 2.7 m, i.e. a sector from 90° to 270°, can be associated with the maize field at site A6. In addition, the footprint model results emphasise that the flux contribution from this maize field is larger than 75% for these wind directions during all atmospheric stability conditions tested. Generally, all flux data were excluded from further analyses within the EVA_GRIPS project if the flux contribution from the target land use type obtained by the footprint analysis was smaller than 80%. For investigations on the energy balance closure problem only periods were analysed for which the turbulent fluxes could be related to the specific site according to this footprint criterion.

5. Ground Heat Flux

The quality of $Q_G(z=0)$ data was assessed during LITFASS-2003 by answering two questions: Firstly, which is the correct approach to determine high quality $Q_G(z=0)$ data from in situ soil measurements? And secondly, are the soil measurements correct, which are serving as the input dataset for calculating $Q_G(z=0)$?

The first question can be answered by applying the findings of a sensitivity analysis that compared different approaches to calculate $Q_G(z=0)$. In this sensitivity study, Liebethal et al. (2005) tested a combination of heat flux plate measurements and calorimetry (PlateCal) against a combination of the gradient approach and calorimetry (GradCal). A detailed review of different methods to measure $Q_G(z=0)$ is given e.g. by Fuchs (1986); herein, only the PlateCal and the GradCal approach are briefly described.

For the PlateCal approach, a heat flux plate is put into the soil to measure the soil heat flux at a certain depth (so-called reference depth z_r) directly. z_r is typically between 0.05 m and 0.10 m. To give $Q_G(z=0)$, the soil heat flux at the reference depth $Q_G(z_r)$ is added by the temporal change in the heat stored in the soil layer between z_r and the soil surface. The temporal change in heat storage is determined from the soil volumetric heat capacity c_v and temporal changes in soil temperature (T_s). Altogether, the equation for calculating $Q_G(z=0)$ from the PlateCal approach is:

$$Q_{G,PlateCal}(z=0) = \frac{U_{HFP}}{c_{HFP}} + \int_0^{z_r} c_v \frac{\partial T_s}{\partial t} \mathrm{d}z \, , \tag{9}$$

where the first summand on the right hand side is the heat flux plate (HFP) measurement and the second summand is the temporal change in heat storage. U_{HFP} is the output voltage and c_{HFP} is the calibration factor of the heat flux plate; t is time.

In contrast to the PlateCal approach, the GradCal approach does not determine $Q_G(z_r)$ from HFP measurements but from the vertical gradient of T_s and the thermal conductivity of the soil λ_s according to Fourier's law of heat conduction. For this approach, z_r is typically 0.10 m. $Q_G(z_r)$ determined from T_s gradient and λ_s is again added by the temporal change in heat storage:

$$Q_{G,GradCal}(z=0) = -\lambda_s \frac{\partial T_s}{\partial z} + \int_0^{z_r} c_v \frac{\partial T_s}{\partial t} \tag{10}$$

In Liebethal et al. (2005) it was tested which of these approaches (PlateCal, GradCal) is less sensitive to measurement errors and is still able to provide correct $Q_G(z=0)$ data even if soil temperature or soil moisture data are slightly erroneous. According to their analysis, the PlateCal approach performs similarly well as the GradCal approach. However, the latter one is preferable because of the less destructive sensor installation. For both approaches, it is critical that z_r is as deep as possible (best between 0.10 m and 0.30 m).

To find the best $Q_G(z=0)$ measurement approach for each site of the LITFASS-2003 experiment, the above mentioned findings of Liebethal et al. (2005) were combined with other considerations. Overall, we established three criteria: The first criterion is the availability of data. For the GradCal approach, a detailed soil temperature and moisture profile is needed, whereas the PlateCal approach requires heat flux plates but fewer temperature and moisture measurements. As a second criterion, we chose the sensitivity of the approach to measurement errors. At each site, the approach with the smallest sensitivity according to Liebethal et al. (2005) is used. For example, a PlateCal approach with z_r = 0.20 m is preferred over a GradCal approach with z_r = 0.10 m because of the larger z_r. At the same z_r, the GradCal approach is preferred. The third criterion is the plausibility of the soil measurements (soil temperatures, soil moistures, heat flux plate measurements) and the $Q_G(z=0)$ results. Detailed information about the checking of the input dataset is given below; for the plausibility check of $Q_G(z=0)$, similar criteria were used. From these three criteria, we decided for every site which of the approaches should be used to calculate $Q_G(z=0)$ (Table 7). At sites A8 and A9, $Q_G(z=0)$ was measured directly with heat flux plates installed only a few millimetres under the soil surface. From the comparison with $Q_G(z=0)$ data from other sites, these measurements appeared to be reliable and no further correction was added.

Table 6: Approaches used to calculate $Q_G(z=0)$ at the sites of LITFASS-2003. If a number is given behind the method (for example, GradCal(5x)), this is the number of different reference depths used. $Q_G(z=0)$ is calculated as the average of the results from the approaches using these reference depths.

site	method	reference depth z_r
A1	*missing soil temperature data: no $Q_G(z=0)$ calculation possible*	
A2	*missing soil temperature data: no $Q_G(z=0)$ calculation possible*	
A3	GradCal (5x)	0.241 m, 0.308 m, 0.381 m, 0.493 m, 0.627 m
A4	GradCal (2x)	0.50 m, 0.70 m
A5	*missing soil moisture data: no $Q_G(z=0)$ calculation possible*	
A6	GradCal	0.20 m
A7	PlateCal	0.10 m
A8	HFP directly under surface	0.002 m
A9	HFP directly under surface	0.002 m
GM	GradCal (3x)	0.30 m, 0.45 m, 0.60 m
HV	PlateCal	0.10 m

After solving the first question about the correct approach for $Q_G(z=0)$ calculation at each site, the second question to answer deals with the quality control of the input dataset (soil temperatures, soil moistures). A direct evaluation of the measurement accuracy is possible for instance from parallel measurements at each depth for soil temperatures or from soil core samples for soil moistures (mostly measured with TDR sensors in LITFASS-2003). Unfortunately, these reference measurements were only available for single sites. At these sites, reference measurements indicated high accuracy of soil temperature and moisture measurements (about ± 5 % for soil temperature and ± 10 % for soil moisture).

However, at most of the sites comparison with reference measurements were not possible. Thus, we screened all soil measurements at every site from different perspectives: Firstly, it was checked if all measurements of a soil quantity show the same course, e.g. if all soil moisture measurements rise quickly after rainfall and fall slowly and steadily thereafter. Another criterion was the coherence of soil quantity profiles (e.g. is the soil temperature near the surface higher than that at a greater depth around noon and deeper at nighttime). Furthermore, the consistency of the measurements from different sites was checked (e.g. similarity of the temperature profiles at two cereal sites). Certainly, the soil type, the canopy height and density and the precipitation at the individual site has to be considered as well in this comparison. From the screening described above, several problematic data series could be identified. Most of them could be corrected; some had to be erased from the data base. For the rest, it remained unclear if the deviations were within the "normal" range or if they indicated erroneous measurements.

The tests and considerations described above helped a lot to ensure high data quality for the LITFASS-2003 soil data, especially for $Q_G(z=0)$. Taking into account the results of the sensitivity analysis and the checking of the raw data, the accuracy of the $Q_G(z=0)$ determination should be within ± 15 % (at least ± 15 Wm^{-2}) for the LITFASS-2003 dataset.

6. Radiation Fluxes

The quality assurance for radiation fluxes in LITFASS-2003 started already two years before the experiment, during the STINHO-1 campaign (**St**ructure of turbulent transport under **inho**mogeneous surface conditions, part of the German research programme Atmosphärenforschung 2000, AFO-2000). It continued during the pre-experiment in 2002 at the GM Falkenberg and the LITFASS-2003 experiment itself.

The STINHO-1 campaign (Arnold et al., 2004; Raabe et al., 2005) was carried out near the research station of the Institute for Tropospheric Research (IfT) in Melpitz (51°32' N, 12°54' E, 86 m a.s.l.). In this experiment, the main question concerning radiation measurements was whether the sensors matched the quality classification given by the manufacturers. For shortwave radiation, sensors of types CM21, CM11 and CM3 were tested (all from Kipp&Zonen); for longwave radiation, sensors of types DD-PIR (Eppley), CG1 and CG3 (both from Kipp&Zonen) were tested. CM3 and CG3 sensors are incorporated in the CNR1 net radiometer from Kipp&Zonen. For this sensor comparison, a detailed report is available (Liebethal, 2003); the most important results are summarised in the following paragraphs.

Shortwave radiation sensors are classified according to the deviations of their measurements from reference measurements (Kasten, 1985; Brock and Richardson, 2001). The sensors tested during STINHO-1 are classified as "secondary standard" (CM21, CM11) and as "second class" (CM3) by Kipp&Zonen. One of the CM21 sensors, which was carefully compared to the Lindenberg station of the BSRN (**B**aseline **S**urface **R**adiation **N**etwork), served as the reference instrument. Our tests confirmed that these classifications were generally correct, although there were some deviations among "secondary standard" sensors slightly exceeding the classification criteria. Most of the CM3 sensors agreed much better with the reference than their classification as "second class" sensors might suggest; they would fulfil the criteria for "first class" instruments, too.

For longwave radiation sensors, there is no comparable official classification scheme. Nevertheless, calibration and intercomparison of longwave radiation sensors has been addressed regularly in literature (e.g. Burns et al., 2003). Burns et al. (2003)

conducted a field intercomparison with ten DD-PIR sensors and present an optimization technique which considerably improved the relative accuracy of these instruments. Additionally, they developed various data quality checks and applied them to their dataset. For the LITFASS-2003 sensors, we also conducted a field intercomparison, in which one of the DD-PIR sensors which was well compared with the BSRN station in Lindenberg served as reference instrument. In our tests, the CG1 and CG3 sensors differed no more than 2.7 % from the reference sensor with an offset of less than 15 Wm^{-2}. These devices therefore meet the demands usually made on them. Greater problems were encountered in relation to some of the DD-PIR sensors and their thermistor measurements. Their raw signal has to undergo three corrections: the division by the calibration factor, the "body correction" and the "dome correction" (Philipona et al., 1995). The latter two corrections require temperature measurements performed with thermistors attached to the body and the dome of the instrument. Obviously, problems with this type of sensor during STINHO-1 were not related to the sensors itself, but were due problems with the thermistor temperature measurements with some of the data loggers.

During LITFASS-2003, post-field consistency checks were performed between the radiation measurements at the different sites. For this purpose, we selected two days of completely clear skies, namely May 29 and May 30, in order to compare the data of the downwelling shortwave and longwave radiation from all sites. The BSRN station of the MOL served as reference measurement. Because of the conformity of all the tested sites with the BSRN station, we can state that the deviations of the shortwave radiation measurements of all sensors are smaller than their classification specifications. Consequently, the shortwave radiation data measured during LITFASS-2003 can be used without any restrictions. Regarding longwave radiation, the conformity of most of the sites with the BSRN station was approximately as good as for the shortwave radiation. Only the conformity of site A1 was significantly worse, where our tests disclosed problems with its CNR-1 sensor. Moreover, measurements disturbed by dew on the domes of non-ventilated sensors and periods in the shade of mounting structures during low sun elevations at some of the sites could be fixed.

7. Energy Balance Closure

Measurements of all components of the energy balance (equation 1) make it possible to verify this budget equation for a specific site at a specific time. The results of many field experiments indicate that the amount of energy which is transported by the turbulent fluxes Q_H and Q_E is not equivalent to the available energy at the surface, which sums up net radiation Q^*_s and ground heat flux $Q_G(z=0)$. The difference between the turbulent energy fluxes and the available energy is often called residual or imbalance. The problem of the experimental energy balance closure was brought to awareness at the end of the eighties, since it became evident during the land surface experiments FIFE (Kanemasu et al., 1992) or KUREX-88 (Tsvang et al., 1991). This issue was discussed during a workshop on instrumental and methodical problems of land surface flux measurements in Grenoble (Foken and Oncley, 1995) and was recently explicated thoroughly by Culf et al. (2004). Wilson et al. (2002) gave an interesting overview on the energy balance closure problem for several experiment sites, which demonstrates that there is a general lack of energy balance closure for FLUXNET sites, with the scalar fluxes of sensible and latent heat being underestimated and/or available energy being overestimated. A mean imbalance in the order of 20% is reported.

Similar energy balance residuals were found for the LITFASS-2003 sites. Figure 3 shows the average diurnal courses of the residuals for selected sites, which represent typical agricultural land use types of the study area. For all sites the residual shows a distinct diurnal course with most negative values between 1000 and 1200 UTC, which corresponds with the time of highest insolation for this longitude. Both, the rape (A7) and the grassland site (N2) have average residual values around -70 W m^{-2} at this time. The averaged values for the residual reach -120 W m^{-2} during noon at the maize site (A6), and even -160 W m^{-2} at the cereal site (A8).

The determination of nighttime residuals is often based on only a few values, because turbulent fluxes were not available due to failure of the quality tests according to Foken and Wichura (1996). Poorly developed turbulence and too large footprint areas during stable stratifications are the usual causes of the insufficient quality. During most of the remaining nighttime situations, the average residual values are almost zero or slightly positive. For site A8, the nighttime values are highest, and therefore the amplitude of the diurnal course is largest compared to the other sites. This might be ascribed to the method of ground heat flux measurement at this site (see Table 7), because here

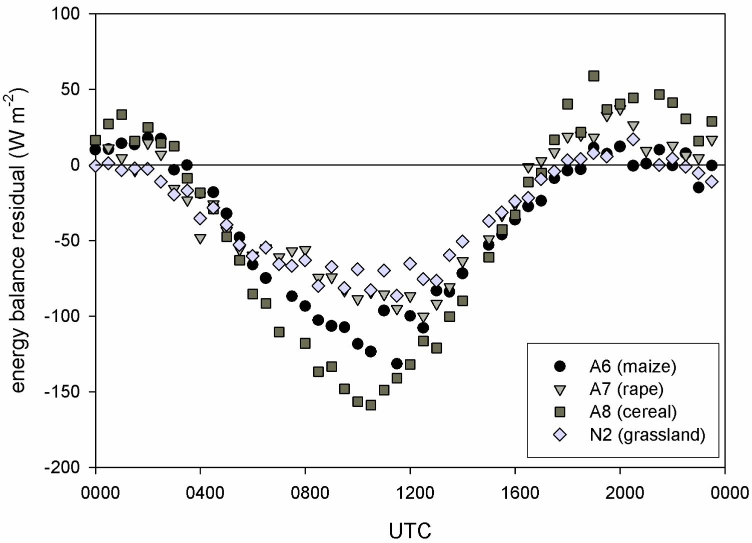

Figure 3: Average diurnal course of the energy balance residual (W m^{-2}) during the LITFASS-2003 experiment for selected sites of different land use type.

$Q_G(z=0)$ was determined from a heat flux plate only, which was buried in 0.002 m depth. Those heat flux plate measurements might be disturbed for several reasons: Firstly, the soil structure above the plate is definitely different from the surrounding soil, and secondly, the placement of the plate very close to the surface inhibits water transport in the soil. The diurnal courses of the other three sites look similar and are in fact not significantly different from each other, because typical standard deviations are in the order of 50 W m^{-2} at noon.

For a detailed analysis of the energy balance closure problem we focus on a single site, A6 (maize). Figure 4.a shows the diurnal courses of the energy balance components plus the experimental imbalance for one selected day, June 7. During nighttime, no experimental imbalance could be calculated, because the turbulent flux measurements failed the quality criteria. But the remaining energy balance terms, namely Q^*_s and $Q_G(z=0)$, are almost compensating each other. Thus, assuming no turbulent energy exchange at night, the energy balance can be closed during nighttime. This provides assurance that our radiation and soil measurements are correct. During daytime, when turbulent fluxes are present, the values of the experimental imbalance range between 5 W m^{-2} and 140 W m^{-2} with maxima around noon.

For this maize site, the impact of the correction procedures on Q_E is to increase by approximately 15% to 25%, which is mainly caused by the Moore and WPL correction, whereas the sensible heat flux is decreased by approximately 10% to 15%, mainly as a result of the Schotanus correction. So, one effect of the corrections is that the sums of the two turbulent fluxes are significantly higher than without the corrections. Moreover,

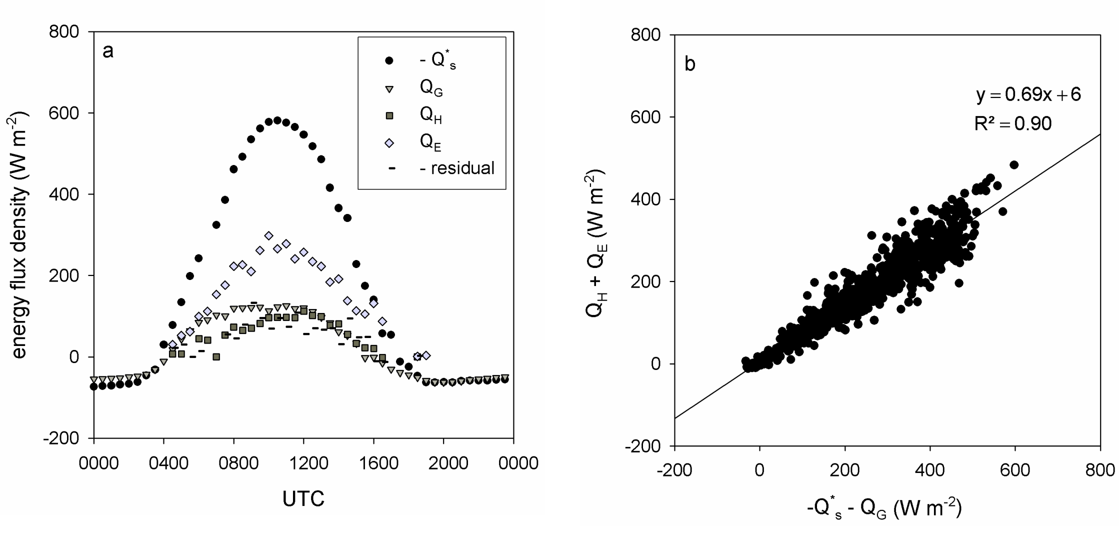

Figure 4: The surface energy balance measured during LITFASS-2003 at site A6 over maize.

a: Typical example for diurnal cycles of the components of the energy balance plus the resulting experimental imbalance, June 7, 2003.

b: Sum of the turbulent energy fluxes vs. the available energy (sum of net radiation and ground heat flux) for the whole LITFASS-2003 measurement period, May 19 to June 17, 2003. The regression equation shows an average imbalance of approx. 30%.

Q_G values are almost doubled in amplitude, taking the soil heat storage above the heat flux plate into account (section 5), and their maximum is reached earlier in the day. The measurement of Q^*_s remains unaffected by any correction procedures. The energy imbalance would have been much larger if the corrections on turbulent and ground heat fluxes were not applied. Their maximum value would have been up to 216 Wm^{-2} (38% of net radiation) compared to 140 Wm^{-2} (26% of net radiation) if all correction corrections are applied thoroughly.

Averaged over the whole LITFASS-2003 measurement period, the experimental imbalance is about 30% of the available energy at this site A6 (Figure 4.b). Compared to the imbalances, which are reported from other experiments (Wilson et al., 2002) this value of 30% is relatively high but not extraordinary. Although all measurements were performed thoroughly and a comprehensive set of flux corrections was applied, we must state that the energy balance closure problem remains during daytime. It is partly reduced by the application of the flux corrections, but they cannot solve this problem.

8. Conclusions

The experiences of former experiments (Beyrich et al., 2002) have shown that high quality data of turbulent fluxes and other components of the energy balance on the earth surface can only be achieved with a uniform quality assurance and quality control system, which is binding for all participants. For the LITFASS-2003 experiment, this scheme included pre-experiments for turbulence and radiation sensors and the adaptation of quality control concepts as reported for eddy covariance data by Foken et al. (2004), including the site characterization by Göckede et al. (2004). The flux calculation with one software package accepted by all participants was a further advantage allowing a comparable dataset and excluding small differences between the resulting fluxes due to different processing algorithms which may add up to 10%. All radiation sensors used during LITFASS-2003 were shown to fulfil the accuracy criteria of a ‘secondary standard’ for shortwave radiation (accuracy 5-10 W m^{-2}) and were of comparable quality for the longwave parts in agreement with recent investigations (Ohmura et al., 1998). For $Q_G(z=0)$, extensive quality checks were conducted to ensure its accuracy, which is estimated to be within ± 15% (at least ± 15 W m^{-2}) for all sites.

More complicated was the determination of the accuracy of the turbulent fluxes. Therefore, the results of several comparison experiments were used. Because of a missing standard for turbulence measuring devices, we followed the recommendations made during a workshop on instrumental and methodical problems of land surface flux measurements, which was held in Grenoble in 1994 (Foken and Oncley, 1995). Here the sonic anemometer designed by Zhang et al. (1986) was recommended as the optimal

Table 7: Accuracy of turbulent fluxes based upon the experiences from the EVA_GRIPS Pre-Experiment in 2002 and the EBEX-2000 intercomparison

anemometer	quality class	sensible heat flux	latent heat flux
Type A,	1-3	5% or 10 W m^{-2}	10% or 20 W m^{-2}
e.g. CSAT3	4-6	10% or 20 W m^{-2}	15% or 30 W m^{-2}
Type B,	1-3	10% or 20 W m^{-2}	15% or 30 W m^{-2}
e.g. USA-1	4-6	15% or 30 W m-2	20% or 40 W m-2

construction. The CSAT3 is a similar device and the comparison of both types showed excellent agreement (Mauder, 2002). These types of anemometers were classified by Foken and Oncley (1995) as type A with the best data quality. Omnidirectional probes like USA-1 are type B. To determine the accuracy of flux measurements, these types as well as the classification of the data according to their quality after Foken et al. (2004) into data for fundamental research (flag 1-3) and data for general use (flag 4-6) can be used. The result is shown in Table 7. Data of lower quality are not listed there. They can only serve for rough orientation (flag 7-8) or should be excluded (flag 9).

Despite these efforts to increase the data quality, the problem of the energy balance closure (Culf et al., 2004) could not be solved. The energy balance was only closed up to 20-30% of the available energy for the LITFASS-2003 sites. But it must be not assumed that the accuracy of the measuring systems is the reason, but instead methodical problems or atmospheric phenomena, which can not be measured with the applied set-up. These could be the different scale of measurement of the methods used, transports at time scales larger than 20-30 minutes, coherent structures etc. But the high accuracy of the measured data makes it possible to analyse such effects in more detail, as it is done, e.g., in a case study by Foken et al. (2005).

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References

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

Beyrich, F., Richter, S. H., Weisensee, U., Kohsiek, W., Lohse, H., DeBruin, H. A. R., Foken, T., Göckede, M., Berger, F. H., Vogt, R., and Batchvarova, E.: 2002, 'Experimental determination of turbulent fluxes over the heterogeneous LITFASS area: Selected results from the LITFASS-98 experiment', *Theor. Appl. Climatol.* **73**, 19-34.

Beyrich, F., Leps, J.-P., Mauder, M., Foken, T., Weisensee, U., Bange, J., Zittel, P., Huneke, S., Lohse, H., Mengelkamp, H.-T., Bernhofer, C., Queck, R., Meijninger, W. M. L., Kohsiek, W., Lüdi, A., Peters, G., and Münster, H.: 2005a, 'Area-averaged surface fluxes over the heterogeneous LITFASS area from measurements', *Boundary-Layer Meteorol.*, submitted (LITFASS-2003 Special Issue).

Beyrich, F., Mengelkamp, H.-T., and Berger, F. H.: 2005b, 'Evaporation over a heterogeneous land surface: EVA_GRIPS and the LITFASS-2003 experiment - an overview', *Boundary-Layer Meteorol.*, submitted (LITFASS-2003 Special Issue).

Brock, F. V., and Richardson, S. J.: 2001, *Meteorological Measurement Systems*, Oxford University Press, New York, 290 pp.

Burns, S. P., Sun, J., Delany, A. C., Semmer, S. R., Oncley, S. P., and Horst, T. W.: 2003, 'A field intercomparison technique to improve the relative accuracy of longwave radiation measurements and an evaluation of CASES-99 pyrgeometer data quality', *J. Atm. Oceanic Tech.* **20**, 348-361.

Culf, A. D., Foken, T., and Gash, J. H. C.: 2004, 'The energy balance closure problem', in P. Kabat and M. Claussen (ed.), *Vegetation, Water, Humans and the Climate. A New Perspective on an Interactive System*, Springer, Berlin, Heidelberg, pp. 159-166.

Dyer, A. J., Garratt, J. R., Francey, R. J., McIlroy, I. C., Bacon, N. E., Bradley, E. F., Denmead, O. T., Tsvang, L. R., Volkov, Y. A., Koprov, B. M., Elagina, L. G., Sahashi, K., Monji, N., Hanafusa, T., Tsukamoto, O., Frenzen, P., Hicks, B. B., Wesely, M., Miyake, M., and Shaw, W.: 1982, 'An international turbulence comparison experiment (ITCE-76)', *Boundary-Layer Meteorol.* **24**, 181-209.

Foken, T., and Oncley, S. P.: 1995, 'Workshop on instrumental and methodical problems of land surface flux measurements', *Bull. Am. Meteorol. Soc.* **76**, 1191-1193.

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

Foken, T., Weisensee, U., Kirzel, H.-J., and Thiermann, V.: 1997, 'Comparison of new-type sonic anemometers', in *12th Symposium on Boundary Layer and Turbulence*, Vancouver, BC, Amer. Meteorol. Soc., Boston, 356-357.

Foken, T.: 1999, Comparison of the sonic anemometer Young Model 81000 during VOITEX-99. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **8**, 12 pp. (Print, ISSN 1614-8916)

Foken, T.: 2003, *Angewandte Meteorologie. Mikrometeorologische Methoden*, Springer, Heidelberg, 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, Dordrecht, pp. 181-208.

Foken, T., Wimmer, F., Mauder, M., Thomas, C., and Liebethal, C.: 2005, 'Some aspects of the energy balance closure problem', *Atmos. Chem. Phys. Discuss.*, submitted.

Fuehrer, P. L., and Friehe, C. H.: 2002, 'Flux corrections revisited', *Boundary-Layer Meteorol.* **102**, 415-457.

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.

Göckede, M., Markkanen, T., Hasager, C. B., and Foken, T.: 2005, 'Update of footprint-based approach for the characterisation of complex measurement sites', *Boundary-Layer Meteorol.*, accepted.

Højstrup, J.: 1981, 'A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux', *Boundary-Layer Meteorol.*, 341-356.

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

ISO: 1993, *Statistics - Vocabulary and Symbols - Part 1: Probability and general statistical terms*, International Organization for Standardization, Geneva, Switzerland, ISO 3534-1, 61 pp.

Jegede, O. O., and Foken, T.: 1999, 'A study of the internal boundary layer due to a roughness change in neutral conditions observed during the LINEX field campaigns', *Theor. Appl. Climatol.* **62**, 31-41.

Kaimal, J. C., Wyngaard, J. C., Izumi, Y., and Coté, O. R.: 1972, 'Spectral characteristics of surface layer turbulence', *Quart. J. Roy. Meteorol. Soc.* **98**, 563-589.

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

Kanemasu, E. T., Verma, S. B., Smith, E. A., Fritschen, L. Y., Wesely, M., Fild, R. T., Kustas, W. P., Weaver, H., Steawart, Y. B., Geney, R., Panin, G. N., and Moncrieff, J. B.: 1992, 'Surface flux measurements in FIFE: An overview', *J. Geophys. Res.* **97**, 18547-18555.

Kasten, F.: 1985, Maintenance, Calibration and Comparison. Instruments and Observ. Methods., Geneve, WMO Report **23**, 65-84 pp.

Lee, X., Massman, W., and Law, B. E. (ed.): 2004, 'Handbook of micrometeorology. A guide for surface flux measurement and analysis', Kluwer Academic Press, Dordrecht, 250 pp.

Liebethal, C.: 2003, Strahlungsmessgerätevergleich während des Experiments STINHO-1. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **21**, 28 pp. (Print, ISSN 1614-8916)

Liebethal, C., and Foken, T.: 2003, 'On the significance of the Webb correction to fluxes', *Boundary-Layer Meteorol.* **109**, 99–106.

Liebethal, C., and Foken, T.: 2004, 'On the significance of the Webb correction to fluxes. Corrigendum', *Boundary-Layer Meteorol.* **113**, 301.

Liebethal, C., Huwe, B., and Foken, T.: 2005, 'Sensitivity analysis for two ground heat flux calculation approaches', *Agric. For. Meteorol.*, DOI: 10.1016/j.agrformet.2005.08.001.

Liu, H., 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.

Mauder, M.: 2002, Auswertung von Turbulenzmessgerätevergleichen unter besonderer Berücksichtigung von EBEX-2000. Master Thesis, Abt. Mikrometeorologie, Universität Bayreuth, Bayreuth, 86 pp.

Mauder, M., and Foken, T.: 2004, Documentation and instruction manual of the eddy covariance software package TK2. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **26**, 44 pp. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

Miyake, M., Stewart, R. W., Burling, H. W., Tsvang, L. R., Koprov, B. M., and Kuznetsov, O. A.: 1971, 'Comparison of acoustic instruments in an atmospheric turbulent flow over water', *Boundary-Layer Meteorol.* **2**, 228-245.

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

Moore, C. J.: 1986, 'Frequency response corrections for eddy correlation systems', *Boundary-Layer Meteorol.* **37**, 17-35.

Ohmura, A., Dutton, E. G., Forgan, B., Fröhlich, C., Gilgen, H., Hegner, H., Heimo, A., König-Langlo, G., McArthur, B., Müller, G., Philipona, R., Pinker, R., Whitlock, C. H., Dehne, K., and Wild, M.: 1998, 'Baseline Surface Radiation Network (BSRN/WCRP): New precision radiometry for climate research', *Bull. Am. Meteorol. Soc.* **79**, 2115-2136.

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

Philipona, R., Fröhlich, C., and Betz, C.: 1995, 'Characterization of pyrgeometers and the accuracy of atmospheric long-wave radiation measurements', *Applied Optics* **34**, 1598-1605.

Raabe, A.: 1983, 'On the relation between the drag coefficient and fetch above the sea in the case of off-shore wind in the near shore zone', *Z. Meteorol.* **33**, 363-367.

Raabe, A., Arnold, K., Ziemann, A., Beyrich, F., Leps, J.-P., Bange, J., Zittel, P., Spieß, T., Foken, T., Göckede, M., Schröter, M., and Raasch, S.: 2005, 'STINHO - Structure of turbulent transport under inhomogeneous surface conditions - part 1: The micro-α scale field experiment', *Meteorol. Z.* **14**, 315-327.

Rannik, U., 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.

Savelyev, S. A., and Taylor, P. A.: 2005, 'Internal Boundary Layers: I. Height Formulae for Neutral and Diabatic Flows', *Boundary-Layer Meteorol.* **115**, 1-25.

Schotanus, P., Nieuwstadt, F. T. M., and DeBruin, H. A. R.: 1983, 'Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations', *Boundary-Layer Meteorol.* **26**, 81-93.

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

Tanner, B. D., Swiatek, E., and Greene, J. P.: 1993, 'Density fluctuations and use of the krypton hygrometer in surface flux measurements', in R. G. Allen (ed.), *Management of irrigation and drainage systems: integrated perspectives*, American Society of Civil Engineers, New York, NY, pp. 945-952.

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

Tsvang, L. R., Koprov, B. M., Zubkovskii, S. L., Dyer, A. J., Hicks, B., Miyake, M., Stewart, R. W., and McDonald, J. W.: 1973, 'A comparison of turbulence measurements by different instruments; Tsimlyansk field experiment 1970', *Boundary-Layer Meteorol.* **3**, 499-521.

Tsvang, L. R., Zubkovskij, S. L., Kader, B. A., Kallistratova, M. A., Foken, T., Gerstmann, W., Przandka, Z., Pretel, J., Zelený, J., and Keder, J.: 1985, 'International turbulence comparison experiment (ITCE-81)', *Boundary-Layer Meteorol.* **31**, 325-348.

Tsvang, L. R., Fedorov, M. M., Kader, B. A., Zubkovskii, S. L., Foken, T., Richter, S. H., and Zelený, J.: 1991, 'Turbulent exchange over a surface with chessboard-type inhomogeneities', *Boundary-Layer Meteorol.* **55**, 141-160.

van Dijk, A.: 2002, 'Extension to 3D of "The effect of line averaging on scalar flux measurements with a sonic anemometer near the surface" by Kristensen and Fitzjarrald', *J. Atm. Oceanic Tech.* **19**, 80–82.

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

Webb, E. K., Pearman, G. I., and Leuning, R.: 1980, 'Correction of the flux measurements for density effects due to heat and water vapour transfer', *Quart. J. Roy. Meteorol. Soc.* **106**, 85-100.

Weisensee, U., Beyrich, F., and Leps, J.-P.: 2003, 'Integration of humidity fluctuation sensors into the Lindenberg boundary layer measurement facilities: Experiences, problems, and future requirements', in *12th Symposium on Meteorological Observations and Instrumentation*, Long Beach, CA, USA, paper 14.1, 275-278.

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

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., and Field, C.: 2002, 'Energy balance closure at FLUXNET sites', *Agric. For. Meteorol.* **113**, 223-243.

Wyngaard, J. C., and Zhang, S. F.: 1985, 'Transducer-shadow effects on turbulence spectra measured by sonic anemometers', *J. Atm. Oceanic Tech.* **2**, 548-558.

Zhang, S. F., Wyngaard, J. C., Businger, J. A., and Oncley, S. P.: 1986, 'Response characteristics of the U.W. sonic anemometer', *J. Atm. Oceanic Techn.* **2**, 548-558.

Appendix C

THE ENERGY BALANCE EXPERIMENT EBEX-2000. PART II: INTER-COMPARISON OF EDDY COVARIANCE SENSORS AND POST-FIELD DATA PROCESSING METHODS

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Abstract
The eddy covariance method is the primary way to measure turbulent fluxes directly. Many investigators have found that these flux measurements often do not satisfy a fundamental criterion - closure of the surface energy balance. This study investigates to which extent the measurement technology of the eddy covariance method can be made responsible for this deficiency, in particular the effects of instrumentation or of the post-field data processing. Therefore, current models of eddy covariance sensors and several post-field data processing methods were compared. The differences in methodology resulted in deviations of 10% for the sensible heat flux and of 15% for the latent heat flux. These disparities were mostly due to different sensor separation corrections and a linear detrending of the data. The impact of different instrumentation on the resulting heat flux estimates was significantly higher. Large deviations from the reference system

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of up to 50% were found for some sensor combinations. However, very good measurement quality was found for a CSAT3 together with a KH20 and also for a UW sonic together with a KH20. If these systems are well calibrated and maintained, an accuracy of better than 5% can be achieved for sensible and latent heat flux measurements. The results from the sonic anemometers Gill Solent-HS, ATI-K, Metek USA-1, and R.M. Young 81000 showed more or less larger deviations from the reference system. The LI-COR LI-7500 open-path gas analyser in the test was one of the first serial numbers of this sensor type and had technical problems regarding direct solar radiation sensitivity and signal delay. These problems are known by the manufacturer and improvements of the sensor were made since then.

Keywords: eddy covariance, turbulent fluxes, quality control, sensor intercomparison, energy balance closure, EBEX-2000

1 Introduction

In 1994, a workshop of the European Geophysical Society in Grenoble (Foken and Oncley, 1995), developed the idea for the energy balance experiment EBEX-2000. One concern was that different types of sonic anemometers showed significant differences in their characteristics. This study investigates to which extent the instrumental and methodological problems in eddy covariance measurements affect the incomplete surface energy balance. Specifically, we compared the most recently available eddy covariance sensors and several post-field data processing methods.

Sensor comparisons help to quantify how large the differences due the instrumentation of eddy covariance stations can be. At the beginning of modern turbulence measurements in the 1960s, sonic comparison experiments were common, because the developers of the sensors often were participants. Four such experiments are published, including interesting surface layer studies. The first experiment was carried out in 1968 near Vancouver, Canada, over the ocean (Miyake et al., 1971), followed by one over steppe in Tsimlyansk, Russia in 1970 (Tsvang et al., 1973). Additional experiments were carried out in 1976 in Conargo, Australia (Dyer, 1981; Dyer et al., 1982) and in 1981 again in Tsimlyansk (Tsvang et al., 1985). In those early comparison experiments mostly prototypes were tested. During the last 10 to 15 years several commercially built sonic anemometers have become available. Most of the sonic anemometer comparisons are only available in grey literature. Many recent micrometeorological experiments have still included a comparison phase, although usually only the results have been reported (Table 1).

Table 1: Participation of recent types of sonic anemometers in selected intercomparison experiments; the reference sonic anemometer type is indicated. LINEX-96/2: **Lin**denberg **Ex**periment; LITFASS-98: **Li**ndenberg **I**nhomogeneous **T**errain – **F**luxes between **A**tmosphere and **S**urface: a long term **S**tudy; MAP-Riviera-99: **M**esoscale **A**lpine **P**rogramme in the Riviera valley; VOITEX-99: **Voit**sumra **Ex**periment; EBEX-2000: **E**nergy **B**alance **Ex**periment.

experiment	**LINEX-96/2**	**LITFASS-98**	**MAP-Riviera-99**	**VOITEX-99**	**EBEX-2000**
literature	(Foken et al., 1997)	(Beyrich et al., 2002)	(Christen et al., 2000)	(Foken, 1999)	this paper
Campbell CSAT 3	X	X	X(reference)	X(reference)	X(reference)
Kaijo-Denki 310/A	X(reference)	X(reference)	-	-	-
Kaijo-Denki 310/B	-	X	-	-	-
Kaijo-Denki TR90-AH	-	-	-	-	X
Solent HS	-	-	X	-	X
Solent R2/R3	X	-	X	X	-
Metek USA-1	X	-	X	X	X
R. M. Young 81000	-	-	-	X	X
ATI K Probe	-	-	-	-	X
UW Sonic	-	-	-	-	X

Fast-response hygrometers also should be compared, in order to determine the accuracy of latent heat flux measurements.

EBEX-2000 was carried out to determine why measurements of the surface energy balance do not close (Oncley et al., 2002). One critical question was whether these eddy covariance sensors produce acceptable data. A second major question is whether typical differences in post-field data processing methods have a large impact on these fluxes. Most of the processing steps and flux corrections are well described in the literature (e.g. Webb et al., 1980; Schotanus et al., 1983; Moore, 1986; Højstrup, 1993; Tanner et al., 1993; Wilczak et al., 2001). Temperature and humidity effects, which are discussed by Högström and Smedman (2004) as a source of error for sonic anemometer measurements, are avoided by the application of these correction algorithms. However, errors in the resulting turbulent heat fluxes can occur due to the methodology because of differences in the selection and in the order of the processing steps, and also because of the use of simplified or modified algorithms and different values for physical constants.

2 Comparison of post-field data processing methods

One of the goals of EBEX-2000 was to determine whether the lack of energy balance closure could be due to differences in the post-field data processing methods used by the various research groups. In order to address this issue, each of the groups participating in EBEX-2000 processed two days of data from one eddy covariance system consisting of a UW sonic anemometer and a KH20 krypton hygrometer. Since each group started with identical time series, we expected the computed fluxes to be quite similar. Table 2 gives an overview of the features implemented in the post-field data processing methods of the EBEX-2000 participants, who represent major research institutions. This comparison was performed in the year 2002. Of course, progress has been made in the data processing methods since that time, particularly in light of this comparison. However, data from 2002 can be used to demonstrate typical differences. For this reason, the processing methods are made anonym and labelled A – E.

In many of the post-field data processing methods a spike detection algorithm (e.g. Højstrup, 1993) is implemented. From the despiked time series covariances can be calculated after either block averaging or linear detrending. Coordinate systems can be transformed either by using two or three dimensional rotation (Kaimal and Finnigan, 1994) or according to the planar fit method (Wilczak et al., 2001). If no additional fast response thermometer is available, the vertical sonic temperature flux (buoyancy flux) has to be converted into the sensible heat flux either according to the equation by Schotanus et al. (1983) or by Liu et al. (2001). Krypton hygrometers have a cross sensitivity to oxygen, which can be corrected (Tanner et al., 1993; van Dijk et al., 2003). Spectral loss due to pathlength averaging, sensor separation or dynamic frequency response can be corrected as suggested by Moore (1986) or Horst (2000). When measuring volume-related fluxes of air constituents like water vapour, the so called WPL-correction has to be applied (Webb et al., 1980) in order to compensate for density fluctuations and a positive vertical mass flow. Some post-field data processing methods include the correction of Brook (1978). However, this correction should not be applied because of incorrect assumptions (Webb, 1982), such as the formulation of the sensible heat flux, which lead to different opinions about which terms are negligible or not.

Finally, it makes a difference if physical “constants” like the specific heat of evaporation λ or the specific heat capacity of the air at a constant pressure c_p are assumed to be constant or if their dependence on temperature and moisture are taken into account. Tools proposed by Foken and Wichura (1996) can be applied for quality assessment and quality control of eddy covariance flux measurements.

In general, differences between the tested post-field data processing methods of up to 2% were seen in the momentum flux (not shown in this paper), 10% in the sensible heat flux, and 15% in the latent heat flux (see Figure 4). About 10% of the difference in la-

Table 2: Data processing steps and physical constants for each group participating at EBEX-2000 as of 2002 plus TK2, which was used for the processing of the eddy covariance intercomparison. The other post-field data processing methods are made anonymous and labelled A, B, C, D and E.

Step	A	B	C	D	E	TK2
1	Despike	Despike	(Despike)	Linear Detrend.	Linear Detrend.	Despike
2	Linear Detrend.	Linear Detrend.	Block Average	3D Rot. $\overline{w}=0;\overline{v}=0;$ $\overline{v'w'}=0$	3D Rot. $\overline{w}=0;\overline{v}=0;$ $\overline{v'w'}=0$	Block Average
3	2D Rot. $\overline{w}=0;\overline{v}=0$	3D Rot. $\overline{w}=0;\overline{v}=0;$ $\overline{v'w'}=0$	Planar fit + $\overline{v}=0$	Moore	$T_{Sonic}\rightarrow T$, Schotanus et al.	Cross Wind, Liu et al.
4	$T_{Sonic}\rightarrow T$, Schotanus et al.	$T_{Sonic}\rightarrow T$, Schotanus et al.	$T_{Sonic}\rightarrow T$, Schotanus et al.; Oxygen; WPL	$T_{Sonic}\rightarrow T$, Schotanus et al.	Oxygen	Planar fit + $\overline{v}=0$
5	Moore	WPL	Brook	WPL	WPL	Oxygen
6	WPL	Moore			Moore	Moore
7		Brook				$T_{Sonic}\rightarrow T$, Schotanus et al.
8						WPL
9						iteration of interdepending processing steps
10						QA/QC, Foken and Wichura
Constants	$\lambda=const$; $c_p=const$	$\lambda(T)$; $c_p(c_{p,dry};q)$	$\lambda(T)$; $c_p(c_{p,dry};q)$	$\lambda=const$; $c_p=const$	$\lambda=const$; $c_p=const$	$\lambda(T)$; $c_p(c_{p,dry};q)$

Moore: spectral correction according to Moore (1986); WPL: Correction for density effects by Webb et al. (1980); Brook: Correction for water vapour fluctuations by Brook (1978); Oxygen: Correction for oxygen cross sensitivity of krypton hygrometers (Tanner, 1989; Tanner et al., 1993; van Dijk et al., 2003); Schotanus et al.: Conversion of buoyancy flux into sensible heat flux according to Schotanus et al. (1983); Liu et al.: Conversion of buoyancy flux into sensible heat flux according to Liu et al. (2001).

tent heat flux values was due to one group (C) not correcting properly for the spatial displacement of about 0.3 m between the sonic anemometer and the hygrometer. The next biggest difference is whether linear detrending was applied to the time series. Fin-

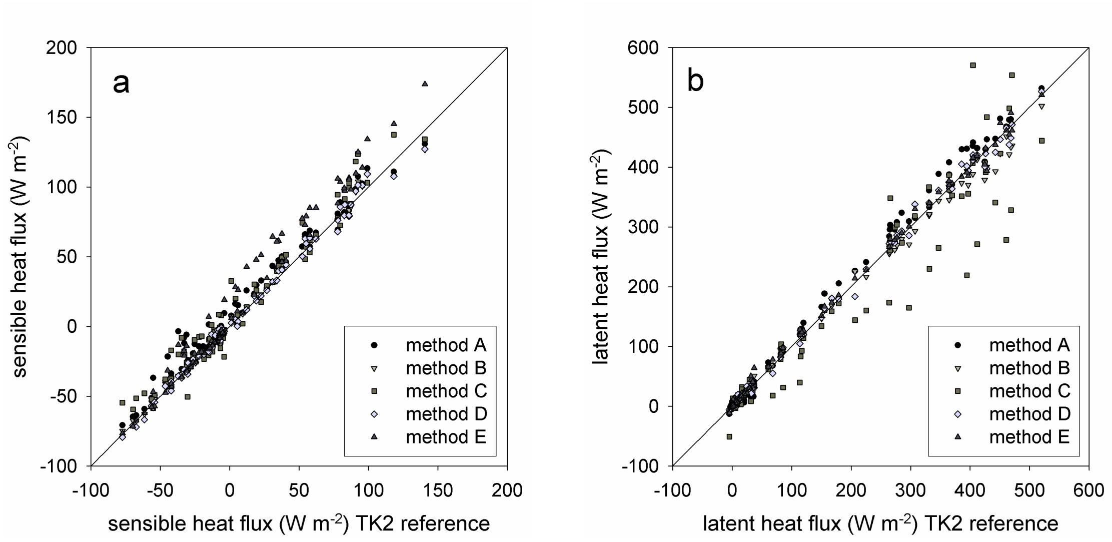


Figure 1: Results for turbulent fluxes calculated from the same time series (measured with the NCAR system at EBEX-2000 site 8, Aug. 9 2000 1700 – Aug. 11, 2000 1700 UTC) using different post-field data processing methods of the EBEX-2000 participants; sensible heat flux on the right (a), latent heat flux on the left (b). Results of methods A,B,C,D and E are plotted against reference software TK2 (Mauder and Foken, 2004).

nigan et al. (2003) state that block averaging is preferred to linear detrending, as it acts as an high-pass filter. Finally, the procedure used to apply the Schotanus correction for the sensible heat flux can have a significant impact. This can be especially seen for method E (Figure1a). The method of anemometer coordinate rotation, and implementations of the oxygen, WPL and other corrections appear to have similar effects on the computed fluxes for all processing methods. Part of the scatter in Figure1a and Figure1b can be attributed to the use of different definitions for physical constants. Another part of this scatter is due to a different order or formulation of processing steps. As a result of this methodology comparison, we agreed to calculate all EBEX-2000 sensor intercomparison data with one software package uniformly (see section 5.1).

3 Comparison of eddy covariance sensors

3.1 Sonic anemometers

Several new models of sonic anemometers were used during EBEX-2000 to determine turbulent fluctuations of wind velocity and temperature. Table3 gives their primary characteristics. Representative instruments of each of these types were tested during side-by-side intercomparisons.

CSAT3, Campbell Scientific: Most of the participants in EBEX-2000 used Campbell Scientific sonic anemometers (CSAT3). Three of these were deployed during the inter-

Table 3: A summary of the sonic anemometer array characteristics.

array	pathlength *l* (mm)	transducer diameter *d* (mm)	*l/d*	orthogonal paths	intersect-ing paths
CSAT 3, Campbell Sci.	120	6.4	19	N	Y
UW, NCAR	200	10	20	N	Y
Solent HS, Gill Instr.	150	11	14	N	Y
K-Probe, ATI	150	10	15	Y	N
TR90-AH, Kaijo Denki	50	5.5	9	Y	partial
USA-1, Metek	175	20	9	N	N
Model 81000, R.M. Young	150	13.8	11	N	Y

comparison period in the beginning of EBEX-2000. The CSAT3 has three intersecting, non-orthogonal, acoustic paths tilted 60 degrees from the horizontal plane. The path-length l is 120 mm and transducers are 6.4 mm in diameter d, so $l/d \approx 19$. The transducers are supported by arms on the top and bottom that meet at the back of the array. Thus, airflow should be unobstructed except for winds coming from the back of the array. With these characteristics, the data are considered free from flow distortion (Wyngaard and Zhang, 1985), though winds from within 30 degrees of the back of the array are discarded. The acoustic temperature data are internally corrected for crosswind contamination.

UW, NCAR: This array was initially built at the University of Washington (Zhang et al., 1986) and has been duplicated by NCAR, now based on the electronics by ATI (see below). Its geometry of three intersecting paths supported from the back was a model for the CSAT3 design and its thinner construction should result in even less distortion of the flow. With $l/d = 20$ and only one, thin, structural element, no flow distortion correction is used, with data from within 20 degrees of the back discarded. Crosswind corrections are applied in post processing.

Solent HS, Gill Instruments: Again, this array has three non-orthogonal paths, though the transducers are rotated so that this array is symmetric to rotation around the longitudinal axis, but not flipping about the longitudinal-vertical plane. With $l/d \approx 14$, a correction for distortion of the flow by the transducers is necessary, even though the transducer orientation is similar to the UW. This is done internally via a lookup table in azimuth and a generic correction in the vertical. For the EBEX-2000 intercomparison study, this correction was turned off, as we intended to examine the sensors' real response. Moreover, studies by Högström and Smedman (2004) showed that these wind-tunnel-based corrections cannot be simply transferred to atmospheric turbulent. Again, the sonic temperature is internally corrected for crosswind contamination.

K probe, ATI: The K-probe has three orthogonal, completely non-intersecting paths with l/d = 15. Kaimal et al. (1990) describe this array as having flow distortion that can be corrected by considering only the effects of a single path. The path velocity is assumed to be attenuated by a factor $1 - f\cos\theta$, where θ is the angle between the wind and along-path vectors. The acoustic temperature is derived only from the vertical path.

TR90-AH, Kaijo-Denki: The Kaijo-Denki TR90-AH has three orthogonal paths $l/d \approx 9$. Each horizontal path intersects the vertical path, but does not intersect the other horizontal path. The transducers are supported by independent arms which meet in the back of the array, so the flow is completely unobstructed only for a 90 degree sector of wind directions. Due to its filigree structure and the pathlength of only 50 mm, the TR90-AH can measure small eddies close to the ground.

USA-1, Metek: The Metek USA-1 has a unique geometry with three non-orthogonal non-intersecting paths supported by a central post of 9 mm in diameter. Although the wake shed by this post is always sampled by one of the paths, the affected path is always nearly perpendicular to the wind and thus observing nearly zero velocity. Therefore, the magnitude of the wake correction is expected to be relatively small. Only the relatively large transducer heads (200 mm) probably cause some transducer-shadow effects. Metek provides two options for a flow distortion correction, which can be performed internally. One works with azimuth dependent correction equations for the three wind components (head correction HC1), the other is based on a three-dimensional look-up table (head correction HC4).

Model 81000, R.M. Young: The R.M. Young sonic uses transducers which are nearly identical to the Solent-HS; however, they are supported by three vertical posts and the electronics are in a tube just below the array. The anemometer probably requires a generic correction for the influence of wakes from these posts (6.4 mm in diameter) and from the transducers (13.8 mm in diameter), but this is not documented. A crosswind correction is applied internally.

3.2 Fast-response hygrometers

A special focus of the EBEX-2000 intercomparison activities was on the measurement uncertainties of latent heat flux using fast-response hygrometers. Most of the instruments deployed were krypton hygrometers. Therefore, this part of the study investigates primarily differences between different sensors of this single sensor type. In addition, a comparison was made using a LI-7500 open path infrared gas analyser at site 7.

KH20, Campbell Scientific: The KH20 krypton hygrometer measures the absorption of ultraviolet light emitted by a krypton gas discharge lamp at a major line at 123.58 nm and a lesser line at 116.49 nm (Tanner and Campbell, 1985). This light is mainly absorbed by water molecules in the measuring path but also to a lesser degree by oxygen in the air. In order to obtain the water content of the measuring volume, one has to correct for the cross sensitivity to oxygen (Tanner et al., 1993; van Dijk et al., 2003). Due to the relatively strong absorption at this wavelength, this instrument is highly sensitive so it is appropriate for deployment even in dry conditions, e.g. deserts, or in low temperatures. Its pathlength is typically about 10 mm.

There are restrictions to the use of the KH20 according to the manufacturers' instructions. It is supposed to be deployed for short, attended studies only, as some components must be protected from precipitation and condensing humidity. It does not measure absolute concentrations. Only relative measurements of fluctuations are possible. Routine maintenance is required to keep source and detector windows free of scale. This scaling is caused by a disassociation of atmospheric constituents by the ultraviolet photons (Tanner and Campbell, 1985). The rate of scaling is a function of the atmospheric humidity. In high humidity environments, scaling can occur within a few hours. This scaling attenuates the signal and can cause shifts in the calibration curve. However, in theory this effect should only cause an offset of the humidity signal and not a change in the slope of the calibration function. Therefore, its impact on the results for variances and covariances over a 30-minute interval should be negligible. Thus, water vapour fluctuation measurements can still be made with this hygrometer. The effects of scaling can be reversed by wiping the windows with a moist swab.

LI-7500, LI-COR: The open path infrared gas analyser LI-7500 from LI-COR works with a fixed pathlength of 125 mm, which is one order of magnitude larger than the KH20. Therefore, it cannot resolve very small eddies close to the ground. The windows are sapphire and quite robust. In contrast to the KH20, the LI-7500 is not only capable of measuring water vapour but CO_2 as well. Infrared light of non-absorbing wavelengths 3.95 µm and 2.40 µm is used as a reference for attenuation corrections. CO_2 and H_2O are measured through absorption at wavelengths centred at 4.26 µm and 2.59 µm. Internal digital signal processing applies antialiasing filtering.

Early serial numbers of this sensor suffered from two major problems, which have now been resolved by the manufacturer. First, the solar-radiation error: The LI-7500's detector is sensitive not only to infrared light, which is emitted by the instrument itself and absorbed by molecules in the measuring path, but also to sunlight. For clear skies with constant irradiance this effect causes only a bias in the LI-7500 signals. However, scattered clouds or changing humidity is reflected in additional variance in the humidity and CO_2 data series. Serial numbers prior to 75H-0283 were affected by this unwanted sensitivity to direct sunlight.

Secondly, a delay time error was published by LI-COR in July 2003. The internal signal processing causes some time delay, which can be controlled via software by the user. The software version 2 was faulty because the delay time setting in the software did not correspond with the real delay time of the signal. Turbulent fluxes of H_2O and CO_2 would be underestimated if a fixed wrong time lag for the calculation of covariances was used. During EBEX-2000 one of the first LI-7500 sensors (SN# 75H-0006) was used, so both errors are potentially relevant for us. The first error should have a small effect since skies during EBEX-2000 were usually cloud free. The second error was compensated for during the data post-processing by the application of a cross correlation analysis to find the maximum covariance between H_2O and the vertical wind velocity for each averaging interval.

4 Experimental set-up

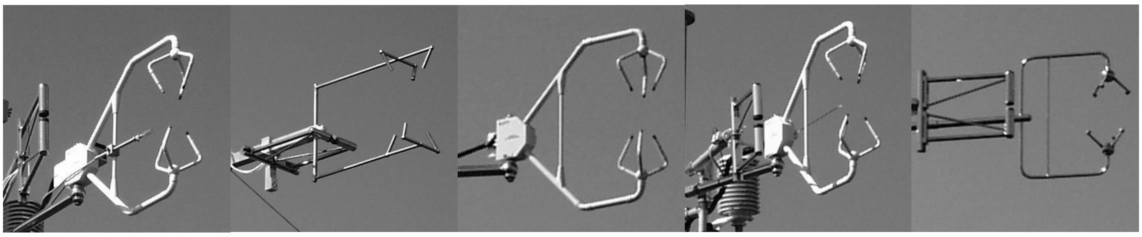
The EBEX-2000 experiment took place in the San Joaquin Valley of California on an irrigated cotton field of half a square mile size near Fresno, CA (Oncley et al., 2002). The canopy height varied between 0.80 m and 0.95 m. The measurement systems were operated from July 20 to August 24, 2000. During that period, the cotton plants were growing rapidly. Consequently, evaporation was the dominant process of energy transfer into the air. This is indicated by typical Bowen ratios on the order of 0.1 to 0.2 at noon. The weather was characterised by clear skies. Air temperatures typically ranged from 15° C during the night to maxima up to 35° C during daytime. The water vapour pressure over the cotton field showed quite strong variations and ranged from 10 hPa to 25 hPa. The experimental setup was comprised of ten sites distributed over the field; each equipped with eddy covariance systems, soil and radiation sensors.

EBEX-2000 featured many side-by-side eddy covariance sensor intercomparisons. For the most part, sensors were placed on adjacent towers to avoid flow interference. The typical distance between the towers was 6 m. Since the EBEX-2000 field site was a relatively uniform crop of cotton for about 1 km upwind, and had extremely flat topography for at least 100 km upwind (Oncley et al., 2002), we assume that the air flow had the same statistics at each sensor location. The wind direction is channelled by larger-scale topography in this location and was from the north-northwest for the vast majority of data collected. The towers were aligned perpendicular to this direction to reduce flow interference.

The first 10 days of the field campaign were reserved for the eddy covariance sensor intercomparison. These sensors were deployed at site 8, as described by Oncley et al. (2005), in the middle of the downwind portion of the field. The sensors were mounted at a height of 4.7 m above ground level. This measuring height was well within the internal boundary layer for this field, which was more than 9 m high at that position, assuming winds from north-northwest. Figure 2 shows this array of towers.

Figure 2: View of the intercomparison array from the northwest. Note the overall uniformity of the terrain; the site 8 profile towers to the left of the intercomparison towers, and the site 9 profile towers in the background on the right.

During the remainder of the experiment, several other pair-wise comparisons were possible with sensor types that, for some reason, could not be deployed in the main intercomparison. This was the case at site 7, where four different eddy covariance systems were operated on different towers in a line of east-west orientation.



a) CSAT3/KH20 (UBT) | b) UW/KH20 (NCAR) | c) CSAT3 (UBS) | d) CSAT3/KH20 (HK) | e) Solent-HS (UBS)

f) TR90-AH (KNMI/WU) | g) ATI-K (NCAR) | h) USA-1 (UBT) | i) R.M. Young (UBT) | j) CSAT3/LI-7500 (UBT)

Figure 3: Representative eddy covariance sensors used during EBEX-2000. The sensors during the intercomparison at site 8 are: CSAT3 deployed by the University of Bayreuth (a), UW sonic deployed by NCAR (b), CSAT3 deployed by the University of Basel (c), CSAT3 deployed by City University of Hong-Kong (d), Solent-HS deployed by the University of Basel (e), Kaijo-Denki deployed by KNMI/WU (f), and K-Probe deployed by NCAR (g). Site 7: USA-1 (h), R.M. Young sonic (i), CSAT3 with KH20 and LI-7500 (j), all deployed by the University of Bayreuth. Note the deployment of krypton hygrometers with all of these except c, j, j.

Figure 3 shows each of the sensors that participated in the intercomparison array. These sonics were deployed by groups from the following institutions: National Center for Atmospheric Research (NCAR), University of Basel (UBS), Royal Dutch Meteorological Institute (KNMI), Wageningen University (WU), City University of Hong Kong (HK), and University of Bayreuth (UBT). All instruments were oriented into the prevailing wind direction. Hygrometers were located downwind of the sonic arrays, in order to minimise flow distortion. Only the KH20 that was deployed together with the Kaijo Denki from KNMI/WU, was located very close to the sonic (see Figure 3f), in order to minimise spectral loss due to sensor separation. This was especially important for this system, because it later was deployed close to the ground in vertical flux profile, where turbulence spectra are shifted to smaller eddy sizes in general.

5 Data preparation for the sensor intercomparison

5.1 Post-field data processing of the turbulence measurements

All turbulence data have been processed in the same way. The calculation was done in two steps. First, the raw turbulence statistics were calculated after a despiking procedure with the NCAR software package (Oncley et al., 2005). Flux corrections and quality checks were applied to these data using the TK2 software package of the University of Bayreuth (Mauder and Foken, 2004). This software was developed according to the guidelines of an AMERIFLUX workshop in 2002 (Lee et al., 2004), which represents the actual state of science. The data have been tilt-corrected using the planar fit method, rotated into the mean wind, and corrected for single-path spatial averaging (Moore, 1986). The krypton hygrometer data were corrected for the oxygen cross-sensitivity of these instruments (Tanner et al., 1993). Sonic temperature fluxes were converted into sensible heat fluxes (Schotanus et al., 1983; Liu et al., 2001). The so-called WPL correction (Webb et al., 1980) was applied in order to take into account density fluctuations and a mean vertical mass flow. Furthermore, all corrections were iterated because of their interdependence. The quality of the data was flagged after a scheme proposed by Foken and Wichura (1996) and updated by Foken et al. (2004), which includes a test on steady state conditions and a test on the development of turbulence based on integral turbulence characteristics.

5.2 Statistical analysis of the intercomparison

In any comparison study it is necessary to choose a reference sensor. We used the Bayreuth CSAT3, which was deployed together with a KH20 (see Figure3a), since its characteristics are well described in earlier intercomparisons (Foken et al., 1997; Foken, 1999; Beyrich et al., 2002). It was deployed in the middle of the intercomparison array and had good data recovery. Furthermore, this sensor was at site 7 during the operations period of EBEX-2000. There the remainder of the anemometers that were not available during the intercomparison period could be compared to it. We had to make one exception regarding the reference instrument, because the ATI-K probe at site 8 was not deployed at the same time as the Bayreuth CSAT3. Here NCAR's UW served as reference instrument, because it showed the best overall agreement with the Bayreuth CSAT3. Table 4 to Table 10 summarise all statistical sensor comparisons. The results of the regression analysis are given as the absolute value of the regression equation *a* (intercept), the regression coefficient *b* or slope of the regression line, and the coefficient of determination R^2. Additionally, comparability *rmsd* and the bias *d* (ISO, 1993) are listed.

$$d = \frac{1}{n}\sum\left(x_{a,i} - x_{b,i}\right) \tag{1}$$

$$rmsd = \sqrt{\frac{1}{n}\sum\left(x_{a,i} - x_{b,i}\right)^2}\ , \tag{2}$$

where n = number of observations, $x_{a,i}$ = ith observation of the sensor being evaluated $x_{b,i}$ = ith observation of the reference instrument.

These comparisons are made for several parameters that can be measured by eddy covariance sensors: averages of wind speed, variances of vertical wind, sonic temperature, and humidity, as well as covariances, particularly friction velocity and turbulent fluxes of sensible and latent heat.

5.3 Data selection

For NCAR's UW sonic, the sector between 250° and 270° seems to be distorted by an obstacle, probably a tower, and this sector was therefore excluded for the intercomparison. At site 7, we found very large differences between fluxes measured by the different sensors. During these situations, which occurred some of the nights, the integral turbulence characteristics σ_w / u_* were below a value of 1.0. These low values indicate that turbulence is not well developed. Therefore, all data with $\sigma_w / u_* < 1.00$ were excluded for the intercomparison because under these conditions we cannot assume that neighbouring sensors are really measuring the same statistics. In contrast, data that failed the steady state test were not excluded, because in this case neighbouring eddy covariance systems still should measure the same turbulence.

6 Results of the sensor intercomparison

6.1 Horizontal wind speed

The first parameter to be compared is the horizontal wind speed measured by the different sonic anemometers. Table 4 shows the results of the statistical analysis. The best

Table 4: Comparison of the horizontal wind speed $\bar{u}$ measurements during EBEX-2000, reference CSAT3 (UBT). Values causing concern are underlined.

sensor	abs. value *a* (m s^{-1})	regression coefficient *b*	R^2	comparability *rmsd* (m s^{-1})	bias *d* (m s^{-1})
UW (NCAR)	-0.00	1.02	0.99	0.08	0.03
CSAT3 (UBS)	-0.01	1.03	0.99	0.09	-0.04
CSAT3 (HK)	-0.06	1.04	1.00	0.08	0.02
Solent-HS (UBS)	-0.09	1.05	0.98	0.11	-0.09
TR90-AH (KNMI/WU)	<u>-0.17</u>	0.96	<u>0.96</u>	<u>0.30</u>	-0.26
ATI-K (NCAR) S8 [*)] $f = 0.16$	-0.06	1.03	1.00	0.06	0.01
ATI-K (NCAR) S8[*)] $f = 0.20$	-0.06	<u>1.06</u>	1.00	0.09	0.07
ATI-K (NCAR) S7	0.01	1.04	0.99	0.13	-0.07
USA-1 (UBT)	<u>-0.12</u>	<u>1.06</u>	0.97	<u>0.19</u>	0.03
R.M. Young (UBT)	<u>0.17</u>	<u>0.92</u>	0.98	0.10	0.01

[*)] Here NCAR's UW served as reference instrument, since the Bayreuth CSAT3 was not deployed at the same as the ATI-K probe at site 8.

agreement can be found for NCAR's UW. With an intercept of 0.00 ms^{-1} and a slope of 1.02, it measures almost the same values as the UBT reference system. The other two CSATs from the Universities of Basel and Hong Kong measure similar wind speeds, too, as expected for instruments of the same type. The Solent-HS deviates a little bit more from the reference system with a regression coefficient of 1.05 and R^2 of 0.98. Systematic differences of more than 5% from the 1:1 line were found for the Kaijo Denki TR90-AH, the USA-1, and the R.M. Young. The two ATI-K probes overestimate the wind speed, too. The use of a flow distortion correction factor of $f = 0.16$ improves the results slightly compared to a factor $f = 0.20$.

6.2 Variance of vertical wind

Next, variances of the measured turbulent parameters are compared. Table 5 shows that the UW sonic and the two CSATs agree well with the reference measurement of the variance of the vertical wind component with $R^2 > 0.98$ and $0.99 < b < 1.02$. The Solent-HS is systematically low by approximately 10%, because it was operated without the internal flow distortion correction, which would increase vertical wind velocities by a generic factor of 1.10. Thus, after the application of this correction it would agree quite well with the reference system. The Kaijo Denki measurements are heavily distorted,

Table 5: Comparison of the vertical wind variance $\overline{w'w'}$ measurements during EBEX-2000, reference CSAT3 (UBT). Values causing concern are underlined.

sensor	abs. value *a* ($m^2\,s^{-2}$)	regression coefficient *b*	R^2	comparability *rmsd* ($m^2\,s^{-2}$)	bias *d* ($m^2\,s^{-2}$)
UW (NCAR)	0.000	0.99	0.98	0.010	-0.001
CSAT3 (UBS)	-0.000	0.99	0.99	0.007	-0.001
CSAT3 (HK)	-0.000	1.02	1.00	0.006	0.001
Solent-HS (UBS)	0.000	<u>0.89</u>	0.99	0.010	-0.006
TR90-AH (KNMI/WU)	-0.013	<u>1.26</u>	0.99	<u>0.021</u>	<u>-0.014</u>
ATI-K (NCAR) S8 [*)] $f = 0.16$	0.000	<u>1.11</u>	1.00	0.008	0.005
ATI-K (NCAR) S8[*)] $f = 0.20$	0.000	<u>1.11</u>	1.00	0.009	0.005
ATI-K (NCAR) S7	-0.000	<u>1.13</u>	0.99	0.010	0.005
USA-1 (UBT)	0.000	<u>0.93</u>	0.99	0.009	-0.004
R.M. Young (UBT)	-0.000	<u>1.06</u>	0.98	0.007	0.003

[*)] Here NCAR's UW served as reference instrument, since the Bayreuth CSAT3 was not deployed at the same time as the ATI-K probe at site 8.

which is indicated by a large intercept *a* of 0.013 $m^2\,s^{-2}$, a slope *b* of 1.26 and, consequently, the largest values for comparability and bias of all instruments tested. The two ATI-K probes report $\overline{w'w'}$ larger by more than 10%, no matter which flow distortion correction factor is applied. Variances of the vertical wind measured by the Metek are systematically lower by 7% and those measured by the R.M. Young are systematically overestimated by 6%.

6.3 Variance of sonic temperature

The measurement accuracy of sonic temperature fluctuations (given in Table 6) is crucial for the determination of the sensible heat flux. Again, the UW and the two CSATs show a very good agreement with the reference system. Although the wind measurements of the TR90-AH are disturbed by the obstruction of the KH20, the sonic temperature measurements appear to be unaffected. The Solent-HS obviously has major problems with sonic temperature measurements, which result in large systematic deviations (b = 1.45) and considerable scatter (R^2 = 0.92). Both the USA-1 and the R.M. Young underestimate sonic temperature fluctuations systematically by approximately 15%.

Table 6: Comparison of the sonic temperature variance $\overline{T_s'T_s'}$ measurements during EBEX-2000, reference CSAT3 (UBT). Values causing concern are underlined.

sensor	abs. value *a* (K^2)	regression coefficient *b*	R^2	comparability *rmsd* (K^2)	bias *d* (K^2)
UW (NCAR)	0.002	1.00	0.99	0.031	0.002
CSAT3 (UBS)	0.003	0.97	0.99	0.031	-0.004
CSAT3 (HK)	0.001	1.00	0.99	0.018	0.001
Solent-HS (UBS)	<u>-0.018</u>	<u>1.45</u>	<u>0.92</u>	<u>0.174</u>	<u>0.080</u>
TR90-AH (KNMI/WU)	0.000	1.00	0.98	0.034	-0.001
ATI-K (NCAR) S8*)	0.003	0.98	1.00	0.024	-0.003
ATI-K (NCAR) S7	0.012	<u>0.94</u>	0.99	0.042	-0.005
USA-1 (UBT)	-0.003	<u>0.86</u>	0.98	0.060	<u>-0.036</u>
R.M. Young (UBT)	0.014	<u>0.85</u>	0.98	0.086	<u>-0.036</u>

*) Here NCAR's UW served as reference instrument, since the Bayreuth CSAT3 was not deployed at the same time as the ATI-K probe at site 8. The flow distortion correction factor *f* is not relevant for sonic temperature measurements.

Their bias is -0.036 K^2. The results of the site 8 ATI-K probe are in good agreement with the reference system, whereas the site 7 underestimates $\overline{T_s'T_s'}$ slightly ($b = 0.94$).

6.4 Variance of absolute humidity

For the variance of absolute humidity $\overline{\rho_v'\rho_v'}$, only the NCAR's KH20, which was deployed with the UW sonic, shows a satisfactory agreement with the reference system (Table 7). Its regression line has a slope of 1.06, with only a little scatter ($R^2 = 0.99$). It has the smallest values for comparability (*rmsd* = 0.143 $g^2\,m^{-6}$) and bias (0.060 $g^2\,m^{-6}$) of all the instruments tested. The comparability and bias of KNMI/WU's KH20 are slightly worse (*rmsd* = 0.159 $g^2\,m^{-6}$; bias = 0.087 $g^2\,m^{-6}$) than those from UW/KH20 (NCAR). This is due to stronger overestimation of humidity fluctuations by this hygrometer indicated by a regression coefficient *b* of 0.12. NCAR's second krypton hygrometer in the test, which was deployed together with the ATI-K probe, also overestimates humidity fluctuations ($b = 1.17$). The humidity fluctuations measured by the KH20 from the University of Basel (UBS) have a strong negative bias of -0.166 $g^2\,m^{-6}$ and they also show a low slope of the regression line ($b = 0.73$) when plotted against those from the reference system CSAT3/KH20 (UBT). Still, the scatter and the intercept are small ($R^2 = 0.99$; $a = 0.006$ $g^2\,m^6$). Something must have been completely wrong with the sensitivity of Hong Kong's KH20 (HK), as it underestimates the humidity vari-

Table 7: Comparison of absolute humidity variance $\overline{\rho_v'\rho_v'}$ measurements during EBEX-2000, reference KH20 (UBT). Values causing concern are underlined.

sensor complex	**abs. value *a*** **(g^2 m^{-6})**	**regression coefficient *b***	R^2	**comparability *rmsd* (g^2 m^{-6})**	**bias *d*** **(g^2 m^{-6})**
UW/KH20 (NCAR)	0.021	1.06	0.99	0.143	0.060
CSAT3/KH20 (HK)	0.021	<u>0.30</u>	0.97	<u>0.621</u>	<u>0.353</u>
Solent-HS/KH20 (UBS)	0.004	<u>0.73</u>	0.99	<u>0.279</u>	<u>-0.166</u>
TR90-AH/KH20 (KNMI/WU)	0.006	<u>1.12</u>	0.99	0.159	0.087
CSAT3/LI-7500 (UBT)	-0.013	<u>1.50</u>	0.99	<u>0.943</u>	<u>0.505</u>
ATI-K/KH20 (NCAR)	-0.014	<u>1.17</u>	0.98	<u>0.354</u>	<u>0.148</u>

ances by 70% (*b* = 0.30). This results in huge values for comparability and bias. For the only sensor in the test which operates at different wavelengths than the others, the LI-7500 infrared gas analyser, it is possible to create a good linear fit when plotted against the reference instrument (R^2 = 0.99), but its slope deviates from 1.00 the most (*b*= 1.50).

Table 8: Comparison of the friction velocity u_* measurements during EBEX-2000, reference CSAT3 (UBT). Values causing concern are underlined.

sensor	**abs. value *a*** **(m s^{-1})**	**regression coefficient *b***	R^2	**comparability *rmsd* (m s^{-1})**	**bias *d*** **(m s^{-1})**
UW (NCAR)	-0.001	0.97	0.98	0.023	-0.003
CSAT3 (UBS)	-0.009	1.02	0.97	0.025	-0.006
CSAT3 (HK)	0.000	0.99	0.99	0.019	-0.003
Solent-HS (UBS)	-0.005	0.99	0.98	0.022	-0.006
TR90-AH (KNMI/WU)	-0.003	1.00	0.97	0.025	0.003
ATI-K (NCAR) S8 [*)] f = 0.16	-0.010	<u>1.09</u>	0.99	0.020	0.003
ATI-K (NCAR) S8[*)] f = 0.20	-0.010	<u>1.10</u>	0.98	0.021	0.005
ATI-K (NCAR) S7	<u>-0.008</u>	<u>1.08</u>	<u>0.94</u>	0.030	0.001
USA-1 (UBT)	-0.003	0.99	<u>0.91</u>	<u>0.037</u>	-0.002
R.M. Young (UBT)	0.004	0.98	<u>0.91</u>	<u>0.027</u>	0.002

[*)] Here NCAR's UW served as reference instrument, since the Bayreuth CSAT3 was not deployed at the same time as the ATI-K probe at site 8.

6.5 Friction velocity

Although the Solent-HS was operated in the non-calibrated mode, i.e. without flow distortion correction, its results for u_* are in good agreement with the reference (Table 8). As expected, the agreement of the UW sonic and the two other CSATs is also good. Even the friction velocities measured with the TR90-AH, which showed significant disturbance of the single wind to the reference. The ATI-K probes show larger deviations. Both sensors overestimate u_* by almost 10%. A flow distortion correction factor f of 0.16 instead of 0.20 improves the results only a little. The Metek and R.M. Young sonics do not measure systematically higher or lower u_* values than the reference, but both show a large amount of scatter (R^2 = 0.91).

6.6 Sensible heat flux

The first four sensors listed in Table 9 show a very good agreement with the reference system for sensible heat flux estimates. These are NCAR's UW, the two CSATs from Basel and Hong Kong and the Solent-HS from Basel, too. Their correlation coefficients R^2 are higher than or equal to 0.97 and the slope of the regression lines are close to one (0.97 – 1.01). The sensible heat fluxes from the R.M. Young sonic are also nearly in the same range as the afore mentioned instruments. The Kaijo Denki sensor overestimates the sensible heat flux (b = 1.22), whereas the USA-1 underestimates H (b = 0.83). The two ATI-K probes behave in different ways. The one at site 8 shows a good correlation (R^2 = 0.98) but a too high regression coefficient b of 1.08, whereas the one at site 7 shows a perfect regression line with a = 0.0 and b = 1.0, but larger scatter (R^2 = 0.92). Again, the use of f = 0.16 instead of 0.20 leads to a slightly better agreement with the reference, which results in a smaller intercept and also a smaller bias.

6.7 Latent heat flux

Latent heat fluxes by the UW/KH20 from NCAR are 5% different from those of the reference system CSAT3/KH20 (UBT). Those form the other NCAR system ATI-K/KH20 almost no bias compared to the reference. The Solent-HS/KH20 (UBS) underestimates latent heat fluxes even more strongly (b = 0.82), which is also expressed by a large negative bias of -26.9 Wm^{-2}. Latent heat fluxes measured by the TR90-AH/KH20 (KNMI/WU) are systematically too high (b = 1.14, d = 28.0 W m^{-2}). The combination CSAT3/KH20 from Hong Kong measures only approximately half as high evaporation rates as the reference system. The combination of the LI-7500 with the CSAT3 from the University of Bayreuth measures significantly higher latent heat fluxes (b = 1.17) than the reference combination of the same sonic with a KH20 krypton hygrometer (Table 10).

Table 9: Comparison of the sensible heat flux *H* measurements during EBEX-2000, reference CSAT3 (UBT). Values causing concern are underlined.

sensor	abs. value *a* (W m^{-2})	regression coefficient *b*	R^2	comparability *rmsd* (W m^{-2})	bias *d* (W m^{-2})
UW (NCAR)	-1.5	1.01	0.97	9.3	-1.4
CSAT3 (UBS)	-1.6	0.97	0.99	6.9	-1.7
CSAT3 (HK)	-0.8	0.97	0.98	6.9	-0.9
Solent-HS (UBS)	-2.3	0.97	0.98	8.0	-2.5
TR90-AH (KNMI/WU)	-0.5	<u>1.22</u>	0.99	9.7	2.3
ATI-K (NCAR) S8 *) $f = 0.16$	0.9	<u>1.08</u>	0.98	6.1	0.5
ATI-K (NCAR) S8*) $f = 0.20$	1.0	<u>1.08</u>	0.98	6.1	0.6
ATI-K (NCAR) S7	0.0	1.00	<u>0.92</u>	8.0	-0.6
USA-1 (UBT)	-1.8	<u>0.83</u>	0.97	12.7	-2.6
R.M. Young (UBT)	-2.8	0.98	0.97	12.8	-3.4

*) Here NCAR's UW served as reference instrument, since the Bayreuth CSAT3 was not deployed at the same as the ATI-K probe at site 8.

Table 10: Comparison of the latent heat flux *λE* measurements during EBEX-2000, reference CSAT3 (UBT). Values causing concern are underlined.

sensor complex	abs. value *a* (W m^{-2})	regression coefficient *b*	R^2	comparability *rmsd* (W m^{-2})	bias *d* (W m^{-2})
UW/KH20 (NCAR)	-1.9	1.05	0.98	39.0	-9.2
CSAT3/KH20 (HK)	-2.7	<u>0.55</u>	0.97	<u>115.0</u>	<u>-68.6</u>
Solent-HS/KH20 (UBS)	0.9	<u>0.82</u>	0.98	53.3	-26.9
TR90-AH/KH20 (KNMI/WU)	3.7	<u>1.14</u>	0.99	54.0	28.0
CSAT3/LI-7500 (UBT)	-0.7	<u>1.17</u>	1.00	35.7	17.5
ATI-K/KH20 (NCAR)	4.9	0.99	0.95	57.1	3.1

7 Discussion of sensor characteristics

Looking at Table 4 – 6, Table 8, and Table 9, which show the parameters measured by sonic anemometers only, we can state that the majority of comparisons have $R^2 > 0.95$ and have a regression coefficient close to 1.00. Of immediate concern are the data from sensors where $R^2 < 0.95$ or exceed a 5% threshold in the slopes of the regression lines (regression coefficients 0.95 - 1.05). These are the wind statistics from the Kaijo-Denki and ATI-K, u_* from the Metek and R.M. Young, and the temperature statistics from the Solent-HS. More problems were found with the humidity measurements of the hygrometers that were tested in the intercomparison.

7.1 Kaijo Denki TR90-AH/KH20 (KNMI/WU)

The Kaijo-Denki differences are clearly due to inadequate correction for the presence of the krypton hygrometer inside the sonic anemometer array. The problems are especially expressed by $\overline{w'w'}$ values systematically higher than the reference by more than 26% and sensible heat flux measurements that are overestimated by more than 20%. The Kaijo-Denki $\overline{T_s'T_s'}$ variance agrees well with the reference, though with the distorted w, the heat fluxes are too large. Extensive wind-tunnel testing showed that the bulk of the hygrometer severely impacted the flow measured by the anemometer. These tests can provide corrections to the data of TR90-AH/KH20 (KNMI/WU). However, as noted above, wind-tunnel-based corrections are generally larger than those encountered in the presence of atmospheric turbulence (Högström and Smedman, 2004).

In order to check the wind-tunnel calibration under outdoor turbulent conditions, a comparison between TR90-AH/KH20 sonic/hygrometer configuration and an unobstructed Kaijo Denki sonic anemometer with 0.20 m pathlength was performed at Cabauw, The Netherlands. A 20% $\overline{w'w'}$ overshoot was observed, which could be removed after correction with the wind-tunnel calibration. The sensible and latent heat fluxes were also in agreement. The friction velocity was already good. Thus, the findings of Högström and Smedman (2004) were not confirmed. Taking all this into consideration, we decided to add the deviation of 13%, which we found for $\overline{w'}$, as correction to the sensible heat flux $\overline{w'T'}$ and the latent heat flux $\overline{w'\rho_v'}$.

7.2 Gill Solent-HS/KH20 (UBS)

The Solent-HS temperature problem has been known for many years. It is quite obvious in a very high regression coefficient for $\overline{T_s'T_s'}$, a bad correlation and a large *rmsd* value for that parameter; although with the lower $\overline{w'w'}$ (with the internal calibration factor of 1.10 turned off), the resulting heat flux is almost acceptable. Several possible reasons

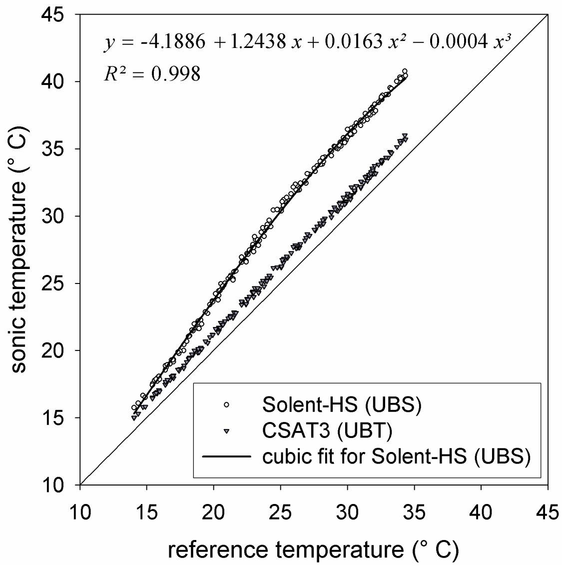


Figure 4: Sonic temperature measurements of Solent-HS (UBS) and CSAT3 (UBT)) versus reference temperature measured by a psychrometer. The CSAT3 shows a dependency on the reference temperature with a slope close to 1. The relationship between the Solent HS and the reference temperature can be described by a polynomial fit of third degree: $y = -4.1886 + 1.2438x + 0.0163x^2 - 0.0004x^3$.

for this behaviour of Solent anemometers are discussed by Vogt (1995). The sonic temperature measured by a Solent anemometer shows a significant dependence on the air temperature. The reason is a temperature dependence of the transducer delay, which results in an erroneous measurement of the speed of sound. Figure 4 shows the temperature dependence of the sonic temperature measurements of the Solent-HS (UBS) and CSAT3 (UBT). The CSAT3 has a dependence on the reference temperature with a slope close to 1.00. In contrast, the relationship between the Solent-HS and the reference temperature can be described by a polynomial fit of third degree:

$$T_{solent} = -0.0004T_{ref}^{\ 3} + 0.0163T_{ref}^{\ 2} + 1.2438T_{ref} - 4.1886 \qquad (3)$$

Equation 3 could be used to correct the raw sonic temperature data of the Solent-HS for the EBEX-2000 experiment period, though the transducer temperature is not necessarily the same as the air temperature.

Not only the sonic anemometer of this sensor combination from the University of Basel showed some problems but also the corresponding krypton hygrometer. It underestimates humidity fluctuations significantly (see Table 7). The behaviour of its sensitivity can be seen in Figure 5, where the absolute humidities measured by the KH20 (UBT), the KH20 (UBS) and a psychrometer are plotted for four consecutive days during EBEX-2000. The absolute humidity measured by the KH20 (UBT) shows an offset, which is not relevant for the calculation of variances or covariances. However, significantly for correct turbulence measurement, its course is parallel to the psychrometer reference humidity measurement. In contrast, the values measured by the

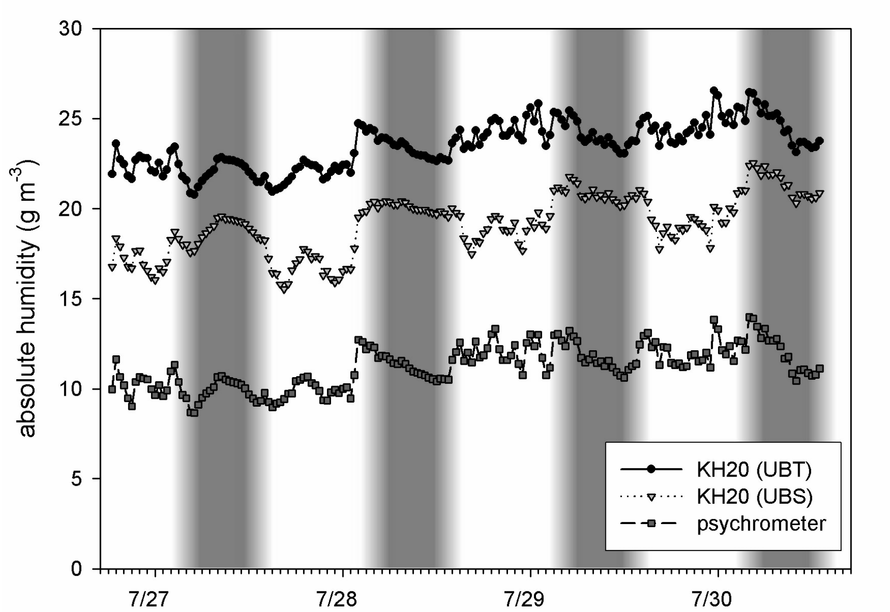


Figure 5: Absolute humidities (g m^{-3}) measured by the KH20 (UBT), the KH20 (UBS) and a psychrometer from July 26, 2000 1700 UTC to July 30, 2000 1700 UTC, all deployed at the same height of 4.7 m above ground level. Note the changing calibration of KH20 (UBS) krypton hygrometer, especially differences between daytime and nighttime. Day/night is indicated by shading of background.

KH20 (UBS) not only show a simple offset compared to the reference, their course is completely different from the psychrometer. During the night, this behaviour can be characterised by a simple offset, but during the day the humidity values of the KH20 (UBS) are relatively lower and have different dynamics than those from the psychrometer. It seems to be an effect of heating up the sensor's enclosure beginning after sunrise and proceeding during the day. Looking at the high frequency time series (not shown in this paper), we also found several sudden drops. As mentioned in section 3.2, some components of the KH20 are sensitive to condensing humidity. We suspect that water condensation in addition to a corrosion of electrical contacts have caused the misbehaviour of the KH20 from Basel. Its sensitivity changes between daytime situations, when temperatures are rising and water inside the sensor's enclosure is evaporating, and nighttime situations, when temperatures are falling and water is condensing inside the sensor's enclosure. Eventually scaling effects also might come into consideration as an explanation of the misbehaviour of this sensor, but it is not clear how they could cause such a repetitive effect from day to day. Nevertheless, since the correlation of the latent heat flux measured by the system Solent-HS/KH20 is relatively high ($R^2 = 0.98$), one option would be the use of the regression equation of the intercomparison analysis (see Table 10), in order to correct the latent heat flux data. It may be better to use two different regression equations, one each for daytime and nighttime.

7.3 Metek USA-1 and R.M. Young 81000 (UBT)

It is not as obvious why the Metek and R.M. Young exhibit scatter in the u_* comparison. The Metek and R.M. Young wind speeds and $\overline{w'w'}$ differences are greater than 5% (and speed also has a large offset), though the errors compensate to make u_* reasonable. Both of their $\overline{T_s'T_s'}$ values are quite low, though again, the higher $\overline{w'w'}$ values make the R.M. Young sensible heat fluxes relatively good on the average. The main problem of the Metek USA-1 is a disturbance of the correlation between the horizontal and the vertical wind components, probably induced by wake effects downstream of a transducer or another supporting structure. According to the theoretical considerations of Wyngaard (1981), probe-induced flow distortion changes the correlation between vertical and horizontal wind components, the so-called crosstalk effect. This is clear in Figure 6 for the Metek sonic. The CSAT3 has correlation coefficients between w and u which are, as one would expect, almost constant for all wind directions at a value of approximately 0.3. Correlation coefficients measured with the Metek, which range from 0.15 to 0.40, are significantly different from the CSAT3 measurements for some wind directions. These wind direction sectors correspond with the arrangement of its quite bulky transducer heads every 60°.

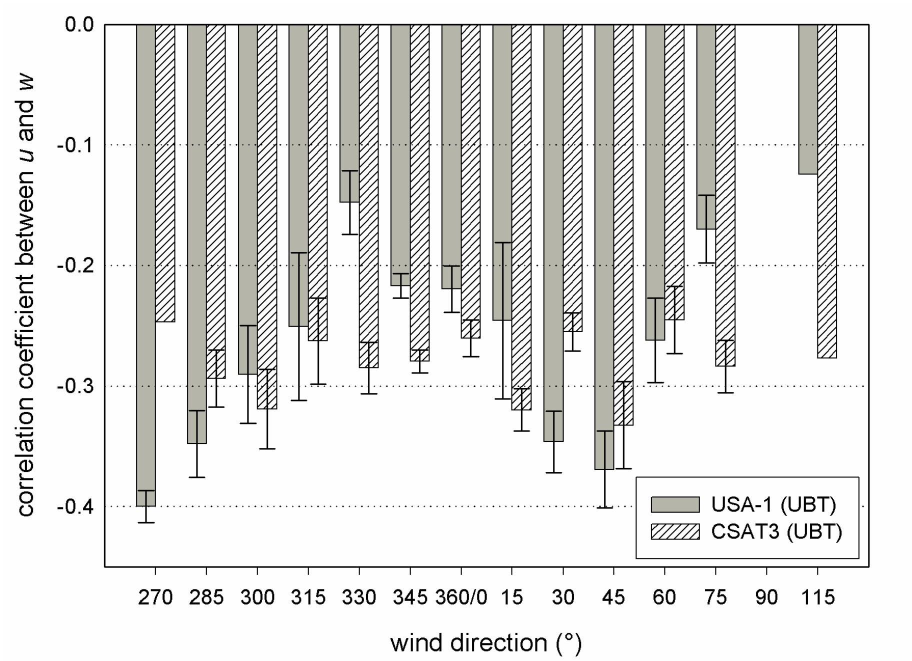


Figure 6: Correlation coefficients between vertical and horizontal wind velocity depending on wind direction, measured by the CSAT3 (UBT) and the Metek USA-1 (UBT) during EBEX-2000 at site 7. The data set is subdivided in 15° wind direction classes. Classes of significantly different averages ($\alpha \leq 0.05$) are 330°, 345°, 30°, 75°.

7.4 ATI-K/KH20 (NCAR)

Based on earlier (unpublished) intercomparison data for the ATI-K probe, which attempted to replicate the study of Kaimal et al. (1990), these had been operated with a single-path correction factor *f* of 20% maximum (for flow along the path). Significant differences from the reference are obvious in Table 4, Table 5, and Table 8 using this correction. Thus, the slightly lower factory default correction of 16% was used to reanalyse these data and appears to have improved the ATI-K/UW comparison slightly. The overestimation of $\overline{w'w'}$ by the ATI-K probe leads to high sensible heat flux data for this sensor. For the ATI-K at site 7, high $\overline{w'w'}$ values appear to be somehow balanced by low $\overline{T_s'T_s'}$ values, which results in reasonable sensible heat fluxes. Although the humidity fluctuations are overestimated by the ATI-K/KH20 complex at site 7, its latent heat fluxes also are in good agreement with the reference.

7.5 UW/KH20 (NCAR)

The UW sonic from NCAR shows generally a very good agreement with the reference CSAT3 (UBT). For all sonic anemometer test parameters, the slopes of the regression lines are in a range from 0.97 to 1.02 and R^2 values are greater than 0.97. The fact that the UW (NCAR) almost measures the same values as the CSAT3 (UBT) confirms the selection of the latter as the reference instrument. The overall comparison results would not be significantly different if we had chosen the UW (NCAR) instead of the CSAT3 (UBT). The KH20 operated together with the UW sonic shows a good agreement with the reference, as well. The deviations for the parameters $\overline{\rho_v'\rho_v'}$ ($b = 1.06$) and λE (b = 1.05) are a little larger than those which were measured with only the sonic anemometer, however the scatter is still small ($R^2 \geq 0.98$). Thus, the problem appears to be the calibration of the KH20's sensitivity. This problem could be solved by calibrating the signals from krypton hygrometers to an accurate slow response sensor, which is deployed at the same time and at the same height.

7.6 Campbell CSAT3 (UBS)

Finally, we will compare all of the CSAT3s. Differences of up to 4% are seen between the three sensors. This is a bit larger than one would expect for essentially collocated sensors on a uniform field, but is acceptable accuracy for EBEX-2000. The mounting of the CSAT3 (UBS) was different from the reference system. It was fixed to a horizontal tube which was attached to a vertical lattice mast, whereas the remainder of the CSAT3s were fixed to vertical single-tube masts. This can be one reason for the small deviations from the reference which we observed.

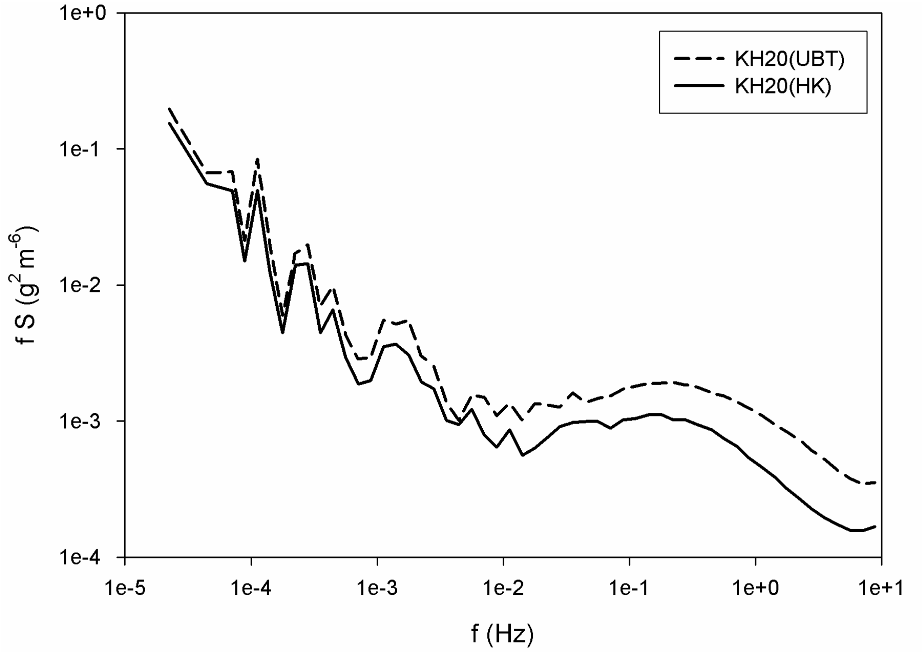


Figure 7: Spectra of KH20 measurements by the instruments from Bayreuth (reference) and Hong Kong. The signal of the KH20 (HK) is significantly damped compared to the UBT instrument, especially at higher frequencies (data set: July 28, 2000 0300 UTC - July 29, 2000 0300 UTC).

7.7 Campbell CSAT3/KH20 (HK)

As mentioned above, the measurements of the CSAT3 from Hong Kong are in very good agreement with the reference, but the variance of humidity measured by the KH20 (HK) is dramatically lower by approximately 70%. Looking at spectra (Figure 7) the calibration factor k_w seems to be reasonable, but an attenuation which increases at higher frequencies, can be seen. It was not possible to find out more about the reasons for this behaviour. Since the R^2 value of 0.97 for the latent heat flux is still high, a correction using the regression coefficients from Table 10 can be considered.

7.8 Campbell CSAT3/LI-7500 (UBT)

The LI-7500 is much better suited for deployment as an absolute instrument than krypton hygrometers, as it doesn't suffer from scaling windows and therefore shows no offset compared to a psychrometer. In Figure 8, the humidity measurements from the LI-7500 (UBT) are shown together with those from a nearby psychrometer. During nighttime, both lines match almost perfectly. But during daytime, the LI-7500 gas analyser measures noticeably higher values than the psychrometer. The difference between both sensors appears to be the largest at noon, when the sun reaches its highest elevation. As this sensor was aligned vertically (Figure 3j), it is likely that this phenomenon can be explained by the solar-radiation error described above. The excellent correlation

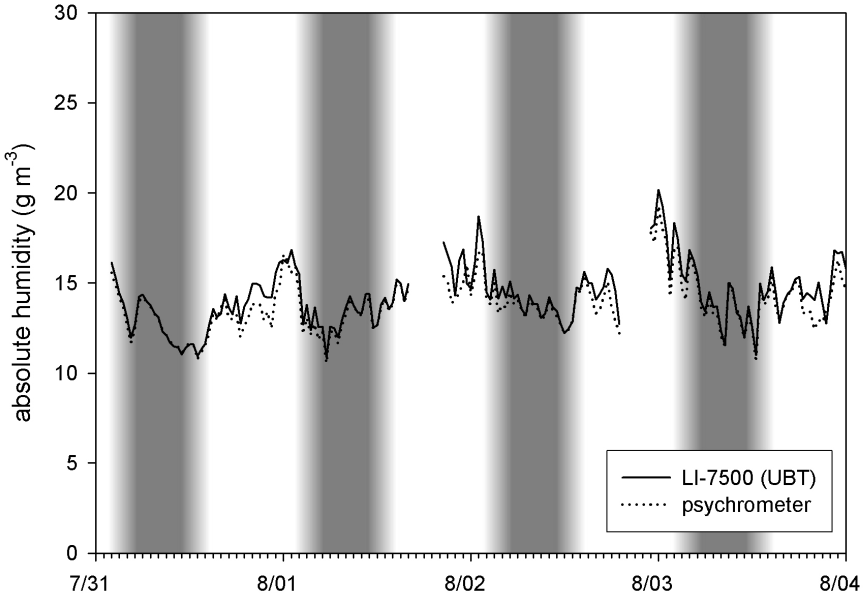


Figure 8: Absolute humidities (g m^{-3}) measured by the LI-7500 (UBT) and a psychrometer from July 31, 2000 0000 UTC to August 4, 2000 0000 UTC, both deployed at the same height of 4.7 m above ground level. Note the changing calibration of LI-7500 (UBT) infrared gas analyser, especially the differences between daytime and nighttime. Day/night is indicated by shading of background.

(R^2 = 1.00) with the reference system allows the use of the regression coefficients from Table 10 in order to obtain comparable results for this sensor combination. Consequently, latent heat fluxes from the combination CSAT3/LI-7500 (UBT) have to be reduced by 17% in general.

8 Conclusions

In order to achieve good eddy covariance sensor intercomparison results, it is important to standardise the mounting of the sensors, data acquisition, data processing and calibration of hygrometers as much as possible. We found excellent agreement between the CSAT3/KH20 (UBT) and the UW/KH20 (NCAR) for all test parameters and also with the other CSATs for the parameters measured by a sonic anemometer only. This justifies the choice of the former as reference for this comparison study, although the results would not be much different if one had chosen the latter.

Most of the eddy covariance systems showed good agreement for heat flux measurements, especially those from NCAR, which were predominantly used for the equipment of the ten sites of EBEX-2000. For the remainder of the systems, wherever we found major deviations, possible reasons for their misbehaviour were analysed and suggestions for correcting these measurements could be made.

Sonic anemometers can be used for absolute measurements of wind velocities. Well-calibrated krypton hygrometers are suitable for relative measurements of turbulent humidity fluctuations but cannot serve as absolute instruments for humidity because of large offsets due to scaling effects of the optical windows. To reduce these unwanted effects, daily cleaning of the windows is necessary and great importance has to be attached to the calibration of these sensors.

The LI-7500 open path gas analyser, which we used during EBEX-2000, suffered some “teething troubles”, as it was one of the first serial numbers. Now that these problems of solar-radiation error and delay time error have been solved by the manufacturer, we expect that this instrument type is satisfactory for the eddy covariance measurement of the latent heat flux.

From this study, the UW and CSAT3 sonics can be classified as well-qualified instruments suitable for fundamental research on turbulence if operated properly. Some minor deficits were found for the Solent-HS and the ATI-K probes. The Metek USA-1 and the R.M. Young showed larger problems regarding flow distortion and cross talk due to transducer-shadow effects. Nevertheless, these sensors can be used for general turbulent flux measurements.

The comparison of post-field data processing methods showed that typical differences in methodologies can result in measurement discrepancies of up to 15% for the sensible and latent heat flux. A proper correction for spectral displacement of sensors was found to be very important. Linear detrending, which should not be applied, has a big impact on the resulting flux, as well. In general, only minor differences were found between different methods due to discrepancies in the order of processing steps and the use of physical constants.

Neither the errors due to different eddy covariance post-field data processing methods nor the errors due to instrumental deficiencies were found to be systematic in such a way that they can explain the energy balance closure problem in general, because most of the errors found are too small or do not affect turbulent fluxes the right direction. However, some discrepancies related to the operation of turbulence instruments have been exposed. Furthermore, the discussion of methodological aspects of the eddy covariance data analysis has led to a better definition of a uniform processing algorithm.

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References

Beyrich, F., Richter, S. H., Weisensee, U., Kohsiek, W., Lohse, H., DeBruin, H. A. R., Foken, T., Göckede, M., Berger, F. H., Vogt, R., and Batchvarova, E.: 2002, 'Experimental determination of turbulent fluxes over the heterogeneous LITFASS area: Selected results from the LITFASS-98 experiment', *Theor. Appl. Climatol.* **73**, 19-34.

Brook, R. R.: 1978, 'The influence of water vapor fluctuations on turbulent fluxes', *Boundary-Layer Meteorol.* **15**, 481-487.

Christen, A., van Gorsel, E., Andretta, M., Calanca, M., Rotach, M., and Vogt, R.: 2000, 'Intercomparison of ultrasonic anemometers during the MAP-Riviera project', in *9th Conference on Mountain Meteorology*, Aspen, CO, 130-131.

Dyer, A. J.: 1981, 'Flow distortion by supporting structures', *Boundary-Layer Meteorol.* **20**, 363-372.

Dyer, A. J., Garratt, J. R., Francey, R. J., McIlroy, I. C., Bacon, N. E., Bradley, E. F., Denmead, O. T., Tsvang, L. R., Volkov, Y. A., Koprov, B. M., Elagina, L. G., Sahashi, K., Monji, N., Hanafusa, T., Tsukamoto, O., Frenzen, P., Hicks, B. B., Wesely, M., Miyake, M., and Shaw, W.: 1982, 'An international turbulence comparison experiment (ITCE-76)', *Boundary-Layer Meteorol.* **24**, 181-209.

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

Foken, T., and Oncley, S. P.: 1995, 'Workshop on instrumental and methodical problems of land surface flux measurements', *Bull. Am. Meteorol. Soc.* **76**, 1191-1193.

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

Foken, T., Weisensee, U., Kirzel, H.-J., and Thiermann, V.: 1997, 'Comparison of new-type sonic anemometers', in *12th Symposium on Boundary Layer and Turbulence*, Vancouver, BC, Amer. Meteorol. Soc., Boston, 356-357.

Foken, T.: 1999, Comparison of the sonic anemometer Young Model 81000 during VOITEX-99. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **8**, 12 pp. (Print, ISSN 1614-8916)

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, Dordrecht, pp. 181-208.

Högström, U., and Smedman, A.-S.: 2004, 'Accuracy of sonic anemometers: Laminar wind-tunnel calibrations compared to atmospheric in situ calibrations against a reference instrument', *Boundary-Layer Meteorol.* **111**, 33-54.

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

Horst, T. W.: 2000, 'On frequency response corrections for eddy covariance flux measurements', *Boundary-Layer Meteorol.* **94**, 517-520.

ISO: 1993, *Statistics - Vocabulary and Symbols - Part 1: Probability and general statistical terms*, International Organization for Standardization, Geneva, Switzerland, ISO 3534-1, 61 pp.

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

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

Lee, X., Massman, W., and Law, B. E. (ed.): 2004, 'Handbook of micrometeorology. A guide for surface flux measurement and analysis', Kluwer Academic Press, Dordrecht, 250 pp.

Liu, H., and Foken, T.: 2001, 'A modified Bowen ratio method to determine sensible and latent heat fluxes', *Meteorol. Z.* **10**, 71-80.

Liu, H., 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.

Mauder, M., and Foken, T.: 2004, Documentation and instruction manual of the eddy covariance software package TK2. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **26**, 44 pp. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

Miyake, M., Stewart, R. W., Burling, H. W., Tsvang, L. R., Koprov, B. M., and Kuznetsov, O. A.: 1971, 'Comparison of acoustic instruments in an atmospheric turbulent flow over water', *Boundary-Layer Meteorol.* **2**, 228-245.

Moore, C. J.: 1986, 'Frequency response corrections for eddy correlation systems', *Boundary-Layer Meteorol.* **37**, 17-35.

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

Oncley, S. P., Foken, T., Vogt, R., Kohsiek, W., de Bruin, H., Bernhofer, C., Christen, A., Grantz, D., Lehner, E., Liebethal, C., Liu, H., Mauder, M., Pitacco, A., Ribeiro, L., and Weidinger, T.: 2005, 'The Energy Balance Experiment EBEX-2000. Part I: Overview and energy balance', *Boundary-Layer Meteorol.*, to be submitted.

Schotanus, P., Nieuwstadt, F. T. M., and DeBruin, H. A. R.: 1983, 'Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations', *Boundary-Layer Meteorol.* **26**, 81-93.

Tanner, B. D., and Campbell, G. S.: 1985, 'A krypton hygrometer for measurement of atmospheric water vapor concentration', in *Moisture and Humidity*, Instrument Society of America, Research Triangle Park, NC, 609-612.

Tanner, B. D., Swiatek, E., and Greene, J. P.: 1993, 'Density fluctuations and use of the krypton hygrometer in surface flux measurements', in R. G. Allen (ed.), *Management of irrigation and drainage systems: integrated perspectives*, American Society of Civil Engineers, New York, NY, pp. 945-952.

Tsvang, L. R., Koprov, B. M., Zubkovskii, S. L., Dyer, A. J., Hicks, B., Miyake, M., Stewart, R. W., and McDonald, J. W.: 1973, 'A comparison of turbulence measurements by different instruments; Tsimlyansk field experiment 1970', *Boundary-Layer Meteorol.* **3**, 499-521.

Tsvang, L. R., Zubkovskij, S. L., Kader, B. A., Kallistratova, M. A., Foken, T., Gerstmann, W., Przandka, Z., Pretel, J., Zelený, J., and Keder, J.: 1985, 'International turbulence comparison experiment (ITCE-81)', *Boundary-Layer Meteorol.* **31**, 325-348.

van Dijk, A., Kohsiek, W., and DeBruin, H. A. R.: 2003, 'Oxygen sensitivity of krypton and Lyman-alpha hygrometers', *J. Atm. Oceanic Tech.* **20**, 143-151.

Vogt, R.: 1995, Theorie, Technik und Analyse der experimentellen Flussbestimmung am Beispiel des Hartheimer Kiefernwaldes. University of Basel, Basel, Switzerland, Stratus **3**, 101 pp.

Webb, E. K., Pearman, G. I., and Leuning, R.: 1980, 'Correction of the flux measurements for density effects due to heat and water vapour transfer', *Quart. J. Roy. Meteorol. Soc.* **106**, 85-100.

Webb, E. K.: 1982, 'On the correction of flux measurements for effects of heat and water vapour transfer', *Boundary-Layer Meteorol.* **23**, 251-254.

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.: 1981, 'The effects of probe-induced flow distortion on atmospheric turbulence measurements', *J. Appl. Meteorol.* **20**, 784-794.

Wyngaard, J. C., and Zhang, S. F.: 1985, 'Transducer-shadow effects on turbulence spectra measured by sonic anemometers', *J. Atm. Oceanic Tech.* **2**, 548-558.

Zhang, S. F., Wyngaard, J. C., Businger, J. A., and Oncley, S. P.: 1986, 'Response characteristics of the U.W. sonic anemometer', *J. Atm. Oceanic Techn.* **2**, 548-558.

Appendix D

Impact of Post-Field Data Processing on Eddy Covariance Flux Estimates and Energy Balance Closure

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Abstract

This study evaluates the impact of post-field data processing methods on eddy covariance flux estimates and the resulting energy balance residual. To that end, a dataset from the LITFASS-2003 field campaign was analysed using an experimental software package. Widely discussed issues in data processing, like an adequate flux averaging time, coordinate transformations, and alternative approaches for the correction of density effects are examined. The impact of all the single processing steps on the turbulent flux estimates of sensible heat, latent heat and CO_2, as well as the impact on the resulting energy balance residual, is demonstrated. Compared to 30 minute covariances without any conversions or corrections, the mean energy balance residual can be reduced by 16% if all necessary procedures are applied to the test dataset. Important procedures for the reduction of the experimental energy balance closure problem are the correction for spectral loss and the correction for density effects. Furthermore, the energy balance residual vanishes almost completely if the covariance averaging time is extended from 30 minutes to 24 hours. The longwave flux contributions are explained through effect, which are caused by the strong heterogeneity of the landscape surrounding the measurement site. The dependence of CO_2 flux estimates on the post-field data processing is even stronger. Their mean value can be halved or doubled through the correction for density effects. The approach after LIU (2005) leads to an increased net assimilation estimate by 26% compared to the classic WPL correction. Large flux contributions from wavelengths longer than 30 minutes were also found for the CO_2 flux.

Zusammenfassung

Diese Studie untersucht den Einfluss von Methoden zur Datennachbearbeitung auf Eddy-Kovarianz Flusswerte und das resultierende Energiebilanz-Residuum. Dazu wurde ein Datensatz der Feldkampagne LITFASS-2003 mit einem experimentellen Softwarepaket analysiert. Viel diskutierte Themen der Datenanalyse, wie eine geeignete Fluss-Mittelungszeit, Koordinatentransformationen und alternative Ansätze zur Korrektur von Dichteeffekten werden geprüft. Der Einfluss aller Einzelbearbeitungsschritte auf die turbulenten Flüsse von fühlbarer Wärme, latenter Wärme, CO_2 und das Residuum der Energiebilanz wird demonstriert. Verglichen mit 30-Minuten-Kovarianzen ohne jegliche Konversionen und Korrekturen kann das mittlere Energiebilanz-Residuum um 16% reduziert werden, wenn alle notwendigen Bearbeitungsschritte auf den Testdatensatz angewendet werden. Wichtige Bearbeitungsschritte zur Reduzierung von Problemen mit der experimentellen Energiebilanzschließung sind die Korrektur spektraler Verluste und die Korrektur von Dichteeffekten. Weiterhin verschwindet das Energiebilanz-Residuum fast vollständig, wenn man die Kovarianz-Mittelungszeit von 30 Minuten auf 24 Stunden ausdehnt. Die langwelligen Flussbeiträge werden mit Effekten, die durch die starke Heterogenität der den Messstandortes umgebenden Landschaft hervorgerufen werden, erklärt. CO_2-Flusswerte hängen noch stärker von der Datennachbearbeitung ab. Ihr Mittelwert kann halbiert oder verdoppelt werden durch die Korrektur von Dichteeffekten. Der Ansatz von LIU (2005) führt zu einem um 26% erhöhten Wert für die Nettoassimilation im Vergleich zur klassischen WPL-Korrektur. Große Flussbeiträge von längeren Wellenlängen als 30 Minuten wurden auch für den CO_2-Fluss gefunden.

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1 Introduction

According to the First Law of Thermodynamics, energy has to be conserved. If we apply this law to the processes at the earth's surface we can write the following energy balance equation.

$$-Q_s^* = Q_H + Q_E + Q_G \,, \tag{1}$$

where
Q^*_s = net radiation,
Q_H = sensible heat flux,
Q_E = latent heat flux,
Q_G = ground heat flux at the surface, including soil storage.
However, this fundamental balance often cannot be equalised by micrometeorological measurements of the surface energy balance components. In most experiments, the available energy at the surface $-Q^*_s - Q_G$ is significantly larger than the sum of the turbulent fluxes $Q_H + Q_E$ (FOKEN and ONCLEY, 1995; WILSON et al., 2002; CULF et al., 2004). Several reasons for this experimental energy balance unclosure are discussed in the literature. Among other reasons, which are not the object of this study, uncertainties in the post-field data processing of eddy covariance measurements of the turbulent fluxes are suspected to be crucial (e.g. MASSMAN and LEE, 2002). Therefore, LEE et al. (2004) formulated recommendations related to the eddy covariance technique for estimating turbulent mass and energy exchange between the terrestrial biosphere and the atmosphere and gave a comprehensive overview on the current state of science regarding micrometeorological issues and methods. Some issues regarding the processing of eddy covariance measurements are still in discussion.

Flow distortion effects caused by the sonic anemometer itself can occur (DYER, 1981; KAIMAL et al., 1990) depending on the design of a sensor. If the pathlength of a sonic anemometer is more than twenty times larger than the diameters of its transducers these effects can be considered negligibly small (WYNGAARD, 1981). Otherwise, a correction of these effects is possible. VOGT (1995) developed such a correction based on wind-tunnel studies for sonic anemometers of type Solent R2 and R3 (Gill Instruments). However, the application of this so-called "matrix calibration" could only partly improve the results of a sonic anemometer field intercomparison (CHRISTEN et al., 2001). Another wind-tunnel based flow distortion correction was recently presented, the "angle of attack dependent calibration" (GASH and DOLMAN, 2003); it also deals with Solent R2 and R3 sonics. Metek developed an equivalent wind-tunnel based flow distortion correction for their USA-1 sonic, the so-called "head correction". Such corrections can alter the resulting flux estimate by up to 10% of the flux (CHRISTEN et al., 2001; VAN DER MOLEN et al., 2004). However, it is still not clear if these corrections, which are based on calibrations in the quasi-laminar field of a wind-tunnel, can be transferred to the application in the turbulent atmosphere. In particular, the results from a field evaluation of a wind-tunnel based flow distortion correction with a hot-film anemometer as reference instrument indicate that this transfer can be problematical (HÖGSTRÖM and SMEDMAN, 2004). The design of the CSAT3 sonic anemometer, which is used for this study, minimises flow distortion effects. Therefore, it is not necessary to apply any further flow distortion correction during the post-processing for this sensor.

Both SAKAI et al. (2001) and FINNIGAN et al. (2003) address the issue of an adequate averaging procedure for the calculation of covariances. They stress that any detrending of the time series acts as high-pass filter and that through the application of too-short averaging intervals flux contributions from longer wavelengths are missed. Both effects lead to reduced flux estimates, which may well be a reason for energy balance closure problems. According to the findings of FINNIGAN et al. (2003), climatology, canopy structure and topography all influence the cospectra and covariance at a given site. They stress that in complex terrain, especially over tall vegetation, the optimum averaging period may be much longer than the classic 30 minutes in order to cover all longwave flux contributions. As an example, they found an optimum averaging time of four hours by minimising the energy balance residual for a selected site near Manaus (Brazilian rain forest). But even longer averaging times are considered to be reasonable depending on the site characteristics. An interesting LES study of the energy imbalance problem by KANDA et al. (2004) points out that eddy covariance flux measurements systematically underestimate the real turbulent fluxes because they neglect the low-frequency flux contribution from turbulent organised structures (TOS), which have much longer time scales than thermal plumes. These TOS can be covered through the extension of the averaging time, but then the scatter of such flux estimates would increase. MAHLI et al. (2004) emphasize that extending sampling periods may solve the energy balance problems but also imply some complications, since it is tricky to separate the locally meaningful fluxes, which we want to measure, from wider-scale advection, which we do not want to measure.

A recent study by FOKEN et al. (2005), which is based on the analysis of cumulative integrals over cospectra, the so-called ogives (ONCLEY, 1989; FOKEN et al., 1995), underlines the importance of an adequate averaging or integration time interval for eddy covariance fluxes. They relate increased energy balance residuals with a misbehaviour of ogive functions, which indicates that the commonly used 30 minute covariances don't cover the whole spectrum of the turbulent flux.

Another issue of actual scientific discussions is the choice of an adequate coordinate system. Data from a poorly aligned sonic anemometer or data from measurements in sloping terrain can be corrected by a coordinate transformation, if the whole stress tensor and the three-dimensional flux vectors are determined (MCMILLEN, 1988). Basically, two different methods of coordinate transformation are discussed in the recent literature. A tilt correction can either be done using the planar fit method (WILCZAK et al., 2001) or, alternatively, using the 2-/3-rotation, which is also called double/triple rotation method (MCMILLEN, 1988; KAIMAL and FINNIGAN, 1994). MCMILLEN (1988) used a running mean obtained from a recursive high pass filter for averaging to calculate rotation angles. KAIMAL and FINNIGAN (1994) determined the angles for the coordinate rotation on the basis of half-hour block averages. In order to reduce the uncertainty of the rotation angles, a major innovation of the planar fit method that rotation angles are determined for much longer time periods of usually several days (WILCZAK et al., 2001). The planar fit method should be preferred according to recent findings by FINNIGAN (2004), since the still commonly used double/triple rotation method leads to erroneous rotation angles, which often give physically impossible results for turbulent fluxes.

A certain loss in the high frequency part of the turbulent spectrum cannot be avoided, because it is related to the instrumentation. Such loss is mainly caused by the spatial separation of sensors, pathlength averaging and dynamic frequency response characteristics of sensor signals. These effects can be described through transfer functions, which can be applied to model spectra in order to correct the measured covariances (MOORE, 1986; MONCRIEFF et al., 1997; HORST, 2000). The adequate choice of spectral models is a source of uncertainty in this correction. For many flux measurement sites in complex terrain or over tall vegetation the classical spectral models (KAIMAL et al., 1972), which were determined over low vegetation in homogeneous terrain, are not valid (MASSMAN and CLEMENT, 2004). The shape of spectra can contain much more noise and the frequency at which the frequency-weighted cospectra reach a maximum value can be shifted. A totally different approach describes the spectral loss by an analogy with inductance in an electronical alternating current circuit (EUGSTER and SENN, 1995), which is much more empirical. This method has advantages for trace-gas flux measurements, because the characteristics of these often imperfect sensors can hardly be described by analytical transfer functions. But it is not relevant to this study.

Turbulent fluxes of air constituents like H_2O and CO_2 need to be corrected for density fluctuations and a mean vertical mass flow caused by heat and water vapour transfer, if they are measured by open-path sensors (LEUNING, 2004). The classic procedure for this correction was proposed by WEBB et al. (1980). It was confirmed by BERNHARDT and PIAZENA (1988) using a different theoretical approach. FUEHRER and FRIEHE (2002) revisited this issue and developed new equations for the mean vertical flow. Although, according to LEUNING (2004), the classic WPL approximation is still applicable for 1-D flows. Recently, an alternative correction procedure was suggested by LIU (2005), which is based on the conservation equation for the total moist air and not only for the dry air as in the approach used in WEBB et al. (1980). LIU (2005) reports that the alternative correction procedure led to increased estimates of CO_2 uptake by the vegetation during the day (up to about 20%), and decreased estimates of CO_2 respiration by the ecosystem during the night (approximately 4%) in comparison to estimates obtained using the Webb et al. approach. Further evaluations of this procedure are desirable, since this first study by Liu was done for a dataset from a relatively unusual site in

Alaska, which cannot be representative for many other flux measurement sites in different climatic regions.

This study investigates the impact of these various steps of post-field data processing on the resulting turbulent flux estimates and evaluates to which degree the selection of these data processing methods contributes to the solution of the energy balance closure problem. Their impact will be evaluated using a 15 day dataset from an agricultural site of the field campaign LITFASS-2003 (Lindenberg Inhomogeneous Terrain – Fluxes between Atmosphere and Surface: a long term Study). This experiment was located in an area southeast of Berlin, Germany, which is considered typical for European temperate latitudes. The measurements were carried out in 2003 in the early summer, because this is the main growing season for the maize plants on this field and therefore high turbulent fluxes were expected (BEYRICH et al., 2004).

A comprehensive experimental software package was developed for this investigation, called TK2 (MAUDER and FOKEN, 2004). It implements the guidelines by LEE et al. (2004) and makes them applicable in practice, it includes the quality assessment proposed by FOKEN and WICHURA (1996) in the updated version of FOKEN et al. (2004). A consistent scheme for the post-field data processing will be presented. It enables us to evaluate the impact of each processing step on the resulting eddy covariance flux estimates and the energy balance residual in the context of the whole data processing algorithm. Starting with already calculated raw covariances for 30 minute intervals, we will analyse all following post-field data processing steps of eddy covariance measurements subsequently. The impact of alternative procedures will also be demonstrated. Such alternatives in present discussions are different averaging intervals for covariances, coordinate transformation after the planar fit or the double rotation method, and the correction for density fluctuations.

2 Methods

2.1 Measurements

The micrometeorological measurements were carried out on a maize field in the area of Falkenberg, Germany (52°10’00” N, 14°07’29” E, 73 m a.s.l.). The aerodynamic measuring height of the turbulence sensors $z - d$ was 2.25 m (z = measurement height, d = zero-plane displacement). A Campbell CSAT3 sonic anemometer and a LI-COR LI-7500 open-path infrared gas analyser served for the measurement of the buoyancy flux and latent heat flux as well as the CO_2 flux. The pathlength of the CSAT3 sonic is 0.12 m. The pathlength of the LI-7500 open-path gas analyser is 0.125 m. The separation between both sensors was 0.30 m.

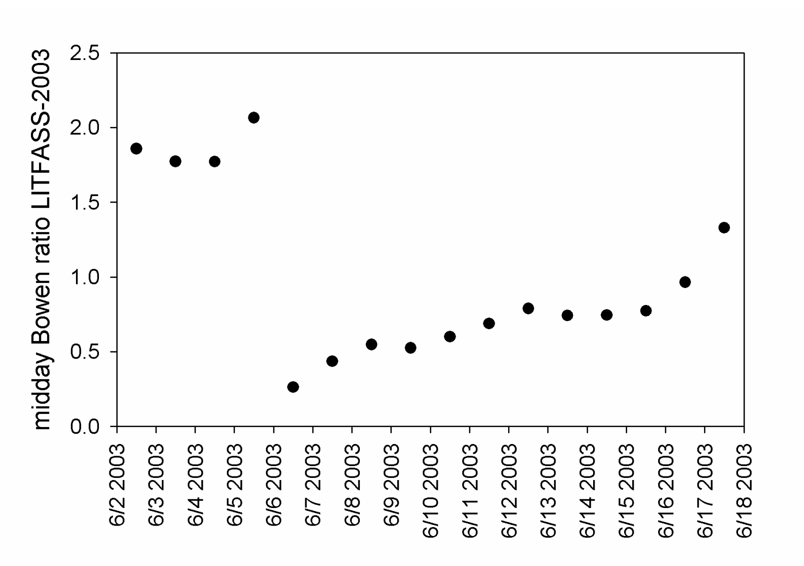

Figure 1: Midday Bowen ratios during LITFASS-2003 at the measurement site (1200 – 1300 UTC).

The radiation components were measured by a Kipp&Zonen CM24 pyranometer/albedometer and an Eppley double direction precision infrared radiometer (PIR). For the ground heat flux determination, a Hukseflux self-calibrating heat flux plate, an IMKO TDR probe and several PT100 soil thermometers were deployed. This ground heat flux determination approach was evaluated in a sensitivity study by LIEBETHAL et al. (2005). Further issues regarding the quality assurance and quality control of the soil and radiation measurements are described in MAUDER et al. (2006).

During the measurement period from June 2 to June 17, 2003, temperature maxima were above 25° C every day. Absolute humidity ranged between 5 and 15 g m^{-3}. During the first few days soil moisture was very low (3 Vol.% in -0.10 m and 6 Vol.% in -0.20 m, which is close to the permanent wilting point). A heavy thundershower on June 5 and June 8 led to an increase of soil water available for evaporation. The soils dried out after these rain events. Until the first rain after a long dry period on June 5, most of the available energy at the surface was transformed into the sensible heat flux, resulting in midday Bowen ratios of around 2. Afterwards, the midday Bowen ratio increased again, from 0.3 on June 6 to 1.3 on June 17, 2003 (Figure 1).

2.2 Data processing

The eddy covariance method is the most direct way to measure turbulent fluxes in the atmospheric surface layer. It is based on the Navier-Stokes equation and similar equations for temperature or gaseous air constituents by the use of the Reynolds' postulates (e.g. STULL, 1988; ARYA, 2001; FOKEN, 2003). The equations for determination of surface fluxes are obtained by further simplifications, which are listed in FOKEN and WICHURA (1996). Amongst others, stationarity and homogeneity have to be assumed in order that derivatives with respect to time and space coordinates vanish in the Navier-

Stokes equation. Hence, the total flux F of a scalar s in the surface layer under stationary conditions without advection in homogeneous terrain can be expressed

$$F = \overline{ws} = \overline{w}\,\overline{s} + \overline{w's'}\,. \qquad (2)$$

With the average vertical wind velocity $\overline{w} = 0$, this equation can be simplified to

$$F = \overline{w's'}\,. \qquad (3)$$

Thus, the vertical turbulent flux of a scalar quantity s can be approximated by the determination of its covariance with the vertical wind component w, if w and s are measured at the same point in space and time.

Before covariances can be calculated, spikes in the time series have to be removed. Therefore, we applied a procedure by VICKERS and MAHRT (1997) based on the study of HØJSTRUP (1993). An eventual time delay between two separate sensors was corrected using a cross-correlation analysis for each averaging interval. This automatic delay correction is especially important for the LI-7500 sensor that we deployed, because the software setting of the delay time was erroneous before the introduction of software version 3, according to LI-COR's customer information in July 2003. The LI-7500 was operated with a software setting of 0.25 s for the delay time. But according to the manufacturer's information, this would stand for an actual time delay of the DAC output signal of 0.18±0.03 s.

Both methods of coordinate transformation, the planar fit method proposed by WILCZAK et al. (2001) and the double rotation (KAIMAL and FINNIGAN, 1994), were applied and the resulting fluxes were compared. For this comparison of coordinate transformations we omitted the triple rotation method, because the determination of the third rotation angle, which forces the covariance $\overline{v'w'}$ to vanish, is considered questionable (MCMILLEN, 1988; AUBINET et al., 2000; FINNIGAN, 2004).

The least-square fitted regression equation according to the planar fit method for this dataset was

$$\overline{w} = 0.00362348 + 0.01787350\overline{u} - 0.00005190\overline{v}\,. \qquad (4)$$

The planar fit rotation angles can be calculated from this equation (WILCZAK et al., 2001). The measured wind data were rotated by -1.024 degrees around the y-axis and by -0.003 degrees around the x-axis for the whole measurement period. Additionally, a bias of 0.00362348 m s^{-1} was subtracted to the values of the vertical wind velocity w. For every 30 minute averaging interval, the data were rotated around the z-axis so that the mean lateral wind component v vanishes.

Spectral loss in the high frequency band was corrected after MOORE (1986). This correction algorithm basically follows the idea that the error $\Delta F/F$ of a turbulent flux, which is caused by spectral loss, can be expressed by

$$\frac{\Delta F}{F} = 1 - \frac{\int_0^\infty T_{x(y)}(f) \cdot S_{x(y)}(f) df}{\int_0^\infty S_{x(y)}(f) df} . \tag{5}$$

The theoretical form of the (co-)spectrum S has to be known as well as the specific transfer function T for the correction. We applied the transfer functions proposed by MOORE (1986) for high frequency loss due to line averaging of the vertical wind velocity, the transfer function for line averaging of the scalars temperature, H_2O and CO_2, and the transfer function for lateral sensor separation. A correction of the longitudinal sensor separation is not necessary, because the covariance was maximized by cross-correlation analysis before. The transfer functions were folded with spectral models proposed by HØJSTRUP (1981) for spectra under unstable stratification, whereas models by KAIMAL et al. (1972) were used for spectra under stable stratification and generally all cospectra. Note that there is an error in the parameterisations of stable cospectra in MOORE (1986). These should therefore not be used, but rather the parameterisations after KAIMAL et al. (1972) instead (MONCRIEFF et al., 1997).

The conversion of the sonic temperature or speed of sound measurements into actual temperature after SCHOTANUS et al. (1983) and LIU et al. (2001) takes into account two effects: firstly, the effect of water vapour fluctuations, which are represented in the sonic temperature measurements, and secondly, the cross-wind effect, which leads to an underestimation of the speed of sound measurement. The CSAT3 sonic already implements a cross-wind correction in the internal signal processing. Therefore, only the water vapour effect was corrected through the post-processing. Consequently, the buoyancy flux $\overline{w'T_s'}$, which was measured using a CSAT3 sonic anemometer, was converted into the sensible heat flux $\overline{w'T'}$.

$$\overline{w'T_s'} = \overline{w'T'} - 0.51\overline{T}\,\overline{w'q'} , \tag{6}$$

where $\overline{T}$ is the mean air temperature and $\overline{w'q'}$ is the latent heat flux.

As the deployed open-path sensor does not measure the desired mixing ratios of air constituents but partial densities (a for partial density of H_2O, ρ_c for partial density of CO_2), one has to take into account the effect density fluctuations of the air and a mean vertical mass flow, which is generated through the effective vertical transport of a constituent. This was done by the classical equations by WEBB et al. (1980), where ρ_a is the density of dry air:

$$\overline{w'a'} = (1 + \mu\sigma)\left(\overline{w'a'}_{measured} + \overline{a}\frac{\overline{w'T'}}{\overline{T}} \right) \tag{7}$$

$$\overline{w'\rho_c'} = \overline{w'\rho_c'}_{measured} + \mu \frac{\overline{\rho_c}}{\overline{\rho_a}} \overline{w'a'} + (1+\mu\sigma)\overline{\rho_c} \frac{\overline{w'T'}}{\overline{T}} \tag{8}$$

and alternatively according to the new approach by Liu (2005).

$$\overline{w'a'} = \overline{w'a'}_{measured} \left\{ \frac{\overline{a}}{\overline{\rho}} (\mu - 1) + 1 \right\} + \frac{\overline{\rho_a}}{\overline{\rho}} \overline{a} (1+\mu\sigma) \frac{\overline{w'T'}}{\overline{T}} \tag{9}$$

$$\overline{w'\rho_c'} = \overline{w'\rho_c'}_{measured} + \frac{\overline{\rho_c}}{\overline{a}} (\mu - 1) \overline{w'a'} + \frac{\overline{\rho_a}}{\overline{\rho}} (1+\mu\sigma) \overline{\rho_c} \frac{\overline{w'T'}}{\overline{T}} \tag{10}$$

where $\mu = \frac{m_a}{m_{water}} = 1.6$ and $\sigma = \frac{\overline{a}}{\overline{\rho_a}}$ (11)

Since many of the correction/conversion algorithms are interdependent, all procedures have to be performed iteratively. Finally, tests were applied to the corrected eddy co-variance fluxes in order to assess the data quality, using the criteria suggested by FOKEN and WICHURA (1996) in the updated version by FOKEN et al. (2004). The data are checked for stationarity and well-developed turbulence and classified. The stationarity test compares a 30 minute covariance with the arithmetic mean of the six 5 minute co-variances within the same 30 minute. The test on well-developed turbulence compares measured normalised standard deviations with empirical models after FOKEN et al. (2004) for these integral turbulence characteristics, which were defined by PANOFSKY et al. (1977):

$$\frac{\sigma_u}{u_*}, \frac{\sigma_w}{u_*}, \frac{\sigma_T}{T_*}, \tag{12}$$

where

$\sigma_{u,w,T}$ = standard deviation of the horizontal wind component u, vertical wind component w, and temperature T,

$u_* = \left(\overline{u'w'}^2 + \overline{u'v'}^2\right)^{1/2}$, $T_* = -\frac{\overline{w'T'}}{u_*}$.

The results of both tests are combined to a quality flag for every 30 minute turbulent flux value on a scale from 1 to 9 following a scheme proposed by FOKEN et al. (2004). Flags 1 to 3 represent the highest quality data and can be used for fundamental research, such as the development of parameterisations. Data flagged as 4 to 6 can be used for the calculation of monthly or annual sums for continuously running systems. Flags 7 and 8 are used only for orientation. Sometimes it is better to use class 7 or 8 data instead of a gap-filling procedure, but these data should not differ significantly from the data before and after it in the time series. Data of flag 9 should be excluded under all circumstances. This study compares impact of the application of these QA/QC tests if only data of highest quality (class 1-3) are used, or if all data not a priori wrong are considered (classes 1-8).

The software package TK2 implements all these features and was used for the post-field data processing of the presented eddy covariance measurements. They are brought into a reasonable sequence according to the scheme presented in Figure 2. A detailed description of the processing algorithm is given in MAUDER and FOKEN (2004). The single processing steps of this software, including alternative methods, were executed successively, and the resulting flux estimates were recorded in separate files.

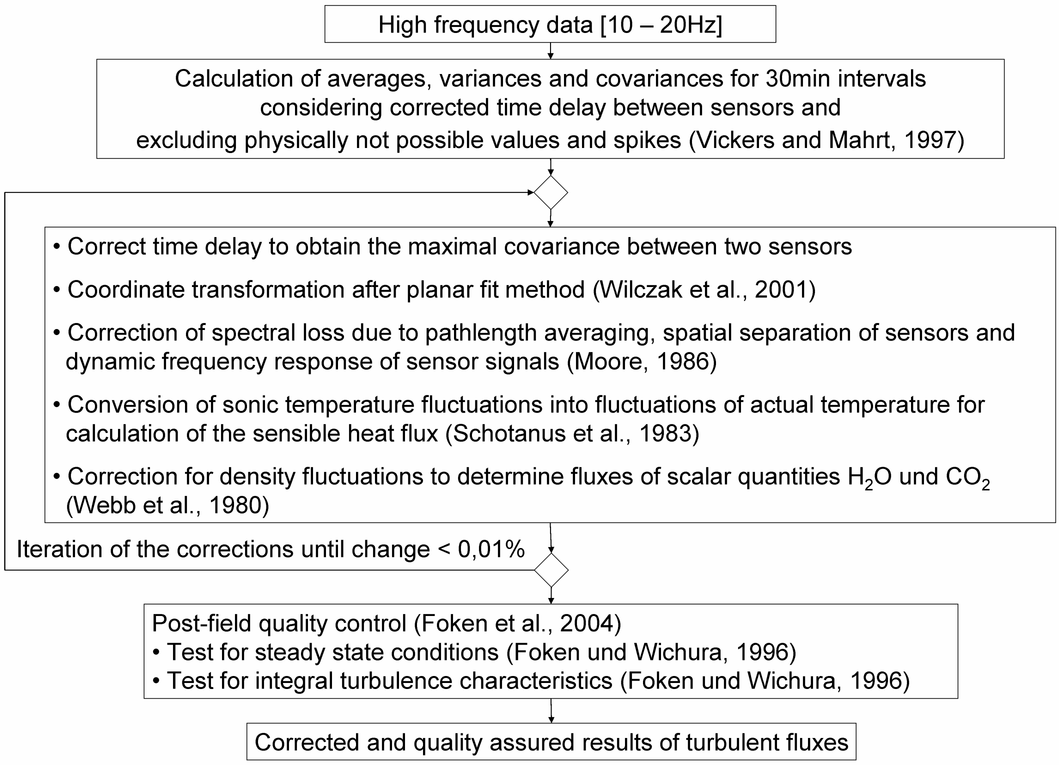

Figure 2: Scheme of the post-field data processing for this study, using a software package developed at the University of Bayreuth (MAUDER and FOKEN, 2004). It performs the entire post-processing of turbulence measurements and produces quality-assured turbulent fluxes.

3 Results

Firstly, the impact of alternative methods of data processing on the resulting turbulent fluxes will be evaluated. Then, mean turbulent flux estimates averaged over the whole measurement period and the energy balance residual will be examined.

$$residual = -(Q_s^* + Q_H + Q_E + Q_G) \tag{13}$$

Finally, the turbulent fluxes will be calculated for different averaging times.

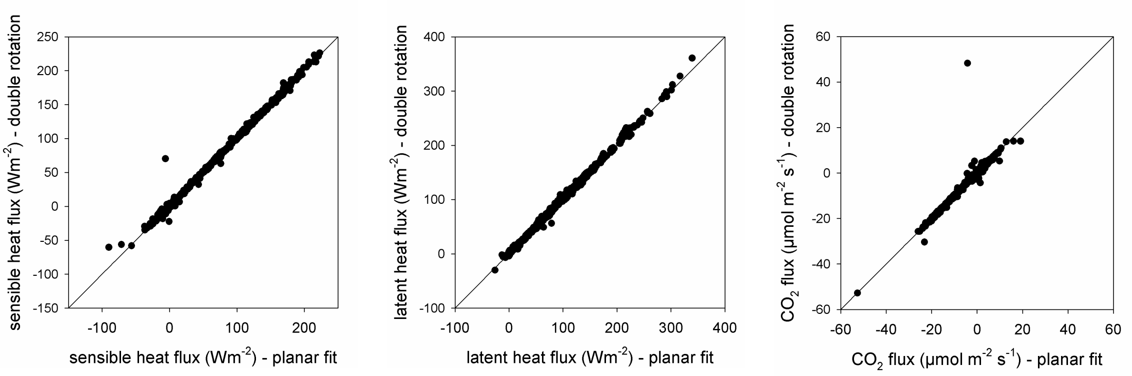

Figure 3: Comparison between tilt-corrected turbulent fluxes after the planar fit method (WILCZAK et al., 2001) and after the double rotation method (KAIMAL and FINNIGAN, 1994) for the sensible heat flux (a), the latent heat flux (b), and the CO_2 flux (c). Dataset from a selected maize site of LITFASS-2003.

3.1 Planar fit - Double rotation

The differences between the tilt correction after the planar fit method (WILCZAK et al., 2001) and the double rotation method (KAIMAL and FINNIGAN, 1994) are small for the test dataset looking at the average value of turbulent fluxes (Figure 3). However, in a few cases are very high sensible heat fluxes and CO_2-fluxes obtained by the double rotation method when the planar fit fluxes are almost zero (Figure 3a, c). Such cases occur usually during nighttime, when wind velocities are very low.

3.2 Correction for density effects

The sensible heat flux is not altered by the corrections for density effects. Only the fluxes of H_2O and CO_2 are affected. For the latent heat flux, the difference between both corrections after WEBB et al. (1980) and LIU (2005) is very little, less than 1% in average (Figure 4). Therefore the energy balance residual is almost the same, too. But LIU (2005) reduces the mean CO_2 flux by 53%, whereas the WPL correction (WEBB et al., 1980) reduces the CO_2 flux by 63%. The differences between those two methods are mostly found for daytime data with negative CO_2 fluxes, which means assimilation, as this is the time when sensible and latent heat fluxes, which these correction procedures depend on, are high. The procedure according LIU (2005) generally leads to higher estimates of CO_2 uptake than the Webb et al. approach. For our dataset, the net CO_2 uptake is 26% higher using Liu's equations. This difference is hard to see in Figure 4b. But it results from the fact that positive CO_2 fluxes remain more or less unchanged by the correction and mostly negative CO_2 fluxes are influenced. Therefore, the impact on the net resulting mean CO_2 flux is relatively large.

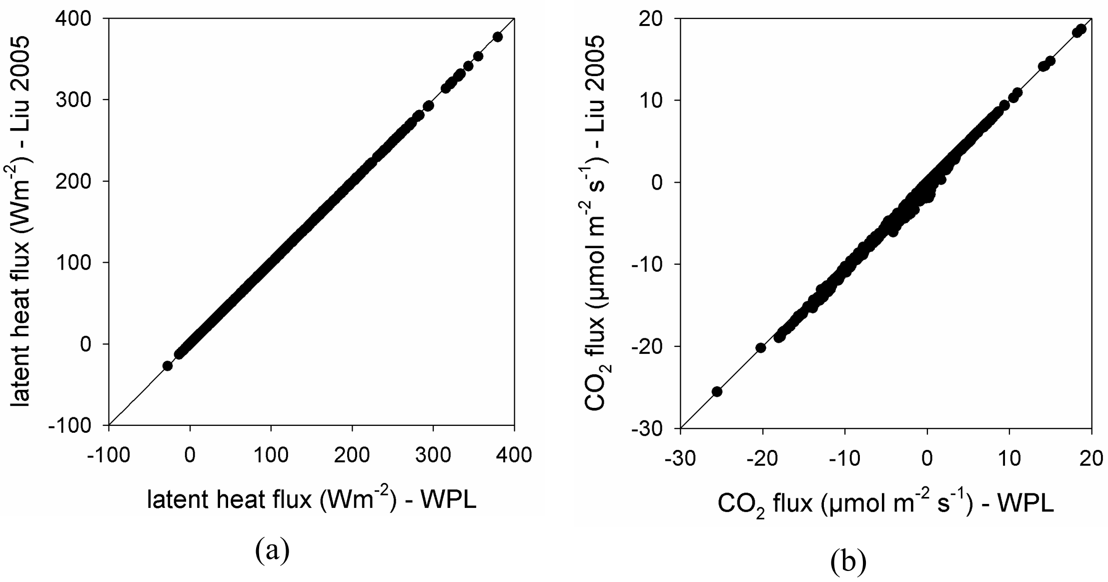

Figure 4: Comparison between density-corrected turbulent fluxes after the WPL method (WEBB et al., 1980) and after the alternative method according to LIU (2005) for the latent heat flux (a), and the CO_2 flux (b). Dataset from a selected maize site of LITFASS-2003.

3.3 Mean impact of post-field data processing steps

The completely uncorrected values averaged over the period from June 2 to June 17, 2003, were 44.4 W m^{-2} for the buoyancy flux, 61.8 W m^{-2} for the latent heat flux, 42.2 W m^{-2} for the residual, and -4.17 µmol m^{-2} s^{-1} for the CO_2 flux (Figure 5). These values don't change significantly after the spike elimination procedure. The mean latent heat flux is increased through the automatic delay time correction by 3% compared to a fixed delay time of 0.25 s. The average CO_2 flux remains almost unaffected by the time delay correction, because both positive and negative fluxes are increased, which is almost averaged out in the mean value. But the absolute value of the midday CO_2 flux is increased by 1% (Figure 5b).

In the case of this sensor set-up, the planar fit correction has only a slight impact on the resulting fluxes of less than 1%. The Moore correction increases the values for the turbulent fluxes significantly (Figure 5). The spectral loss had to be corrected through a supplement on the absolute values of the latent heat flux and the CO_2 flux, which caused an increase of the mean latent heat flux by 9.6% and 6.8% for the mean CO_2 flux. Again, the increase of both positive and negative values averages out partly for the mean CO_2 flux. The absolute values of the midday CO_2 fluxes are increased by 8.6% (Figure 5b). The Moore correction for the sensible heat flux only needed to be done because of pathlength averaging of the sonic, which leads to an increase of 1.1%. Altogether, the Moore correction of the turbulent energy fluxes decreases the mean residual by 15%.

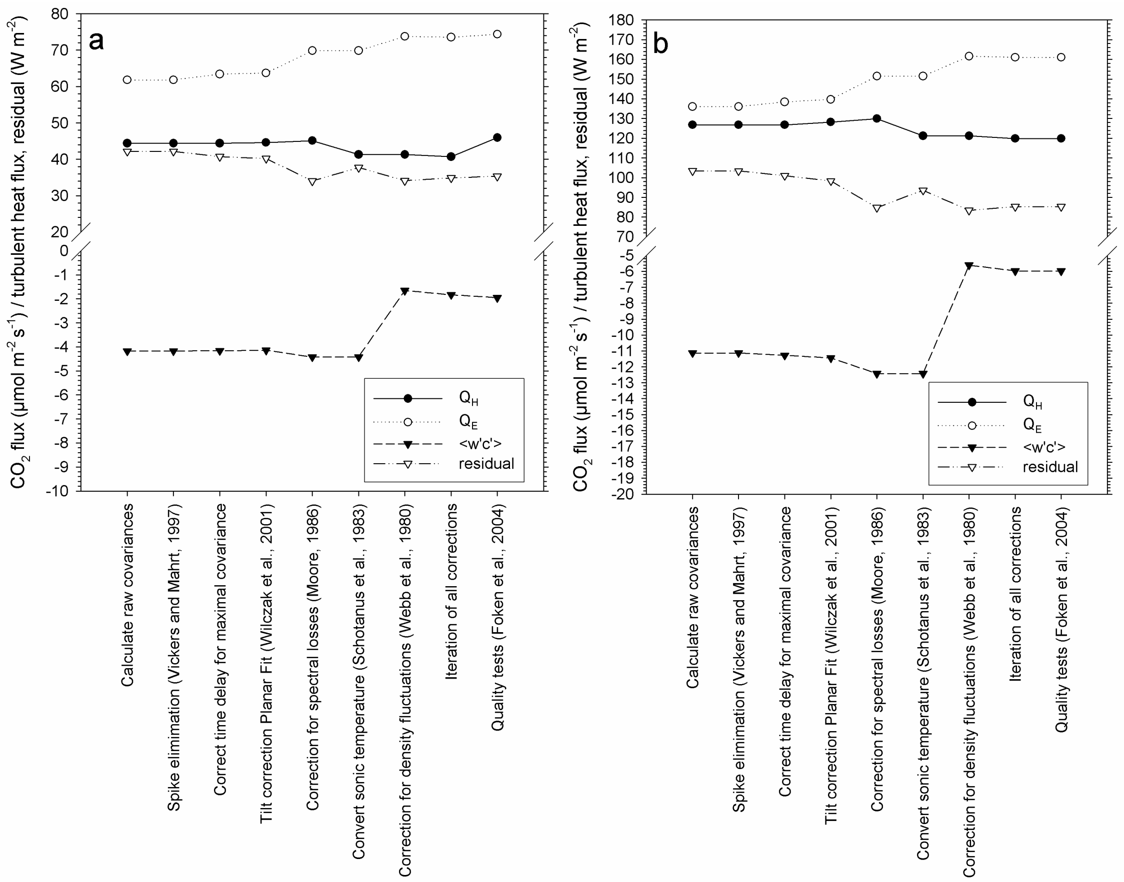

Figure 5: Impact of single post-field data processing steps on the sensible heat flux Q_H, the latent heat flux Q_E, the carbon dioxide flux $\langle w'c' \rangle$, and the surface energy balance residual, based on 30 minute averaging time, a) averaged over the entire measurement period, b) averaged over midday hours only (1200 – 1300 UTC). Dataset from a selected maize site of LITFASS-2003.

The next processing step, the Schotanus conversion, affects only the $\overline{w'T_s'}$ covariance. In this case, it decreases its average value by 8.4%, which increases the residual again by 11%. The WPL correction affects only the fluxes of the air constituents H_2O and CO_2. Unlike the Moore correction or the Schotanus conversion, it doesn't have a relative effect on the absolute flux values (Figure 6b, c). It rather shifts these fluxes into the positive direction, as also described by LIEBETHAL and FOKEN (2003; 2004) for datasets from a Californian cotton field and a German grassland site. Therefore, the positive mean latent heat flux is increased by 5.6% and the absolute value of the negative mean CO_2 flux is decreased by 63%. The mean midday CO_2 uptake estimate is even reduced by 55% through the WPL correction (Figure 5b).

The impact of the iteration is greatest for the CO_2 flux (-10% in average) because of the interdependence of its WPL correction on the sensible heat flux and the latent heat flux. The second biggest impact of the iteration was found for the mean sensible heat flux (-1.5%) due to the strong interdependence of its Schotanus correction on the latent heat flux. The impact of the iteration on the mean latent heat flux is small (-0.3%) compared to the CO_2 flux, because its relative WPL correction is also smaller. This iteration increases the mean energy balance residual by 2.3%.

The last processing step is the quality test. This procedure does not change the flux values itself but provide criteria, as to which flux values are reasonable and which are to be discarded due to violation of the assumptions of the eddy covariance method. When the turbulent flux values failed the quality tests, the corresponding energy balance residuals could not be calculated, at least if they were measured during daytime. But if they were measured during nighttime, the residuals were computed from the net radiation and the soil heat flux only, since we assume that the turbulent heat fluxes are very small during nighttime anyway. Sorting out flux values of bad quality increases the average sensible heat flux the most (+13%). The mean latent heat flux also is increased but to a minor degree (+1.1%). Since predominantly values with low fluxes and consequently low absolute residuals are sorted out, the mean residual is increased slightly (+1.3%) through this procedure. None of the midday flux data were classified as lower quality. Therefore, the values of the mean midday fluxes are not altered through the quality tests (Figure 5b).

The whole post-field data processing leads to a reduction of the mean energy balance residual of 16% (Table 1). Its average midday maximum of 133 W m^{-2} is reduced to 118 W m^{-2} (Figure 6d). This reduction is caused principally by an increase of the mean latent heat flux through the post-field data processing (+20%), whereas the overall impact on the sensible heat flux is relatively small (+4%). The biggest impact of all post-field data processing steps was found for the average negative CO_2 flux, which was approximately halved compared to raw 30 minute covariances (Table 1).

The greatest impact during the transformation of the buoyancy flux (raw data) into the sensible heat flux was found for the Schotanus conversion (Figure 6a). The latent heat flux is mainly affected by the Moore and WPL correction (Figure 6b). These are also the two processing steps of major impact on the CO_2 flux (Figure 6c).

Table 1: Overall impact of the post-field data processing on the turbulent fluxes and the energy balance residual, based on 30 minute averaging time. Dataset from a selected maize site of LITFASS-2003.

overall impact of the post-field data processing	
sensible heat flux	+4%
latent heat flux	+20%
CO_2 flux	+53%
energy balance residual	-16%

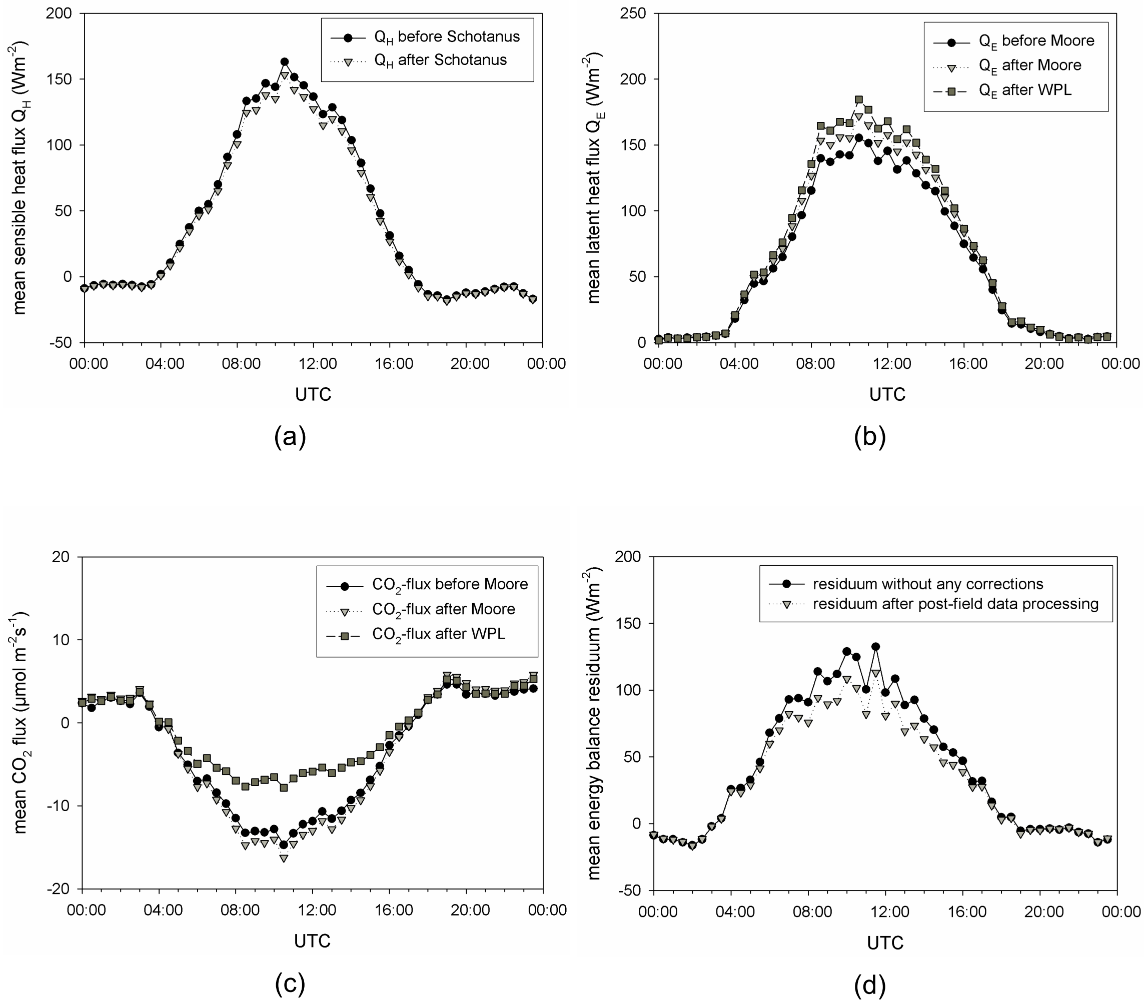

Figure 6: Average diurnal course of the sensible heat flux (a), the latent heat flux (b), the CO2 flux (c), and the energy balance residual (d) before and after processing steps of major impact, based on 30 minute averaging time. Dataset from a selected maize site of LITFASS-2003.

3.4 Flux averaging time

The turbulent fluxes of sensible and latent heat, the CO_2 flux and the energy balance residual were calculated for several averaging times between 5 and 1440 minutes (= 24 hours). The averaging time window was moved in 5 minute steps over the time series, so that these intervals were overlapping for averaging times greater than 10 minute. Therefore, we obtain a comparable number of values for all flux time series independent of the averaging time (Figure 7).

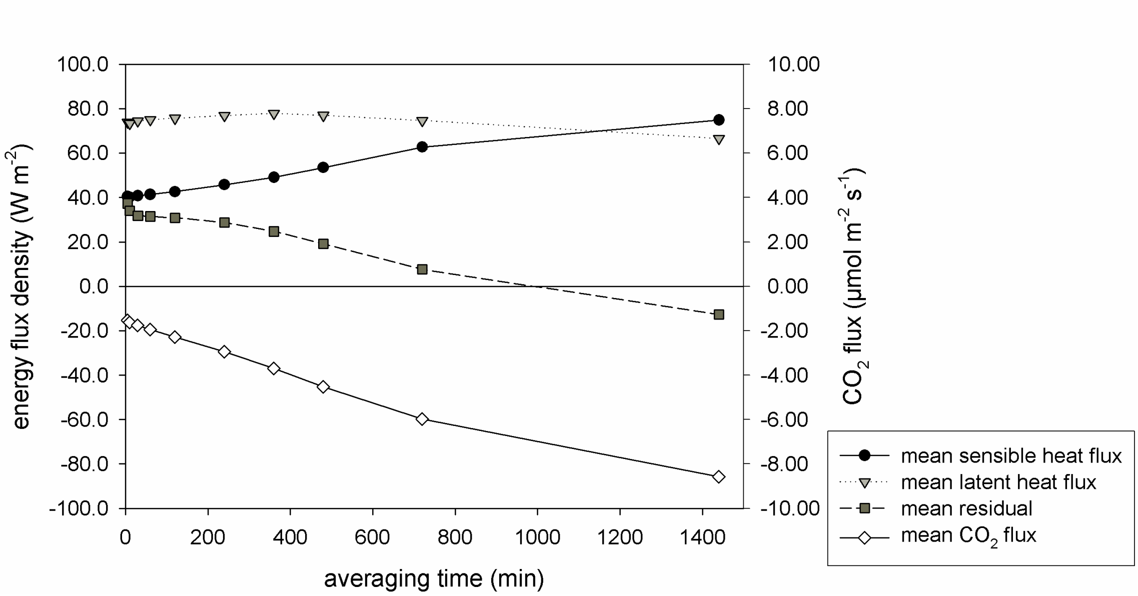

Figure 7: Mean turbulent flux estimates and the resulting energy balance residual for different averaging times. Dataset from a selected maize site of LITFASS-2003.

All flux estimates change significantly in magnitude going from 5 minute covariances to longer averaging times. The mean sensible heat flux calculated from 5 minute covariances is 40.1 W m^{-2}. It is slightly higher for the conventional 30 minute covariances (40.8 W m^{-2}) and increases further to 53.5 W m^{-2} if 480 minute covariances are averaged. The mean 1440 minutes sensible heat flux is 74.9 W m^{-2}. The mean latent heat flux increases more or less continuously, going from 5 minute covariances with 73.9 W m^{-2}, over 74.5 W m^{-2} for 30 minute covariances to 77.9 W m^{-2} for 360 minute covariances before it decreases again for longer averaging times, ending up at 66.9 W m^{-2} for 1440 minutes. We observe a continuous decrease of the resulting energy balance residual for increasing averaging times. Its value for the established 30 minute interval of 31.8 W m^{-2} in average is reduced to 7.6 W m^{-2} for an averaging interval of 720 minutes and decreases further to -12.7 W m^{-2} for 1440 minutes, which means an overbalance.

The impact of different averaging intervals on the CO_2 flux was found to be even higher than for the other two turbulent fluxes. Its mean value calculated from 5 minute covariances of -1.53 µmol m^{-2} s^{-1} decreases to -8.51 µmol m^{-2} s^{-1}, when going to 1440 minute averaging time; this means a quintuplication of the net assimilation estimate for this maize canopy. A more detailed analysis can be made looking at mean diurnal courses of the turbulent fluxes calculated with different averaging intervals (Figure 8).

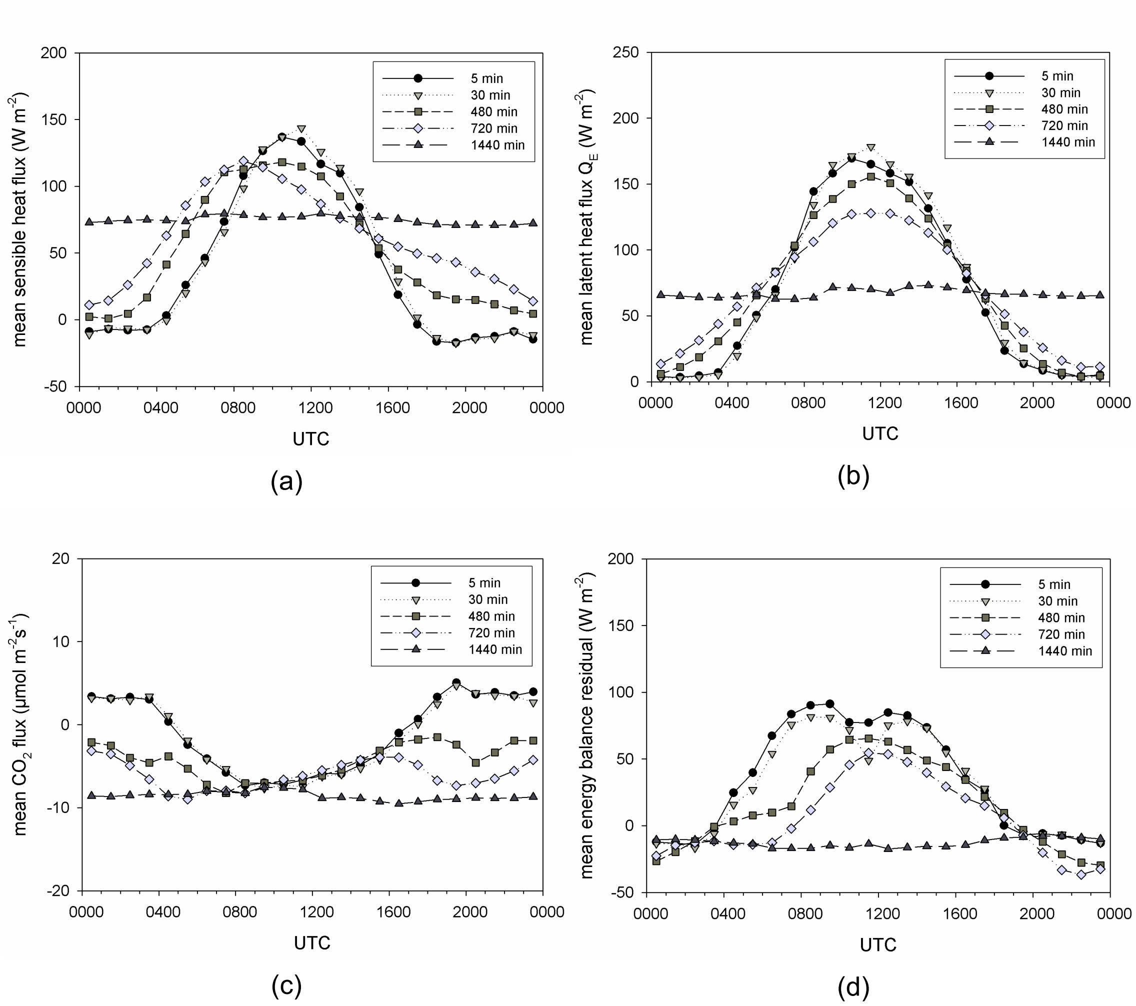

Figure 8: Average diurnal course of the sensible heat flux (a), the latent heat flux (b), the CO_2 flux (c), and the energy balance residual (d). The turbulent fluxes were calculated for different overlapping averaging intervals: 5 minutes, 30 minutes, 480 minutes, 720 minutes, and 1440 minutes. Dataset from a selected maize site of LITFASS-2003.

The mean diurnal courses of all measured turbulent fluxes are quite similar for 5 minute and 30 minute averaging intervals. The maxima of the sensible and latent heat flux are even higher for 30 minutes than for 5 minutes, which indicates additional flux contributions from wavelengths between 5 and 30 minutes. The maximum of the energy balance residual for 30 minutes is reduced compared to the 5 minute interval, and the extension of the averaging time leads to a flattened diurnal course of the net radiation and the ground heat flux, whereas the turbulent fluxes slightly increased.

It seems that all turbulent fluxes gain longwave contributions during nighttime, which can be seen from the 480 minute and 720 minute averaged covariances. For the sensible heat flux, additional long-wave flux contributions are observed in the morning hours, which also increase from 480 minute to 720 minute averaging intervals (Figure 8a). The increased energy fluxes for increasing averaging intervals reduce the resulting energy balance residual further. The surplus available energy during daytime for the traditional 30 minute interval can partly be balanced when taking into account the flux contributions from wavelengths longer than 30 minutes. Figure 8d shows that during nighttime the turbulent heat fluxes even slightly overbalance the available energy from net radiation and ground heat flux for intervals longer than 30 minutes. This indicates a missing storage term, which can be presumably found in the plant canopy, since the soil storage is already included in the ground heat flux data. But a missing storage term can only partly explain the observed behaviour of the energy balance residual, because still an average residual remains even for 720 minute intervals. However, for a 1440 minute averaging interval the residual decreases further and becomes slightly negative. Going from 720 minute to 1440 minute intervals increases the sum of the turbulent heat fluxes and therefore reduces the energy balance residual. The mean diurnal course of all turbulent fluxes and the residual is almost completely flat, since most of the variations are covered within the averaging interval for 1440 minutes or 24 hours.

4 Discussion

The post-field data processing was applied to the measurements at a certain site. Therefore, the results regarding their impact on the eddy covariance flux estimates are only partly transferable to measurements under different conditions. The dependence on the measurement set-up, the site, and the meteorological conditions will be discussed briefly.

Of course, the impact of the spike elimination procedure is dependent on the number and the magnitude of spikes in a time series. The dataset examined was almost free of spikes. Therefore, the impact of this procedure on the mean turbulent fluxes was insignificant. Spikes would have a bigger impact if they would occur in both time series of a covariance simultaneously.

The planar fit method would have a bigger impact if the sonic anemometer was misaligned or if it was standing on a slope or on top of a hill. The error of the determined rotation angle according to the double rotation method can be quite large. Especially during nighttime, when wind velocities are small, little absolute errors of the wind component measurement can result in large rotation angles, which transform real horizontal fluxes artificially into the vertical flux estimate. In contrast, the rotation angles determined from a planar fit are stable, as they are calculated for a longer time period of several days or even months and not for every half hour as in the double rotation method. Another disadvantage of the double rotation method is that it works with only two rotation axes in a three-dimensional coordinate system, which are furthermore predetermined by the arbitrary orientation of the sonic anemometer coordinate system.

The Moore correction for spectral loss in the high frequency band is strongly dependent upon the measurement set-up. Our set-up (see section 2.1) is quite typical for eddy covariance measurements over water surfaces or low vegetation. Over tall vegetation, measurement heights would generally be higher. Since eddy sizes increase with height, the impact of the Moore correction will be smaller there.

The impact of the WPL correction that we found for our dataset is more than twice as big as in the study by LIEBETHAL and FOKEN (2003; 2004) for experiments over irrigated cotton and mountainous grassland. The differences between these experiments can be ascribed to higher Bowen ratios during LITFASS-2003 (Figure 1) than during the other two experiments examined in LIEBETHAL and FOKEN (2003; 2004).

Unlike the CSAT3 that we used for the measurements of LITFASS-2003, other sonic anemometers do not implement a cross-wind correction in their internal processing (e.g. Solent R2 and Metek USA-1). If that was the case, the cross-wind term of the equations proposed by SCHOTANUS et al. (1983) and LIU et al. (2001) would have to be applied in addition to equation 6. This processing step would then cause a larger decrease of the $\overline{w'T_s'}$ covariance.

One critical issue regarding the extension of the averaging time to 24 hours is, weather the stationarity criterion is still fulfilled. The weak stationarity definition, which is applied here, requires that mean values μ and variances σ^2 are time-invariant. Clearly, both μ and σ^2 can be dependent on the length of the averaging interval. Looking at a turbulent time series, it will always make a difference if μ and σ^2 are calculated for 10 seconds, 10 minutes or 10 hours. But once μ and σ^2 are determined for a certain averaging time, these values must not change when the averaging interval is shifted over the time series in order to fulfil the stationarity criterion.

For the standard 30 minute interval the stationarity criterion is often fulfilled, as it covers the micro-turbulent transport, which is met at frequencies > 10^{-3} Hz (e.g. FOKEN, 2003). On the other hand, the changes due to the diurnal course usually happen on longer wavelengths than 30 minutes. Averaging times longer than 30 minutes, e.g. 2 or even 6 hours, often contain a trend in the time series. Certainly, a two hour nighttime temperature average will in most cases be significantly different from a two hour average around midday. In this case, the stationarity criterion would be violated. But the stationarity criterion will often be fulfilled again for an averaging time of 24 hours, because day to day averages and variances of parameters like wind velocity, temperature or humidity usually don't differ that much. The whole diurnal course is contained completely within a 24 hour interval. Only general weather changes could cause larger differences, e.g. the passage of a front. This could be tested in the dataset with a simple trend analysis, equivalent to the stationarity test of VICKERS and MAHRT (1997).

According to our findings, when increasing averaging time, the classic model spectra (KAIMAL et al., 1972; HØJSTRUP, 1981) are not valid for this dataset, since we observe much more longwave contributions. Therefore, the Moore correction that we applied is probably too high. In order to make a worst case estimation, we calculated the 1440 minute eddy covariance fluxes completely without the Moore correction. This resulted in a mean energy balance residual of -6.7 W m^{-2} compared to -12.7 W m^{-2} with the whole Moore correction. The real mean residual must be somewhere in between these two values. The mean CO_2 flux without the Moore correction is -7.6 µmol m^{-2} s^{-1} instead of -8.6 µmol m^{-2} s^{-1} with the Moore correction. The approach presented by MASSMAN and CLEMENT (2004) could be a solution to cope with such spectra with very low frequency flux contributions. This method probably has to be adopted site-specifically.

5 Conclusions

The whole data processing starting from 30 minute covariances reduced the energy balance residual by 16%. The Moore and the WPL correction are the most relevant procedures for this reduction of the energy balance closure problem, as they increase the latent heat flux estimates.

Furthermore, the mean energy balance residual could be drastically reduced by taking into account flux contributions from wavelengths longer than the conventional 30 minutes. The energy balance could almost be closed for a 24 hour averaging time. Only a mean residual between -6.7 W m^{-2} and -12.7 W m^{-2} remained, depending on the validity of the Moore correction.

The presence of these additional longwave flux contributions can probably be attributed to the distinct heterogeneity in the surrounding of this site, because KANDA et al. (2004) identified inhomogeneous heating from the surface as a major reason for the development of turbulent organised structures of very long time scale.

This issue of averaging or integration interval seems to be crucial for the energy balance closure problem and requires further investigations with more datasets from different sites and possibly other methods like the analysis of ogives.

CO_2 flux measurements are of special interest for carbon cycle studies in the context of global warming, e.g. FLUXNET (BALDOCCHI et al., 2001). Of all the processing steps, the correction due to density effects (-63%) had by far biggest impact on the CO_2 flux. Two alternative methods for this correction were evaluated. The approach recently proposed by LIU (2005) leads to a 26% increased net assimilation estimate compared to the traditional WPL correction for the test dataset. LIU (2005) takes into account the expansion/compression of moist air and not only dry air like WEBB et al. (1980) do, which sounds more realistic and reasonable. As for the other turbulent fluxes, the selection of an adequate averaging time is also critical for the CO_2 flux, since the net assimilation is more than quintupled going from the classical 30 minute covariances to 24 hour averaging time.

References

ARYA, S. P., 2001: Introduction to Micrometeorology, - Academic Press, San Diego, 415 p.

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, - Advances in Ecological Research **30**, 113-175.

BALDOCCHI, D., FALGE, E., GU, L. H., OLSON, R., HOLLINGER, D., RUNNING, S., ANTHONI, P., BERNHOFER, C., DAVIS, K., EVANS, R., FUENTES, J., GOLDSTEIN, A., KATUL, G., LAW, B., LEE, X. H., MALHI, Y., MEYERS, T., MUNGER, W., OECHEL, W., U, K. T. P., 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 vapor, and energy flux densities, - Bull. Am. Meteorol. Soc. **82**, 2415-2434.

BERNHARDT, K., and PIAZENA, H., 1988: Zum Einfluß turbulenzbedingter Dichteschwankungen auf die Bestimmung turbulenter Austauschströme in der Bodenschicht, - Z. Meteorol. **38**, 234-245.

BEYRICH, F., ADAM, W., BANGE, J., BEHRENS, K., BERGER, F. H., BERNHOFER, C., BÖSENBERG, J., DIER, H., FOKEN, T., GÖCKEDE, M., GÖRSDORF, U., GÜLDNER, J., HENNEMUTH, B., HERET, C., HUNEKE, S., KOHSIEK, W., LAMMERT, A., LEHMANN, V., LEITERER, U., LEPS, J.-P., LIEBETHAL, C., LOHSE, H., LÜDI, A., MAUDER, M., MEIJNINGER, W. M. L., MENGELKAMP, H.-T., QUECK, R., RICHTER, S. H., SPIEß, T., TITTEBRAND, A., WEISENSEE, U., and ZITTEL, P., 2004: Verdunstung über einer heterogener Landoberfläche. Das LITFASS-2003 Experiment. Deutscher Wetterdienst, Forschung und Entwicklung, Offenbach, Arbeitsergebnisse **79**, 100 p.

CHRISTEN, A., VAN GORSEL, E., VOGT, R., ANDRETTA, M., and ROTACH, M., 2001: Ultrasonic anemometer instrumentation at steep slopes: Wind tunnel study - field comparison - measurements, - In: MAP Meeting 2001, Schliersee, Germany, 4.

CULF, A. D., FOKEN, T., and GASH, J. H. C., 2004: The energy balance closure problem, - In: KABAT, P. and CLAUSSEN, M., (Eds.), Vegetation, Water, Humans and the Climate. A New Perspective on an Interactive System, 159-166. - Springer, Berlin, Heidelberg.

DYER, A. J., 1981: Flow distortion by supporting structures, - Boundary-Layer Meteorol. **20**, 363-372.

EUGSTER, W., and SENN, W., 1995: A cospectral correction model for measurements of turbulent NO_2 flux., - Boundary-Layer Meteorol. **74**, 321-340.

FINNIGAN, J. J., CLEMENT, R., MALHI, Y., LEUNING, R., and CLEUGH, H. A., 2003: A re-evaluation of long-term flux measurement techniques, Part I: Averaging and coordinate rotation, - Boundary-Layer Meteorol. **107**, 1-48.

FINNIGAN, J. J., 2004: A re-evaluation of long-term flux measurement techniques, Part II: Coordinate systems, - Boundary-Layer Meteorol. **113**, 1-41.

FOKEN, T., DLUGI, R., and KRAMM, G., 1995: On the determination of dry deposition and emission of gaseous compounds at the biosphere-atmosphere interface, - Meteorol. Z. **4**, 91-118.

FOKEN, T., and ONCLEY, S. P., 1995: Workshop on instrumental and methodical problems of land surface flux measurements, - Bull. Am. Meteorol. Soc. **76**, 1191-1193.

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, Heidelberg, 289 p.

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, 181-208. - Kluwer, Dordrecht.

FOKEN, T., WIMMER, F., MAUDER, M., THOMAS, C., and LIEBETHAL, C., 2005: Some aspects of the energy balance closure problem, - Atmos. Chem. Phys. Discuss., submitted.

FUEHRER, P. L., and FRIEHE, C. H., 2002: Flux corrections revisited, - Boundary-Layer Meteorol. **102**, 415-457.

GASH, J. H. C., and DOLMAN, A. J., 2003: Sonic anemometer (co)sine response and flux measurement: I. The potential for (co)sine error to affect sonic anemometer-based flux measurements, - Agric. For. Meteorol. **119**, 195-207.

HÖGSTRÖM, U., and SMEDMAN, A.-S., 2004: Accuracy of sonic anemometers: Laminar wind-tunnel calibrations compared to atmospheric in situ calibrations against a reference instrument, - Boundary-Layer Meteorol. **111**, 33-54.

HØJSTRUP, J., 1981: A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux, - Boundary-Layer Meteorol., 341-356.

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

HORST, T. W., 2000: On frequency response corrections for eddy covariance flux measurements, - Boundary-Layer Meteorol. **94**, 517-520.

KAIMAL, J. C., WYNGAARD, J. C., IZUMI, Y., and COTÉ, O. R., 1972: Spectral characteristics of surface layer turbulence, - Quart. J. Roy. Meteorol. Soc. **98**, 563-589.

KAIMAL, J. C., GAYNOR, J. E., ZIMMERMAN, H. A., and ZIMMERMAN, G. A., 1990: Minimizing flow distortion errors in a sonic anemometer, - Boundary-Layer Meteorol. **53**, 103-115.

KAIMAL, J. C., and FINNIGAN, J. J., 1994: Atmospheric Boundary Layer Flows: Their Structure and Measurement, - Oxford University Press, New York, NY, 289 p.

KANDA, M., INAGAKI, A., LETZEL, M. O., RAASCH, S., and WATANABE, T., 2004: LES study of the energy imbalance problem with eddy covariance fluxes, - Boundary-Layer Meteorol. **110**, 381-404.

LEE, X., MASSMAN, W., and LAW, B. E. (Eds.), 2004: Handbook of micrometeorology. A guide for surface flux measurement and analysis, - Kluwer Academic Press, Dordrecht, 250 p.

LEUNING, R., 2004: Measurements of trace gas fluxes in the atmosphere using eddy covariance: WPL correction revisited, - In: LEE, X., MASSMAN, W. J. and LAW, B. E., (Eds.), Handbook of Micrometeorology. A Guide for Surface Flux Measurement and Analysis, 119-132. - Kluwer, Dordrecht.

LIEBETHAL, C., and FOKEN, T., 2003: On the significance of the Webb correction to fluxes, - Boundary-Layer Meteorol. **109**, 99–106.

LIEBETHAL, C., and FOKEN, T., 2004: On the significance of the Webb correction to fluxes. Corrigendum, - Boundary-Layer Meteorol. **113**, 301.

LIEBETHAL, C., HUWE, B., and FOKEN, T., 2005: Sensitivity analysis for two ground heat flux calculation approaches, - Agric. For. Meteorol., DOI: 10.1016/j.agrformet.2005.08.001.

LIU, H., 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.

LIU, H., 2005: An alternative approach for CO_2 flux correction caused by heat and water vapour transfer, - Boundary-Layer Meteorol. **115**, 151–168.

MAHLI, Y., MCNOUGHTON, K. G., and VON RANDOW, C., 2004: Low frequency atmospheric transport and surface flux measurements, - In: LEE, X., MASSMAN, W. J. and LAW, B., (Eds.), Handbook of Micrometeorology. A Guide for Surface Flux Measurement and Analysis, 101-118. - Kluwer, Dordrecht.

MASSMAN, W. J., and LEE, X., 2002: Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges, - Agric. For. Meteorol. **113**, 121-144.

MASSMAN, W. J., and CLEMENT, R., 2004: Uncertainty in eddy covariance flux estimates resulting from spectral attenuation, - In: LEE, X., MASSMAN, W. J. and LAW, B. E., (Eds.), Handbook of Micrometeorology. A Guide for Surface Flux Measurement and Analysis, 67-99. - Kluwer, Dordrecht.

MAUDER, M., and FOKEN, T., 2004: Documentation and instruction manual of the eddy covariance software package TK2. Universität Bayreuth, Abt. Mikrometeorologie, Arbeitsergebnisse **26**, 44 p. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

MAUDER, M., LIEBETHAL, C., GÖCKEDE, M., LEPS, J.-P., BEYRICH, F., and FOKEN, T., 2006: Processing and quality control of flux data during LITFASS-2003, - Boundary-Layer Meteorol., revised.

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., and VERHOEF, A., 1997: A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide, - J. Hydrol. **188-189**, 589-611.

MOORE, C. J., 1986: Frequency response corrections for eddy correlation systems, - Boundary-Layer Meteorol. **37**, 17-35.

ONCLEY, S. P., 1989: Flux parametrization techniques in the atmospheric surface layer. Ph.D. Thesis, University of California, Irvine, CA, 202 p.

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.

SAKAI, R. K., FITZJARRALD, D. R., and MOORE, K. E., 2001: Importance of low-frequency contributions to eddy fluxes observed over rough surfaces, - J. Appl. Meteorol. **40**, 2178-2192.

SCHOTANUS, P., NIEUWSTADT, F. T. M., and DEBRUIN, H. A. R., 1983: Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations, - Boundary-Layer Meteorol. **26**, 81-93.

STULL, R. B., 1988: An Introduction to Boundary Layer Meteorology, - Kluwer Acad. Publ., Dordrecht, Boston, London, 666 p.

VAN DER MOLEN, M. K., GASH, J. H. C., and ELBERS, J. A., 2004: Sonic anemometer (co)sine response and flux measurement: II. The effect of introducing an angle of attack dependent calibration, - Agric. For. Meteorol. **122**, 95-109.

VICKERS, D., and MAHRT, L., 1997: Quality control and flux sampling problems for tower and aircraft data, - J. Atm. Oceanic Tech. **14**, 512-526.

VOGT, R., 1995: Theorie, Technik und Analyse der experimentellen Flussbestimmung am Beispiel des Hartheimer Kiefernwaldes. University of Basel, Basel, Switzerland, Stratus **3**, 101 p.

WEBB, E. K., PEARMAN, G. I., and LEUNING, R., 1980: Correction of the 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, K., GOLDSTEIN, A., FALGE, E., AUBINET, M., BALDOCCHI, D., BERBIGIER, P., BERNHOFER, C., CEULEMANS, R., DOLMAN, H., and FIELD, C., 2002: Energy balance closure at FLUXNET sites, - Agric. For. Meteorol. **113**, 223-243.

WYNGAARD, J. C., 1981: The effects of probe-induced flow distortion on atmospheric turbulence measurements, - J. Appl. Meteorol. **20**, 784-794.

Appendix E

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Surface Energy Flux Measurements at a Tropical Site in West Africa during the Transition from Dry to Wet Season

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Summary

In one of the first micrometeorological experiments at a tropical site in West Africa, direct measurements of all surface energy balance components were carried out. The experiment NIMEX-1 in Ile-Ife, Nigeria (7°33'N, 4°33'E), was conducted from February 19, 2004 to March 9, 2004, during the transition from the dry to the wet season. Three typical weather situations could be observed: firstly, monsoonal winds from southwest blew over desiccated soils. Almost 100% of the available energy at the surface was transformed into the sensible heat flux. Secondly, after several thundershowers, monsoonal winds swept over soils of increased water content, which led to a partitioning of the available energy corresponding to Bowen ratios between 0.3 and 0.5. Thirdly, harmattan winds advected dry dusty air from northern directions, which reduced the incoming shortwave radiation. Again, Bowen ratios range from 0.3 and 0.5 during daytime, whereas latent heat fluxes are still high during nighttime due to a distinct oasis effect. No systematic unclosure of the surface energy balance could be found for the NIMEX-1 dataset. Unlike other experiments in Europe, most of the ogives for the sensible and latent heat flux were found to be convergent during NIMEX-1 in Ile-Ife. This can be attributed to the homogeneity of the surrounding bush, which lacks the defined borders found in agriculturally cultivated landscapes.

1. Introduction

Energy exchange processes at the earth's surface are the driving forces in the atmospheric boundary layer. Measurements of these processes can improve our understanding of the global climate system. These measurements are carried out at many sites representing different geo-ecological conditions and are often organised in international programs like FLUXNET (Baldocchi et al. 2001). But still surface energy flux data from less developed countries especially in Africa are underrepresented. For the Sahel-zone the HAPEX-Sahel experiment (Goutorbe et al. 1994; Goutorbe et al. 1997) produced a valuable dataset. These turbulent heat fluxes were measured using the eddy covariance

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method for different sites representing typical Sahelian ecosystems (Lloyd et al. 1997). Especially the tiger bush, an area of patterned woodland, was investigated intensively (Culf et al. 1993; Blyth and Harding 1995; Kabat et al. 1997; Wallace and Holwill 1997). The energy exchange processes in regions closer to the equator would also be of high interest.

Typical for the climate in tropical West Africa is the interplay between monsoon and harmattan winds, which meet at the Intertropical Convergence Zone (ITCZ). Usually, the monsoon is linked to southerly wind directions and the advection of moist marine air masses from the Gulf of Guinea to the area of the West African countries. In this context we speak of the wet season, which lasts roughly from April to October in this area. The dry season from November to March is determined by winds blowing from northeasterly directions, advecting a cold, dry and often dusty continental air mass from the Saharan desert or sub-Saharan regions. These northeasterly trade winds are locally known as harmattan (Adedokun 1978; Balogun 1981; Nieuwolt 1982).

The circulation patterns over West Africa are of special interest, as they are an object of global teleconnections (Janicot et al. 1998). They are also influenced by El Niño events according to a general circulation model study by Camberlin et al. (2001). Dry conditions in the wet months of July to September can occur occasionally over West Africa close to the surface position of the ITCZ as a result of El Niño, since such events tend to result in enhanced northeasterlies/reduced monsoon flow. Moreover, this region recently was the focus of scientific interest in context of studies on the global water cycle GLOWA (van de Giesen et al. 2001) because the availability of water is a critical factor in the development of the sub-humid and semi-arid countries of West Africa. Often land degradation is connected with a changing water regime (Xue et al. 2004). This region is especially short of water resources at the end of the dry season, when people expect the first rain. In a model study about this spring to summer transition of the West African monsoon, Fontaine et al. (2002) stressed the key role of surface energy budgets and their horizontal gradients in the boundary layer. The soil moisture distribution seems to be responsible for anomalies during these transitions (Cook 1994). To substantiate these results, further micrometeorological in-situ measurements in this region are desirable.

Up to now, none of the experiments to investigate surface energy fluxes in tropical West Africa measured all components of the energy balance directly. Most of them (e.g. Jegede et al. 1997; Balogun et al. 2002a) made use of the flux-gradient similarity and the assumption of a closed energy balance for the Bowen-Ratio method (Bowen 1926; Fuchs and Tanner 1970 ; Ohmura 1982). During one experiment (Balogun et al. 2002b), the Modified Bowen-Ratio technique (Liu and Foken 2001) was also applied. In this comparison of two Bowen-ratio methods, at least the sensible heat flux was measured by the eddy covariance method directly. However, the latent heat flux was still deter-

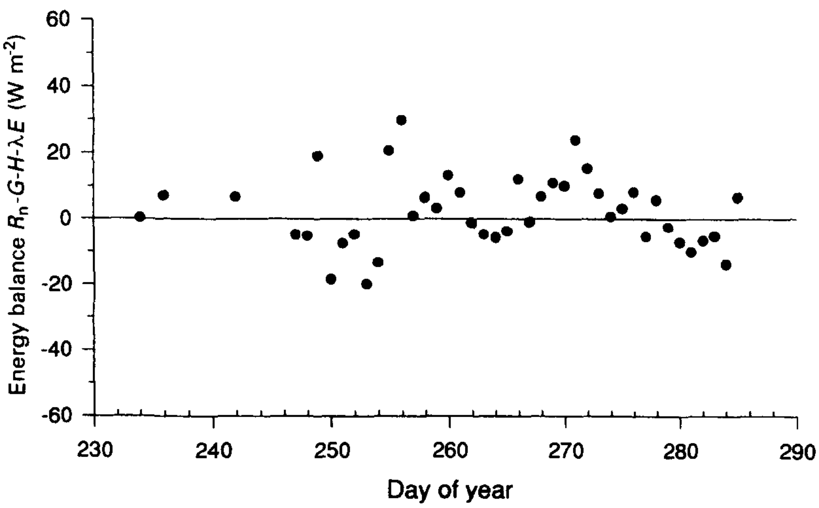

Fig. 1: Energy balance closure for the eddy correlation system at the fallow savannah site (Kabat et al. 1997).

mined using the flux-gradient similarity because no fast-response hygrometer was available during earlier experiments. Thus, it was not possible to study the problems of the experimental energy balance closure (Culf et al. 2004) for a tropical site, because direct surface measurements for all energy fluxes were unavailable until now. Further north in the Sahel-zone (Kabat et al. 1997), the data didn't show a systematic bias in energy balance closure (Fig. 1) as we know it from measurements in temperate latitudes of Europe and North America (e.g. Wilson et al. 2002; Culf et al. 2004). An energy balance experiment in tropical West Africa can open up further perspectives on the issue of experimental energy balance closure under different geo-ecological conditions.

In view of this scientific background, a micrometeorological experiment in Nigeria, NIMEX-1, was organised (Jegede et al. 2004a). It provides direct measurements of all components of the energy balance at the surface during the transition from the dry to the wet season. These measurements will be discussed in the context of the meteorological conditions over West Africa during the measurement period in February and March of 2004.

2. Experiment description

2.1. Measurement site

The measurement site for NIMEX-1 was located on an experimental field of the Obafemi Awolowo University, Ile-Ife, Nigeria (7°33'N, 4°33'E). It is 135 km away from the Gulf of Guinea coast. The climate in this region can be classified as Aw after Köppen (Essenwanger 2001), i.e. tropic with a dry season in winter and a wet season in summer. The NIMEX-1 experimental site comprised an area of five hectares of flat terrain at an elevation of 288 m a.s.l. (Fig. 2). Its vegetation can be characterised as fallow

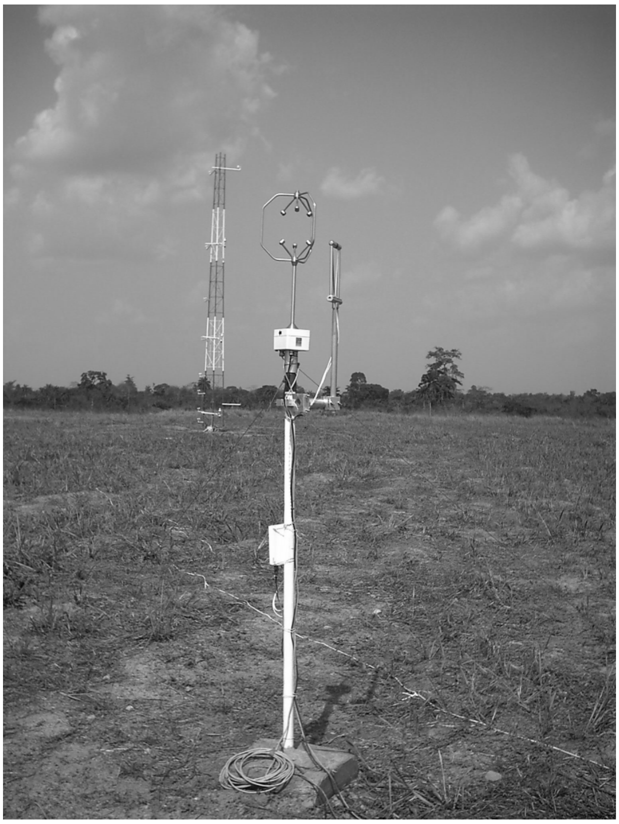

Fig. 2. NIMEX-1 field site with the eddy covariance system in the front consisting of a Metek USA-1 sonic anemometer together with a Campbell KH20 krypton hygrometer (2.48 m above ground level). The 15 m profile tower can be seen in the background.

bush-land of 0.30 m canopy height, which is the target area of the investigation. The canopy consisted primarily of low shrubs. This field site is surrounded by areas also covered by shrubs as well as sporadically higher bushes and trees. The eddy covariance flux measurements were carried out in the period from February 19, 2004, to March 9, 2004, whereas the profile and radiation measurements were carried out beyond this intensive observation period.

Considering a measurement height of 2.48 m for the eddy covariance system, we assumed that for most situations a large proportion of the measured turbulent flux can be attributed to this field. This was checked by a footprint analysis based on Göckede et al. (2005). Table 1 shows the flux contribution from the target area in percent depending on the stability parameter *z/L* and on wind direction, where *z* is the aerodynamic measuring height and *L* is the Obukhov length.

Table 1. Contribution of the measured eddy covariance flux from the target area in %, according to a footprint analysis based on Göckede et al. (2005).

	Wind direction (°)																							
z/L	0	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345
-0.2	100	100	100	100	100	100	100	99	97	91	90	83	92	94	99	100	100	100	100	100	100	100	100	100
-0.1	95	99	100	99	100	99	99	94	86	84	82	87	86	88	90	98	100	99	99	97	100	97	93	97
0	94	90	95	98	93	97	98	87	84	82	83	83	86	82	88	97	99	93	98	93	93	95	88	87
0.1	90	92	97	91	88	93	93	87	77	77	72	77	80	78	83	92	92	90	93	93	91	84	82	87
0.2	89	85	88	91	87	87	92	79	80	73	62	69	77	73	76	88	86	87	92	86	85	82	78	78

Under unstable stratification ($z/L < 0$) for most wind directions, the flux contribution from the target area is higher than 90%. Under neutral conditions ($z/L = 0$), the flux contribution from the target area is always higher than 80%. For stable stratifications ($z/L > 0$), the footprint area is larger in general and includes the surrounding bush-land. Consequently, in this case the flux contribution from the target area is smaller. We find the smallest flux contribution from the target area (62%) of all calculated cases for $z/L = 0.2$ at a wind direction of 150° (SSE), where the border of the field is closest to the eddy covariance station.

In addition to the turbulent heat fluxes, the ground heat flux and net radiation were measured, in order to determine each term of the energy balance equation (1) independently. The energy balance is defined

$$-Q_s^* = Q_H + Q_E + Q_G, \tag{1}$$

where Q_s^* is net radiation, Q_H is sensible heat flux, Q_E is latent heat flux, Q_G is ground heat flux.

Table 2. Instrumentation of NIMEX-1 for the measurements presented in this paper.

parameter	**sensor**	**measurement height above ground level**	**sampling rate**	**averaging interval**
ground heat flux (W m^{-2})	Hukseflux HFP01SC self-calibrating heat flux plate	-0.02 m	1Hz	1 min
net radiation (W m^{-2})	Kipp&Zonen CNR1 net radiometer	1.92 m	1Hz	1 min
sensible heat flux (W m^{-2})	Metek USA-1 3-D ultrasonic anemometer	2.48 m	16Hz	30 min
latent heat flux (W m^{-2})	Campbell Sci. KH20 krypton hygrometer	2.43 m	8Hz	30 min
temperature (° C)	T. Friedrichs Frankenberger psychrometer	0.94 m 4.88 m	1Hz	1 min
humidity (hPa)	T. Friedrichs Frankenberger psychrometer	0.94 m 4.88 m	1Hz	1 min
volumetric soil moisture (%)	Campbell Sci. CS616 water content reflectometer	-0.05 m	1Hz	1 min

The net radiation was measured by a Kipp&Zonen CNR1 net radiometer. The sensible and the latent heat flux were measured by a Metek USA-1 sonic anemometer and a Campbell KH20 krypton hygrometer. The ground heat flux was measured at a depth of 0.02 using a self-calibrating heat flux plate, which allows incorporation the soil's actual thermal conductivity (Liebethal et al. 2005). The heat storage of the uppermost thin soil layer and of the vegetation was not measured during this experiment. We assume that there is a small amount of heat storage in the uppermost soil layer and in the vegetation. But this is considered to be small compared to the surface energy fluxes, as this heat storage has little mass.

Basic atmospheric and soil parameters were measured, too. The instrumentation used for this investigation is listed in Table 2. We set a high value on the quality of the selected instruments in order to obtain a reliable dataset. For more details see Jegede et al. (2004a; 2004b).

2.2. Data analysis and quality assessment

The data acquisition and reduction was realised using CR10X dataloggers from Campbell Scientific and PCs using programmes developed at the Obafemi Awolowo University, Ile-Ife and the University of Bayreuth. The data from slow response sensors were sighted daily and simple visual quality tests were performed (Foken 2003). For the eddy covariance data analysis, the comprehensive software package TK2 (Mauder and Foken 2004) was used in order to apply all necessary corrections and quality tests on the data. This programme considers the recommendations of Lee et al (2004) and applies them to a standardised routine. It implements the following processing steps:

- elimination of electronically and meteorologically non-plausible values
- detection of spikes according to Vickers and Mahrt (1997) based on Højstrup (1993)
- determination of the time delay between hygrometer and sonic using cross-correlations analysis
- cross-wind correction of the sonic temperature according to Liu et al.(2001)
- planar Fit method for coordinate transformation (Wilczak et al. 2001)
- spectral corrections according to Moore (1986) using spectral models by Kaimal et al. (1972) and Højstrup (1981)
- conversion of the buoyancy flux into sensible heat flux according to Schotanus et al. (1983) and Liu et al. (2001)
- correction of the latent heat flux for density fluctuations and for mean vertical mass flow after Webb et al. (1980)
- iteration of the correction steps because of their interdependence
- quality control, applying tests for steady state conditions and well-developed turbulence (Foken and Wichura 1996; Foken et al. 2004)

3. Results of the measurements and interpretation

3.1. Weather and soil conditions

During the intensive observation period of NIMEX-1, basically two different wind conditions prevailed. From February 23 to March 4, 2004, winds from south-southwest were dominant (Fig. 3a). The resultant wind vector for this time period pointed to 205°. Under these monsoonal wind conditions, moist air was advected from the Gulf of Guinea, which is reflected in high absolute humidity values of approximately 20 g m^{-3} at the NIMEX-1 site in Ile-Ife (Fig. 4). With temperature maxima around 35° C and minima around 25° C, this resulted in maximal water vapour deficits between 5 and 10 hPa at noon. During nighttime, water vapour deficits went down to almost zero (Fig. 4).

In the course of March 4, 2004, the wind direction changed. From March 5 till the end of the experiment on March 9, winds from north and north-northeast prevailed. The resultant wind vector for this period pointed to a direction of 5° (Fig. 3b). Under these harmattan-like conditions, dry and dusty air was advected from Saharan and Sahelian areas north of the measurement site in Ile-Ife. Temperatures became a few degrees lower. Absolute humidity dropped drastically to a level of approximately 5 to 10 g m^{-3}. The resulting water vapour deficits were almost twice as high as before March 4. From March 5 to March 7, even during nighttime, water vapour deficits didn't fall below 5 hPa (Fig. 4). While humidity decayed, the content of particles in the air increased drastically. The sun was hardly visible behind a veil of dust. Visibility was down to less than 500 m.

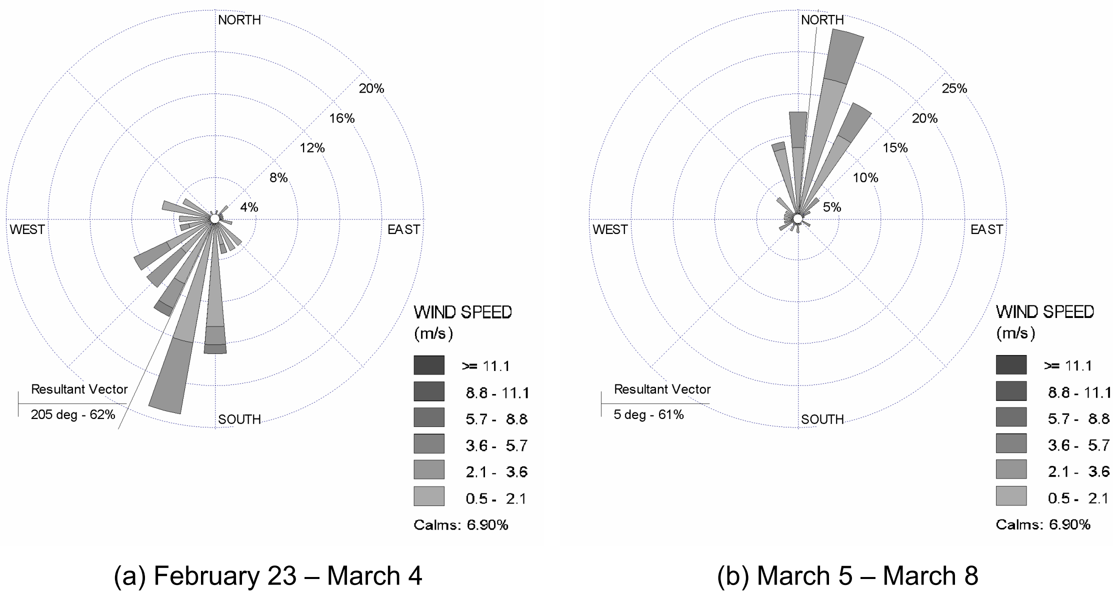

Fig. 3. Wind distribution during the NIMEX-1 experiment for two sub-periods of opposite wind directions in Ile-Ife, Nigeria.

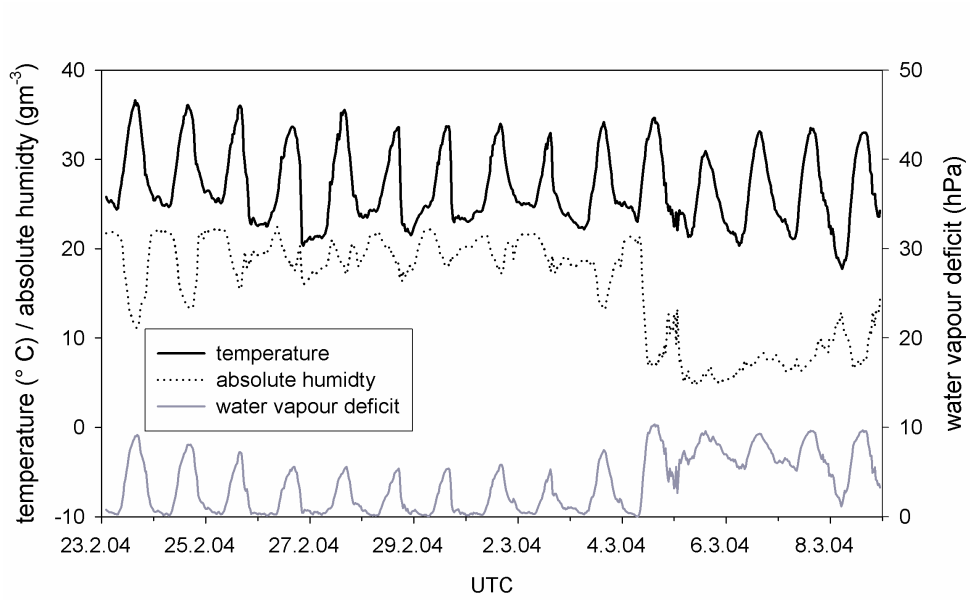

Fig. 4. Temperature, absolute humidity and water vapour deficit during NIMEX-1 in Ile-Ife, Nigeria.

At the beginning of NIMEX-1, after several weeks without precipitation during the dry season, soils at the measurement site were desiccated. The volumetric soil moisture levelled off at 5% (Fig. 5), which equals the permanent wilting point of the on-site loamy sand (AGBoden 1994). Thunderstorms in the late afternoon of February 25 and the following days were accompanied by considerable rainfalls (Fig. 5). These increased the volumetric soil moisture to approximately 15% on March 1. Thenceforward, the soil moisture decreased again due to evaporation and reached a level of 8% until March 9.

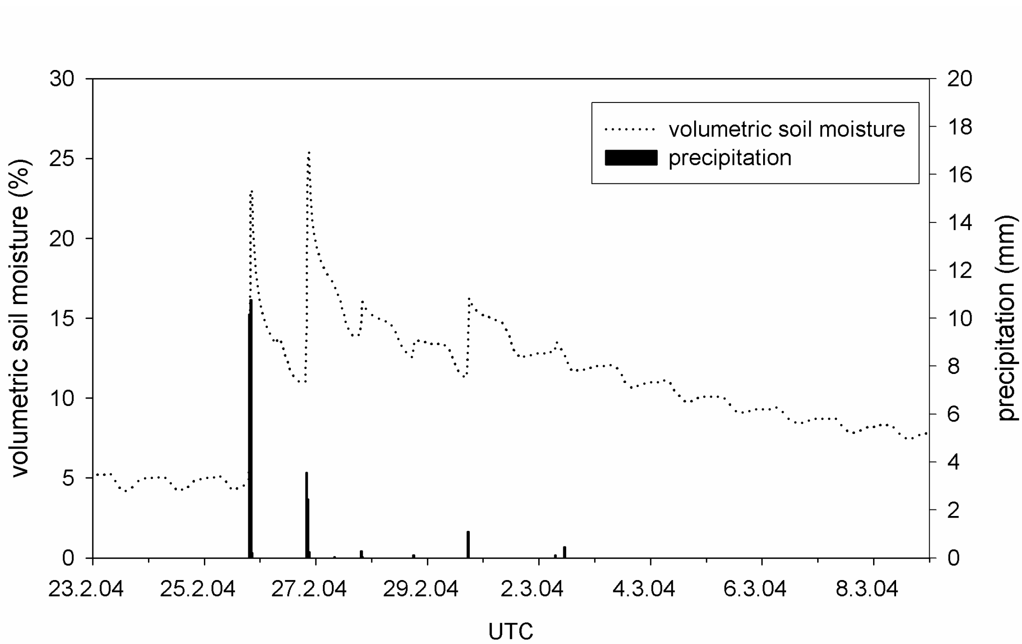

Fig. 5. Volumetric soil moisture and precipitation aggregated to 30 minutes during NIMEX-1 in Ile-Ife, Nigeria.

3.2. Radiation and energy fluxes

For a detailed analysis of the surface energy balance, three days were selected. They represent three sub-periods of different typical soil and weather conditions during the transition from the dry to the wet season. The first sub-period from February 23 to February 25, 2004, was characterised by dry soils, monsoonal winds from south-southwest, advection of moist marine air, cirrus uncinus and cirrostratus perlucidus clouds. For reasons of data availability and quality, February 23 was selected as exemplary for this sub-period. Through the haze during that time, the downwelling shortwave radiation reached values down to -850 W m^{-2} at noon (Fig. 6). With an albedo of 0.24 maximal 200 W m^{-2} were reflected as upwelling shortwave radiation. The downwelling longwave radiation, which was emitted by low clouds and moist haze or the clear sky, reached its minimum in the evening at 1900 UTC with values around -480 W m^{-2}. Predominantly wilted plants acted as emitting surfaces for the upwelling longwave radiation. Its maximum value of almost 600 W m^{-2} was reached one hour before at 1600 UTC. This equals a maximal surface temperature of almost 50° C.

The second sub-period lasted from February 26 to March 4, 2004. The main difference compared to the preceding sub-period was the increased soil moisture due to repeated thundershowers. Furthermore, the cloud cover changed slightly. Hence, more scattered cloudiness due to cumuli and sometimes cumulonimbi in the afternoons were to be met. March 3, 2004, was selected to represent this sub-period. The scattered cloudiness increased the downwelling shortwave radiation, which now reached values down to -900 W m^{-2} (Fig. 6). Meanwhile, the albedo had decreased to a value of 0.18 due to the greening of the plant canopy. Consequently, only maximal 160 Wm^{-2} was reflected as upwelling shortwave radiation. Unfortunately, the longwave radiation time series shows a data gap in the afternoon of March 3, when we expect their maximal values.

The third sub-period from March 5 to the end of NIMEX-1 on March 9, 2004, can be distinguished from the previous ones because of different wind conditions. Hence, harmattan winds from north to north-northeast prevailed. Dusty and dry air was advected. March 6, 2004, can be used to represent the conditions during this sub-period exemplarily. Because of the dense dust veil, the downwelling shortwave radiation was reduced and reached only -745 W m^{-2} by noon of that day (Fig. 6). The albedo had increased again to a value of 0.21. Thus, maximal 155 W m^{-2} shortwave radiation were reflected from the slightly desiccated plants. Again, the course of the longwave radiation didn't behave significantly different from the previous days of NIMEX-1.

Changing cloudiness and albedo conditions lead to different net radiation during the three sub-periods of NIMEX-1. Therefore, the available energy for the turbulent heat fluxes also differed. On February 23 we observed net radiation values down to -455 W m^{-2} at noon (Figure 7). Considering a maximal soil heat flux of 135 Wm^{-2}, an

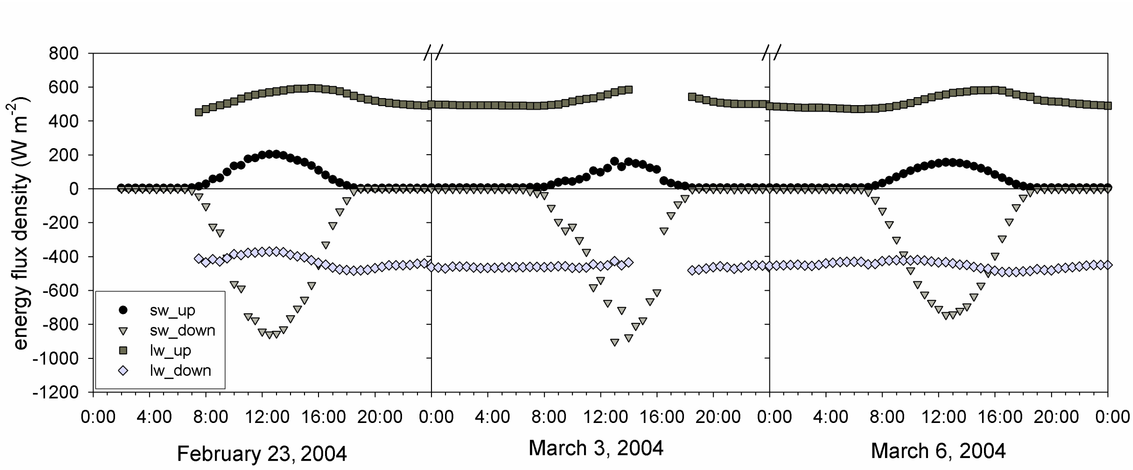

Fig. 6: Radiation components on three selected days during NIMEX-1 representing three different typical soil and weather conditions. (sw_up: upwelling shortwave radiation, sw_down: downwelling shortwave radiation, lw_up: upwelling longwave radiation, lw_down: downwelling longwave radiation)

amount of maximal 320 Wm^{-2} was available for the turbulent energy fluxes. On that day, the available energy was almost completely transformed into sensible heat. Sensible heat fluxes reached a maximum value of 320 W m^{-2} at 1230 UTC, which is equal to the maximal available energy. The latent heat flux slowly increased in the course of that morning to a level around 50 W m^{-2} but collapsed already at 1200 UTC because no more soil water was available for evapotranspiration. On February 23 the energy balance residual scattered around zero with a daily average of -7 W m^{-2}.

The net radiation curve for March 3, 2004, showed some scatter due to the cloud conditions and reached a maximum amount of almost -600 W m^{-2}, which is 145 W m^{-2} more negative than one week before (Figure 7). The soil heat flux was higher, too. It reached a high of nearly 180 W m^{-2}. Consequently, at most 420 W m^{-2} was available for the turbulent energy fluxes. Now, with sufficient soil moisture for evapotranspiration, latent heat flux values reached up to 320 W m^{-2} at 1300 UTC. At the same time, the sensible heat flux was 102 W m^{-2}. The sensible heat flux had its maximum half an hour later at 1330 UTC with 140 W m^{-2}, when the latent heat flux was only 270 W m^{-2}. This is tantamount to Bowen ratios between 0.3 and 0.5. Anyhow, in both cases the energy balance is practically closed, when you allow a measurement uncertainty of 10 W m^{-2}. The daily averaged residual was -13 W m^{-2} on that day.

Under the harmattan conditions of March 6, 2004, net radiation was lower again. It reached values as low as -465 W m^{-2} on that day (Figure 7). Its diurnal course ran smoothly because of the presence of a constant dust veil and the absence of clouds. With soil heat fluxes as high as 130 W m^{-2}, an amount of maximal 335 W m^{-2} was available for the turbulent energy exchange. The latent heat flux reached its maximum value of 240 W m^{-2} at 1530 UTC quite late on that day. The sensible heat flux had its maximum of 110 W m^{-2} already at 1300 UTC. Again, Bowen ratios ranged between 0.3 and

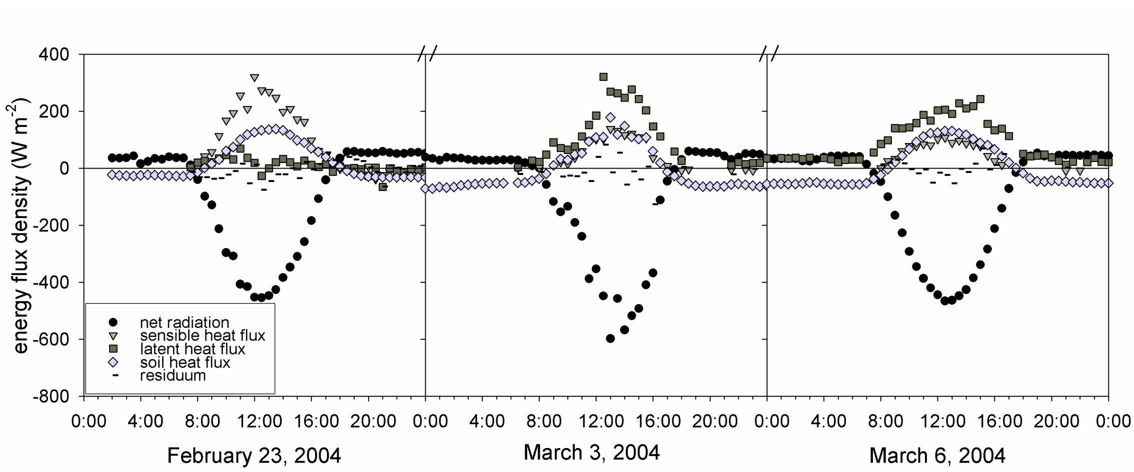

Fig. 7. Directly measured energy balance components on three selected days during NIMEX-1 representing three different typical soil and weather conditions:
February 23, 2004, with low soil moisture, low nighttime water vapour deficit, SSW winds;
March 3, 2004, with high soil moisture, low nighttime water vapour deficit, SSW winds;
March 6, 2004, with high soil moisture, high nighttime water vapour deficit, SSW winds.

0.5, and the energy balance was closed quite well with a little scatter around zero. Its daily average was only 2 W m^{-2}. Unlike the other two sub-periods, on that day the latent heat fluxes didn't fall to zero during nighttime. They remained on a level of 20 to 40 W m^{-2}. High water vapour deficits due to advection of dry air drove evapotranspiration even without radiative forcing during nighttime – a typical oasis effect.

In order to go deeper into the issue of energy balance closure at the NIMEX-1 site, one can plot the sum the turbulent heat fluxes against the available energy at the surface (Fig. 8). For this purpose we look at the whole NIMEX-1 intensive observation period, since we didn't find significant differences between the three sub-periods regarding the energy balance closure. The data scatter with a coefficient of determination R^2 of 0.97 more ore less around the 1:1 line. The slope of the regression line is 0.95 with a positive intercept of 3.2 W m^{-2}. A slight tendency for the turbulent fluxes to be smaller than the available energy can be seen. But this is not significant.

4. Discussion

To understand the good energy balance closure during NIMEX-1, one should recall the reasons given for non-closure during other experiments in the literature (Culf et al. 2004). One reason can be measurement errors associated with the individual instruments. For the NIMEX-1 energy balance measurements, we tried to avoid such errors by choosing high quality sensors, which were well-calibrated, well-tested and well-maintained (see Table 2). Problems of different footprint areas of the eddy covariance,

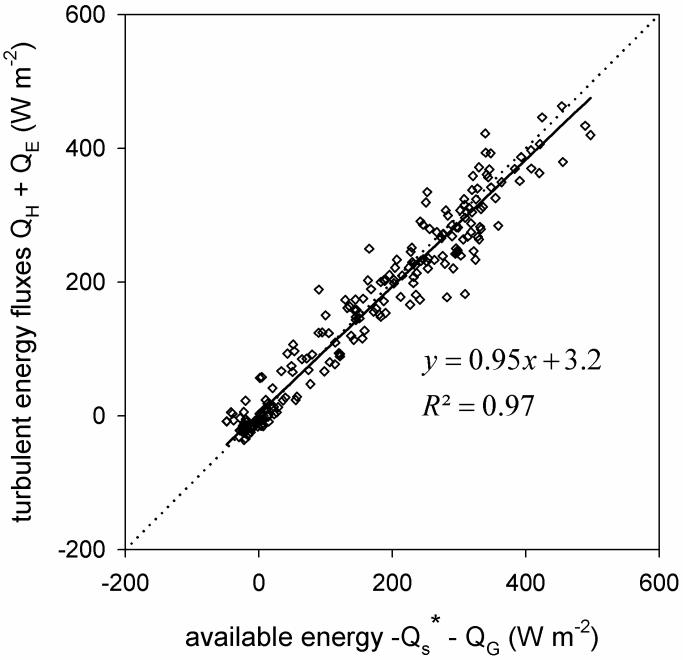

Fig. 8. Turbulent energy fluxes versus available energy during NIMEX-1 and linear regression.

the radiation and the soil measurements could also be minimised on this quite uniform field site (see section 2.1). Calculation and data analysis errors were counteracted through the use of a comprehensive standardised software package (see section 2.2).

But even with the minimisation and prevention of these sources of errors for surface energy flux measurements, often the energy balance does not close (Aubinet et al. 2000; Mauder et al. 2005; Oncley et al. 2005). Another possible reason for a non-closed surface energy balance is the operation of eddy covariance measurements in non-homogeneous terrain (Panin et al. 1998; Culf et al. 2004). Heterogeneous terrain can induce instationarities or long-scale turbulent fluxes, which impair the eddy covariance method. Ogive functions (Oncley 1989; Foken et al. 1995) can be used to detect such problems. Foken et al. (2005) applied this method to data from the inhomogeneous terrain of the LITFASS-2003 experiment (Beyrich and Mengelkamp 2005), where the energy balance could be experimentally closed by only 69% (Mauder et al. 2005). They found misbehaviour of the ogive functions to be a good indicator for such energy balance closure problems.

We also calculated ogive functions for the whole NIMEX-1 intensive observation period as cumulative integral over 150 minutes for the covariances of sonic temperature $\overline{w'T'}$ and humidity $\overline{w'a'}$.

$$Og_{w,x}(f_0) = \int_{\infty}^{f_0} Co_{w,x}(f)\, df \qquad (2)$$

The three different cases for the behaviour of the ogive functions according to Foken et al. (2005) were defined in Table 3. In the ideal convergent case, the ogive function increases during integrating from high frequencies to low frequencies until a certain value is reached and remains on a more or less constant plateau before a 30 minute integration time. If this condition is fulfilled, the 30 minute covariance is a reliable estimate for the turbulent flux, because we can assume that the whole turbulent spectrum is covered within that interval and that there are only negligible flux contributions from longer wavelengths (case 1). Because of the variability of spectra we tolerate deviations of 10% for the plateau value when defining case 1 (Table 3). Fig. 9 can serve as an example for this case. But it can also occur that the ogive function shows an extreme value and decreases again afterwards (case 2) or that the ogive function doesn't show a plateau but is increasing throughout (case 3). Ogive functions corresponding to case 2 or 3 indicate that a 30 minute flux estimate is possibly inadequate.

Ogive functions were determined for 150 minute integration periods. Adjacent periods overlap each other by 120 minutes. Periods containing too large data gaps or spikes were excluded for this spectral analysis method (Table 4). Regarding the temperature

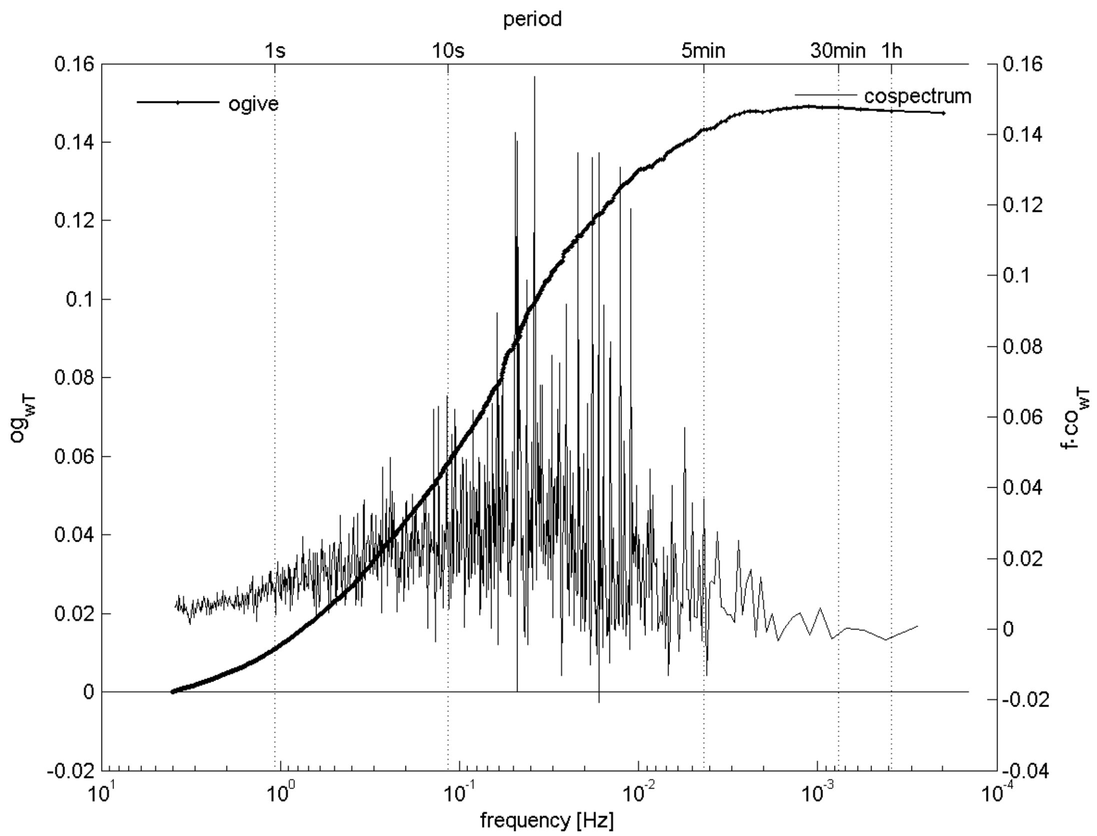

Fig. 9. Example of a convergent ogive function and the cospectrum for $\overline{w'T'}$ from the NIMEX-1 experiment (March 2, 2004, 1200 – 1330 UTC).

Table 3. Definition of three different cases for the behaviour of ogive functions.

case		criterion
1	convergent ogives within the 30 minute interval	$\frac{\lvert Og(150\,\text{min})\rvert}{\max\lvert Og\rvert} > 0.9$ and $\frac{\lvert Og(30\,\text{min})\rvert}{\max\lvert Og\rvert} > 0.9$
2	ogives with a distinct extreme value before a 150 minute integration time	$\frac{\lvert Og(150\,\text{min})\rvert}{\max\lvert Og\rvert} \le 0.9$
3	not convergent ogive even for 150 minutes	$\frac{\lvert Og(30\,\text{min})\rvert}{\max\lvert Og\rvert} \le 0.9$ and $\frac{\lvert Og(150\,\text{min})\rvert}{\max\lvert Og\rvert} > 0.9$

covariance $\overline{w'T'}$ 177 ogives could be analysed. 143 of them (81%) were classified as convergent (case 1), 28 (16%) ogives as case 2, and 6 (3%) as case 3. Most of the non-convergent ogives were found at times when the sensible heat flux has a negative sign, which occurred in the late afternoons and during nighttime. Under these stable stratifications, turbulent fluxes were small anyway and therefore not relevant for the energy balance closure problem.

188 ogives could be analysed for the humidity covariance $\overline{w'a'}$, of which 158 (84%) were classified as convergent (case 1). 15 (8%) were determined as case 2, and another 15 (8%) ogives were found to fit case 3. Again, most of the non-convergent cases occurred during stable nighttime conditions. Some non-convergent daytime ogives were found on March 4, 2004. As pointed out above, on this day the wind direction changed from southwest to northeast. The highly instationary humidity field of this day is probably the reason for the non-convergence of these ogives. Possibly, the relatively good energy balance closure during NIMEX-1 can be attributed to the relatively large proportion of convergent ogives (Table 4); whereas for LITFASS-2003, large energy balance residuals were related to nonconvergent ogives (Foken et al. 2005).

Table 4. Number of convergent ogives (case 1), ogives with an extreme value (case 2), and nonconvergent ogives (case 3) for NIMEX-1 and the ogives of fluxes of sensible heat (Og_{wT}) and latent heat (Og_{wa}).

	case 1	case 2	case 3
Og_{wT}	143	28	4
Og_{wa}	158	15	15

A comparison of satellite images from the NIMEX-1 and the LITFASS-2003 shows the different characteristics of these two dissimilar landscapes. The image of the NIMEX-1 area (Fig. 10a) shows the city of Ile-Ife in the south surrounded by uniform bush-land almost without any distinguishable structuring. On the other hand, the LITFASS-2003 is characterised by a large forest area in the west and agricultural land in the east, with several lakes of different size in between (Fig. 10b). On a smaller scale, the agricultural land is sub-divided in distinct patches of different crops. These have clearly defined borders, which generate sudden changes in surface parameters like aerodynamic roughness height, surface temperature and soil moisture. Such sudden changes can hardly be identified in the NIMEX-1 area.

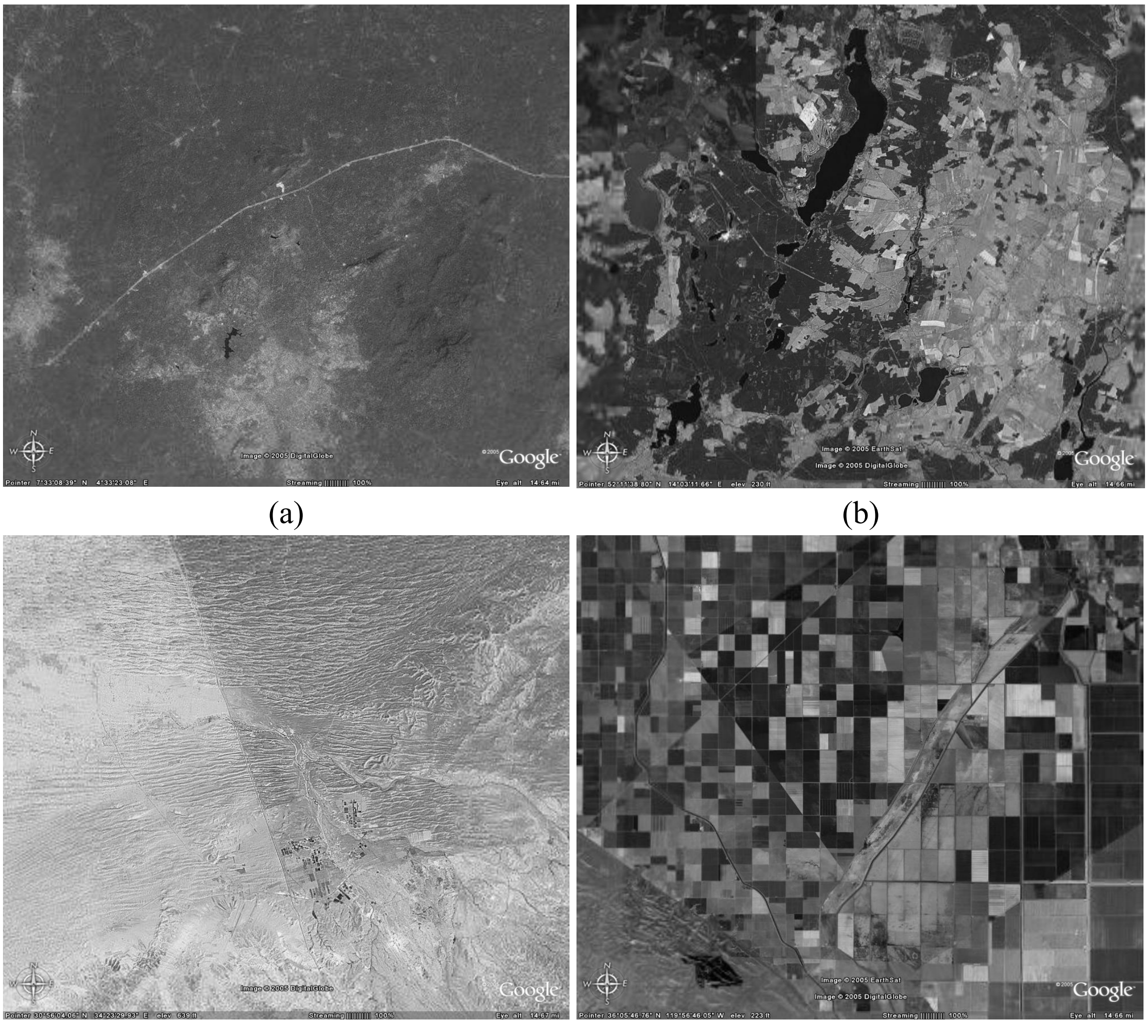

Fig. 10. Visible band satellite images from the (a) NIMEX-1 area around Ile-Ife, Nigeria, (b) the LITFASS-2003 area around Lindenberg, Germany, (c) the Negev desert nearby Nizzana, Israel, and (d) the EBEX-2000 nearby Kettleman City, California area. The experiment sites are located approximately in the centres of the images. The same zoom-factor is applied for all images; they cover an area of approx. 27 x 23 km (Google 2005).

A surface energy balance study by Heusinkveld et al. (2004) can serve as another example for the relevance of landscape's homogeneity for the surface energy balance closure. These measurements were carried out in the Israeli Negev desert (30°56' N, 34°23' E, 190 m a.s.l.). This area is quite homogeneous and features no anthropogenic borders due to cultivation (Fig. 10c). Although in other geo-ecological respects the conditions were completely different there, the energy balance could also nearly be closed experimentally with a residual of the 96% of the net radiation. In contrast, the energy balance experiment EBEX-2000 in California (Fig. 10d) had a midday energy balance residual of 110 W m^{-2} (16% of net radiation). The patches in California are larger than in the Lindenberg area, but nevertheless very sharp borders can be seen between them as in the Lindenberg area.

5. Conclusions

NIMEX-1 provides a data set of excellent quality for surface energy flux measurements, which can be used for further research like calibration and validation of atmospheric models.

Surface energy fluxes under the three prevailing weather conditions of monsoon and harmattan could be analysed in their context of air and soil parameters. In Ile-Ife, harmattan conditions are typical for the dry season between the beginning of December and the beginning of February. After regular monsoon conditions at the end of February and significant thundershowers at the beginning of March indicating the upcoming wet season, the wind direction changed on March 4. Harmattan conditions returned, which led to a distinct oasis effect in Ile-Ife.

No systematic bias of the energy balance closure could be found for the NIMEX-1 data set. Most of the ogives of the sensible and the latent heat flux were convergent under the conditions of this site in tropical West Africa, which show that the assumptions of the eddy covariance method regarding stationary conditions and absence of horizontal advection were fulfilled. The good energy balance closure could be attributed to the homogeneity of the terrain surrounding the NIMEX-1 experiment site. There are no distinct borders like those between different patches of an agriculturally cultivated landscape. However, such heterogeneities occur in Europe or North America, where the experimental surface energy balance closure is often worse. Furthermore, a large proportion of convergent ogives was found for NIMEX-1 indicating that, most of the times, the entire turbulent flux is recovered within the traditional 30 minute covariances. This supports the thesis that heterogeneity-induced longwave flux contributions are responsible for experimental energy balance closure problems. More data of further experiments should be analysed under this aspect.

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References

Adedokun, JA (1978) West African precipitation and dominant atmospheric mechanisms. Arch. Meteorologie Geoph. Biokl., Ser A. 27: 289 - 310

AGBoden (1994) Bodenkundliche Kartieranleitung, 4. Aufl. E. Schweizerbart'sche Verlagsbuchhandlung, Hannover, 392 pp.

Aubinet, M et al. (2000) Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Advances in Ecological Research 30: 113-175

Baldocchi, D et al. (2001) FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc. 82: 2415-2434

Balogun, AA, Jegede, OO, Foken, T, Olaleye, JO (2002a) Estimation of sensible and latent heat fluxes over bare soil using bowen ratio energy balance method at a humid tropical site. J. African Meteorol. Soc. 5: 63-71

Balogun, AA, Jegede, OO, Foken, T, Olaleye, JO (2002b) Comparison of two Bowen-ratio methods for the estimation of sensible and latent heat fluxes at Ile-Ife. J. African Meteorol. Soc. 5: 63-69

Balogun, EE (1981) Convective activity over Nigeria during the monsoon. Proceedings of the International Conference on Early Results of FGGE and Large Scale Aspects of Its Monsoon Experiments, Tallahassee, Florida, January, 12-17, 22-27.

Beyrich, F, Mengelkamp, H-T (2005) Evaporation over a heterogeneous land surface: EVA_GRIPS and the LITFASS-2003 experiment - an overview. Boundary-Layer Meteorol.: submitted (LITFASS-2003 Special Issue)

Blyth, EM, Harding, RJ (1995) Application of aggregation models to surface heat flux from the Sahelian tiger bush. Agric. For. Meteorol. 72: 213-235

Bowen, IS (1926) The ratio of heat losses by conduction and by evaporation from any water surface. Physical Review 27: 779-787

Camberlin, P, Janicot, S, Poccard, I (2001) Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic vs. ENSO. International Journal of Climatology 21: 973-1005

Cook, KH (1994) Mechanisms by which surface drying perturbs tropical precipitation fields. J. Climate 7: 400-413

Culf, AD, Allen, SJ, Gash, JHC, Lloyd, CR, Wallace, JS (1993) Energy and water budgets of an area of patterned woodland in the Sahel. Agric. For. Meteorol. 66: 65-80

Culf, AD, Foken, T, Gash, JHC (2004) The energy balance closure problem. In: P Kabat, M Claussen (Editors), Vegetation, Water, Humans and the Climate. A New Perspective on an Interactive System. Springer, Berlin, Heidelberg, pp. 159-166.

Essenwanger, OM (2001) Classification of Climates. Elsevier, Amsterdam, 113 pp.

Foken, T, Dlugi, R, Kramm, G (1995) On the determination of dry deposition and emission of gaseous compounds at the biosphere-atmosphere interface. Meteorol. Z. 4: 91-118

Foken, T, 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, Heidelberg, 289 pp.

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

Foken, T, Wimmer, F, Mauder, M, Thomas, C, Liebethal, C (2005) Some aspects of the energy balance closure problem. Atmos. Chem. Phys. Discuss.: submitted

Fontaine, B, Philippon, N, Trzaska, S, Roucou, P (2002) Spring to summer changes in the West African monsoon through NCEP/NCAR reanalyses (1968-1998). J. Geophys. Res. 107: 4186

Fuchs, M, Tanner, CB (1970) Error analysis of Bowen ratios measured by differencial psychrometry. Agricultural Meteorology 7: 329-334

Göckede, M, Markkanen, T, Hasager, CB, Foken, T (2005) Update of footprint-based approach for the characterisation of complex measurement sites. Boundary-Layer Meteorol.: accepted

Google (2005) Google Earth. www.google.com.

Goutorbe, JP, Lebel, T, Dolman, AJ, Gash, JHC, Kabat, P, Kerr, YH, Monteny, B, Prince, SD, Stricker, JNM, Tinga, A, Wallace, JS (1997) An overview of HAPEX-Sahel: A study in climate and desertification. J. Hydrol. 188-189: 4-17

Goutorbe, J-P et al. (1994) HAPEX-Sahel: A large-scale study of land-atmosphere interactions in the semi-arid tropics. Ann. Geophys. 12: 53-64

Heusinkveld, BG, Jacobs, AFG, Holtslag, AAM, Berkowicz, SM (2004) Surface energy balance closure in an arid region: role of soil heat flux. Agric. For. Meteorol. 122: 21-37

Højstrup, J (1981) A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux. Boundary-Layer Meteorol.: 341-356

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

Janicot, S, Harzallah, A, Fontaine, B, Moron, V (1998) West African Monsoon Dynamics and Eastern Equatorial Atlantic and Pacific SST Anomalies (1970–88). J. Climate 11: 1874-1882

Jegede, OO, Fasheun, TA, Adeyefa, ZD, Balogun, AA (1997) The effect of atmospheric stability on the surface-layer characteristics in a low-wind area of tropical West Africa. Boundary-Layer Meteorol. 85: 309-323

Jegede, OO et al. (2004a) The Nigerian Micrometeorological Experiment (NIMEX-1): An Overview. Ife J. Sci. 6: 191-202

Jegede, OO, Okogbue, EC, Balogun, EE (Editors) (2004b) Proceedings of the workshop on the Nigerian Micrometeorological Experiment. July 15, 2004 at Ile-Ife, Nigeria. Comfort Press and Publishing Co., Ikeja-Lagos, Nigeria, 66 pp.

Kabat, P, Dolman, AJ, Elbers, JA (1997) Evaporation, sensible heat and canopy conductance of fallow savannah and patterned woodland in the Sahel. J. Hydrol. 188-189: 494-515

Kaimal, JC, Wyngaard, JC, Izumi, Y, Coté, OR (1972) Spectral characteristics of surface layer turbulence. Quart. J. Roy. Meteorol. Soc. 98: 563-589

Lee, X, Massman, W, Law, BE (Editors) (2004) Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer Academic Press, Dordrecht, 250 pp.

Liebethal, C, Huwe, B, Foken, T (2005) Sensitivity analysis for two ground heat flux calculation approaches. Agric. For. Meteorol.: DOI: 10.1016/j.agrformet.2005.08.001

Liu, H, Foken, T (2001) A modified Bowen ratio method to determine sensible and latent heat fluxes. Meteorol. Z. 10: 71-80

Liu, H, 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, CR, Bessemoulin, P, Cropley, FD, Culf, AD, Dolman, AJ, Elbers, J, Heusinkveld, B, Moncrieff, JB, Monteny, B, Verhoef, A (1997) A comparison of surface fluxes at the HAPEX-Sahel fallow bush sites. J. Hydrol. 188-189: 400-425

Mauder, M, Foken, T (2004) Documentation and instruction manual of the eddy covariance software package TK2. Arbeitsergebnisse, Universität Bayreuth, Abt. Mikrometeorologie, 26, 44 pp. (Print, ISSN 1614-8916; Internet, ISSN 1614-8926)

Mauder, M, Liebethal, C, Göckede, M, Leps, J-P, Beyrich, F, Foken, T (2005) Processing and quality control of flux data during LITFASS-2003. Boundary-Layer Meteorol.: revised

Moore, CJ (1986) Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorol. 37: 17-35

Nieuwolt, S (1982) Tropical Climatology. John Wiley and Sons, London, 207 pp.

Ohmura, A (1982) Objective criteria for rejecting data for Bowen ratio flux calculations. J. Appl. Meteorol. 21: 595-598

Oncley, SP (1989) Flux parametrization techniques in the atmospheric surface layer. Ph.D. Thesis, University of California, Irvine, CA, 202 pp.

Oncley, SP et al. (2005) The Energy Balance Experiment EBEX-2000. Part I: Overview and energy balance. Boundary-Layer Meteorol.: to be submitted

Panin, GN, Raabe, A, Tetzlaff, G (1998) Inhomogeneity of the land surface and problems in parametrization of surface fluxes in natural conditions. Theor. Appl. Climatol. 60: 163-178

Schotanus, P, Nieuwstadt, FTM, DeBruin, HAR (1983) Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations. Boundary-Layer Meteorol. 26: 81-93

van de Giesen, N, Kunstmann, H, Jung, G, Liebe, J, Andreini, M, Vlek, PLG (2001) The GLOWA Volta project: Integrated assessment of feedback mechnisms between climate, landuse, and hydrology. Advances in Global Change Research 10: 151-170

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

Wallace, JS, Holwill, CJ (1997) Soil evaporation from tiger-bush in south-west Niger. J. Hydrol. 188-189: 426-442

Webb, EK, Pearman, GI, Leuning, R (1980) Correction of the 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

Wilson, K, Goldstein, A, Falge, E, Aubinet, M, Baldocchi, D, Berbigier, P, Bernhofer, C, Ceulemans, R, Dolman, H, Field, C (2002) Energy balance closure at FLUXNET sites. Agric. For. Meteorol. 113: 223-243

Xue, Y, Hutjes, RWA, Harding, RJ, Claussen, M, Prince, SD, Lebel, T, Lambin, EF, Simon, JA, Dirmeyer, PA, Oki, T (2004) The Sahelian Climate. In: P Kabat, M Claussen (Editors), Vegetaion, Water, Humans and the Climate. A New Perspective on an Interactive System. Springer, Berlin, Heidelberg, pp. 59-77.

Appendix F

Innovative gap-filling strategy for annual sums of CO_2 net ecosystem exchange

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Abstract

The determination of carbon dioxide net ecosystem exchange (NEE) with the eddy covariance (EC) method has become a fundamental tool for the investigation of the carbon balance of terrestrial ecosystems. This study presents a strategy for the processing, subsequent quality control and gap-filling of carbon dioxide eddy covariance flux measurements for the derivation of annual sums of NEE. A set of criteria is used for quality assessment identified periods with instrumental or methodological failures. These criteria included tests for the methodological prerequisites of the EC method.

The complete evaluation scheme was applied to data recorded above a spruce forest at the FLUXNET-station Waldstein-Weidenbrunnen (DE-Wei) in 2003. Comparison of this new evaluation scheme to the use of a friction velocity (u_*) threshold criterion of $0.3\,\mathrm{m\,s^{-1}}$ indicates less systematic distribution of data gaps. The number of available high quality night-time measurements increased. This effect was most pronounced during summer, when data is essential for a robust parameterisation of respiratory fluxes. Non-linear regression analysis showed that air temperature and global radiation explain most of the variability of NEE and further seasonal segregation of the data based on an objective method did not significantly improve predictions at this evergreen forest site.

Key words: Net ecosystem exchange, Carbon dioxide exchange, Eddy covariance, Data filling, Quality control

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Nomenclature

symbol	description, unit
a	ecosystem quantum yield, [$\mathrm{mmol\,m^{-2}\,s^{-1}}$]
d	displacement height, [m]
E_0	parameter of *Lloyd-Taylor* function which describes temperature sensitivity, [K]
f	coriolis parameter [$\mathrm{s^{-1}}$]
F_C	CO_2 net ecosystem exchange (NEE), [$\mathrm{mmol\,m^{-2}\,s^{-1}}$]
$F_{C,\mathrm{day}}$	CO_2 net ecosystem exchange at day-time, [$\mathrm{mmol\,m^{-2}\,s^{-1}}$]
$F_{C,\mathrm{sat}}$	CO_2 net ecosystem exchange at light saturation, [$\mathrm{mmol\,m^{-2}\,s^{-1}}$]
F_E	corrected CO_2 eddy flux, [$\mathrm{mmol\,m^{-2}\,s^{-1}}$]
$F_{R,\mathrm{eco}}$	ecosystem respiration rate at night-time, [$\mathrm{mmol\,m^{-2}\,s^{-1}}$]
$F_{R,10}$	ecosystem respiration rate at 10 °C, [$\mathrm{mmol\,m^{-2}\,s^{-1}}$]
$F_{\Delta\mathrm{S}}$	CO_2 storage flux, [$\mathrm{mmol\,m^{-2}\,s^{-1}}$]
L	Obukhov length, [m]
R_g	global radiation, [$\mathrm{W\,m^{-2}}$]
R^2	coefficient of determination, [1]
S_{xy}	standard error of linear regression, here in [$\mathrm{mmol\,m^{-3}}$]
t	time, [s]
T	air temperature, [K]
T_0	parameter of *Lloyd-Taylor* function, [K]
T_p	air temperature, measured with a platinum wire thermometer, [°C]
T_s	sonic air temperature, measured with a sonic anemometer, [°C]
z_m	measurement height, [m]
z_+	normalising factor with the value of 1 m
$\overline{\rho_C}$	mean CO_2 density, [$\mathrm{mmol\,m^{-3}}$]
σ_w	standard deviation of the vertical wind velocity, [$\mathrm{m\,s^{-1}}$]
ζ	stability parameter, [1]

Abbreviations	
AGC-value	diagnostic value which indicates if the optical path of the LI-7500 is obstructed, [%]
CET	Central European Time
De-Wei	FLUXNET-station Waldstein-Weidenbrunnen, Fichtelgebirge, Germany
ITC_σ	relative deviation of the integral turbulence characteristic, [1]
NEE	net ecosystem exchange, [$mmol\,m^{-2}\,s^{-1}$]
PAI	plant area index, [$m^2\,m^{-2}$]
PAR	photosynthetic active radiation
PWD	present weather detector
TK2	Turbulence Knight 2 evaluation software

1 Introduction

Carbon dioxide exchange of ecosystems with the atmosphere is investigated worldwide at many stations by directly measuring turbulent fluxes applying the eddy-covariance method (Baldocchi et al., 2001). The derivation of annual sums of the CO_2 net ecosystem exchange (NEE) requires careful assessment of the collected data including criteria for rejecting invalid data and gap-filling strategies to replace rejected and missing data. Standardised methodologies are proposed for most of the necessary corrections to eddy covariance data (Aubinet et al., 2000, 2003). However, strategies for gap-filling are still subject to discussion within the research community (Falge et al., 2001; Hui et al., 2004; Gu et al., 2005). The comparison of different methods (mean diurnal variation, look-up tables, nonlinear regression) showed small differences in the accuracy of the gap-filling method itself but that the accuracy is sensitive to the criteria applied to rate the data quality and reject certain data (Falge et al., 2001). The quality assessment must effectively check for instrument failures and for the fulfilment of the prerequisites of the eddy-covariance method.

Especially the selection and treatment of night-time flux data bares the potential for *selective systematic error* in annual sums of NEE due to underestimation or double accounting of respiratory fluxes (Goulden et al., 1996; Moncrieff et al., 1996; Massman and Lee, 2002). Often the validity of night-time flux data is rated according to the friction velocity u_*. Data are rejected based on a absolute threshold of u_* in order to exclude situations with weak turbulent mixing in which (i) often stationarity and development of turbulence are not sufficient for the eddy-covariance method and (ii) the measured NEE seems to underestimate respiratory fluxes and there is a chance for decoupling of exchange processes within the vegetation canopy. CO_2 is then suspected to leave the ecosystem by ways that are not adequately accounted for by the eddy covariance measurements and modelled respiration rates are used instead of measured NEE. This method requires the objective determination of a critical u_* threshold (Gu et al., 2005), which can not be found at all sites. The use of a fixed u_* threshold often rejects a large proportion of flux measurement data during summer nights. It is, however, especially during summer nights when respiratory CO_2 fluxes show the highest rates due to their positive correlation with temperature. Therefore the correct representation of summer night fluxes is essential for the derivation of the annual sum of CO_2 exchange.

Many studies show that the rejection of periods with low u_* values results in systematic decrease of annual sums of NEE in the order of 50-100 $\mathrm{gC\,m^{-2}\,a^{-1}}$ (Goulden et al., 1996; Falge et al., 2001; Carrara et al., 2003; Hui et al., 2004) scaling with the value of the u_* threshold criterion. Therefore, the use of absolute thresholds in u_* as data rejection criterion must be questioned as long as there is no direct evidence for CO_2 leaving the ecosystem by ways that are not adequately accounted for during periods with low u_*. Consequently, more precise criteria are needed to assess the quality of the flux data especially under low turbulence conditions.

This study presents a strategy for the processing, subsequent quality control and gap-filling of CO_2 eddy covariance flux measurements for the derivation of annual sums of net ecosystem exchange. It applies methods for quality control and assurance proposed by Foken and Wichura (1996) and updated by Foken et al. (2004). Instead of using absolute thresholds for a certain parameter of turbulence, these methods assess the degree of stationarity in the flux data and the degree to which the development of turbulence agrees with basic flux-variance similarity. Both criteria represent fundamental prerequisites for the eddy-covariance method. In this study we present the complete evaluation scheme. The evaluation scheme is furthermore tested with data from the FLUXNET-Station Waldstein-Weidenbrunnen (DE-Wei) in the Fichtelgebirge Mountains, Germany, which frequently faces harsh environmental conditions especially in winter time. We analyse how the quality assessment used in this study influences the distribution of gaps in the NEE dataset. Special attention is given to the availability of measured data during summer nights for the determination of the night-time respiratory fluxes and how the quality assessment relates to the use of a u_* filter criterion.

2 Method

2.1 Experimental data

The FLUXNET-Station Waldstein-Weidenbrunnen (DE-Wei) is located in the Fichtelgebirge Mountains in Germany (50°08' N, 11°52' E,) at a forested mountain ridge at 775 m a.s.l. The CO_2-Flux measurements are performed on a 33 m tall tower over spruce forest (*Picea abies*) using a sonic anemometer (R2 until 19 May 2003, since then R3-50, Gill Instruments Ltd., Lymington, UK) and an open path gas analyser for CO_2 and H_2O (LI-7500, LI-COR Inc., Lincoln, NE, USA). The forest has a mean canopy height of 19 m and a plant area index (PAI) of 5.2 (Thomas and Foken, 2005a) and the terrain has a slope of 2° (Rebmann et al., 2005; Thomas and Foken, 2005b). Understorey vegetation is sparse and consists of small shrubs and grasses. A detailed description of the research site can be found in Gerstberger et al. (2004).

The additional instrumentation setup at the tower is a present weather detector (PWD11, Vaisala, Helsinki, Finland) at 21 m above ground level (slightly above the forest canopy) to obtain the synoptic weather code (WMO-code 4680, WMO, 1995) and visibility for an exact determination of any rain or fog period, a vertical profile of air temperature and air humidity measurements by radiation protected and electrical ventilated psychrometers (Theodor Friedrichs GmbH & Co., Schenefeld, Germany) at five different heights, a vertical profile of wind velocity measurements (standard cup anemometers, T. Friedrichs, Germany) at seven different heights inside the coniferous forest and above the canopy, a vertical profile of soil temperature measurements between 5 cm and 50 cm depth and long and shortwave radiation measurements (CM14,CG2) at the tower top.

A locally developed profile system continuously measuring CO_2 mixing ratios at eight different levels from the forest floor to 33 m was running from 13 June to 2 August 2003 during the intensive experiment campaign WALDATEM-2003 (Wavelet Detection and Atmospheric Turbulent Exchange Measurements 2003, Thomas et al., 2004).

2.2 Flux determination and flux corrections

Eddy covariance measurements of turbulent fluxes are the basis for the annual NEE estimation. In general, turbulent fluxes are calculated as the covariance between the two high frequency time series of vertical wind velocity and a scalar, e.g. temperature, humidity or carbon dioxide mixing ratio, which are measured at one point in time and space. Inherent to these atmospheric measurements are deficiencies which cause more or less important violations of assumptions to the underlying theory. Therefore, quality tests of the raw data, several corrections of the covariances as well as quality tests for the resulting turbulent fluxes are necessary.

For the analysis of the presented data set from the Waldstein-Weidenbrunnen site measurements of 2003 the comprehensive software package TK2 was used, which was developed at the University of Bayreuth (Mauder and Foken, 2004). It is capable of performing the whole post-processing of turbulence measurements and producing quality assessed turbulent flux estimates. This data analysis scheme implements the recommendations of an AMERIFLUX workshop covering methodological aspects of eddy covariance measurements (Lee et al., 2004). These recommendations formed the basis of the TK2 processing algorithm, on which a consistent analysis sequence incorporating the current state of science was created. The major components of this system are:

- Detection of spikes after Vickers and Mahrt (1997) based on Højstrup (1993).
- Determination of the time delay between sensors (e.g. LI-7500 gas analyser and sonic) using cross correlations analysis.
- Cross wind correction of the sonic temperature after Liu et al. (2001), if not already implemented in sensor software (e.g. necessary for Gill Solent-R2, redundant for Gill Solent R3-50 or Campbell CSAT3).
- Planar Fit method for coordinate transformation (Wilczak et al., 2001).
- Spectral corrections after Moore (1986) using the spectral models by Kaimal et al. (1972) and Højstrup (1981).
- Conversion of fluctuations of the sonic temperature into fluctuations of the actual temperature after Schotanus et al. (1983).
- Density correction for scalar fluxes of H_2O and CO_2 and correction for mean vertical mass flow after Webb et al. (1980).
- Iteration of the correction steps because of their interdependence.
- Quality assessment, applying tests for steady state conditions and well-developed turbulence (integral turbulence characteristics) after Foken and Wichura (1996) in the version proposed by Foken et al. (2004).

Additional to the built-in functions of the software package we rejected invalid CO_2 measurements due to sensor saturation or electrical problems by applying a site specific maximum threshold to the absolute mean CO_2 density $\overline{\rho_C}$ of $17\,\mathrm{mmol\,m^{-3}}$ and rejecting half-hour periods with extremely low variance in the CO_2 density ($<0.02\,\mu\mathrm{mol\,m^{-3}}$).

At complex FLUXNET-Stations like Waldstein-Weidenbrunnen it is common that a lot of different measurement, data logging and storing systems are used. Potential discrepancy in the synchronisation between the high-speed measurements (10-20 Hz) of the turbulence system and the one to five second (or longer) measurement intervals of the accompanying standard meteorological instrumentation has to be considered in respect to the subsequent flux data correction and NEE gap-filling or data aggregation. Synchronisation can be assured by using radio controlled time referencing during the recording. Few missing data in the radiation and temperature measurements (about 4 days in 2003) were filled by calculating average diurnal cycles from a 14 day period. Corresponding flux data was not included in the regression analysis (Section 2.5).

Further processing of the CO_2 eddy flux data, the application of the quality criteria as well as the parameterisation and gap-filling procedures are summarised in Fig. 1 and are explained in more detail in the following Sections.

2.3 Flux data quality assessment

2.3.1 Environmental conditions

Environmental conditions at the FLUXNET-Station Waldstein-Weidenbrunnen are harsh especially during winter time. Under humid conditions measurements with the sonic anemometer and the open path CO_2 sensor are frequently disturbed by fog or ice formation at tower and instrument structures. Such disturbance does not necessarily result in missing values so that data has to be carefully selected during post processing, to eliminate all periods in which measurements of the CO_2 flux are not trustworthy.

The present weather detector (PWD) allowed efficient identification of periods with any form of precipitation or fog (criterion 1, Fig. 1). We found that rain gauge measurements were not sufficiently precise in the identification of light precipitation events, which already disturb sonic anemometer and open path gas analyser measurements. When using an LI-7500 open path sensor, an alternative for the identification of fog can be made available by recording the 'AGC value' from the digital output, which indicates disturbances within the measurement path. We allowed a time of 30 min after every precipitation or fog event for drying of the instrument windows.

The combination of humid and freezing conditions leads to ice formation on the instruments in winter time. These situations were identified by comparing the sonic temperature (T_s) of the sonic anemometer with air temperature measured at the tower top with a platinum wire thermometer of a ventilated psychrometer (T_p). From Fig. 2 it is obvious that (i) the relation must be determined individually for every sonic anemometer and (ii) large deviations occur only below or close to the freezing point. Data for which the measurement of T_s is significantly disturbed could be identified and flagged as bad quality (criterion 2, Fig. 1) by defining a confidence interval of $\pm 4\sigma$ to the linear regression determined from values above $0\,^o$C and extrapolating this criterion to below $0\,^o$C. The observed disturbance is likely the result of ice blocking the measurement path or the transducers of the sonic anemometer.

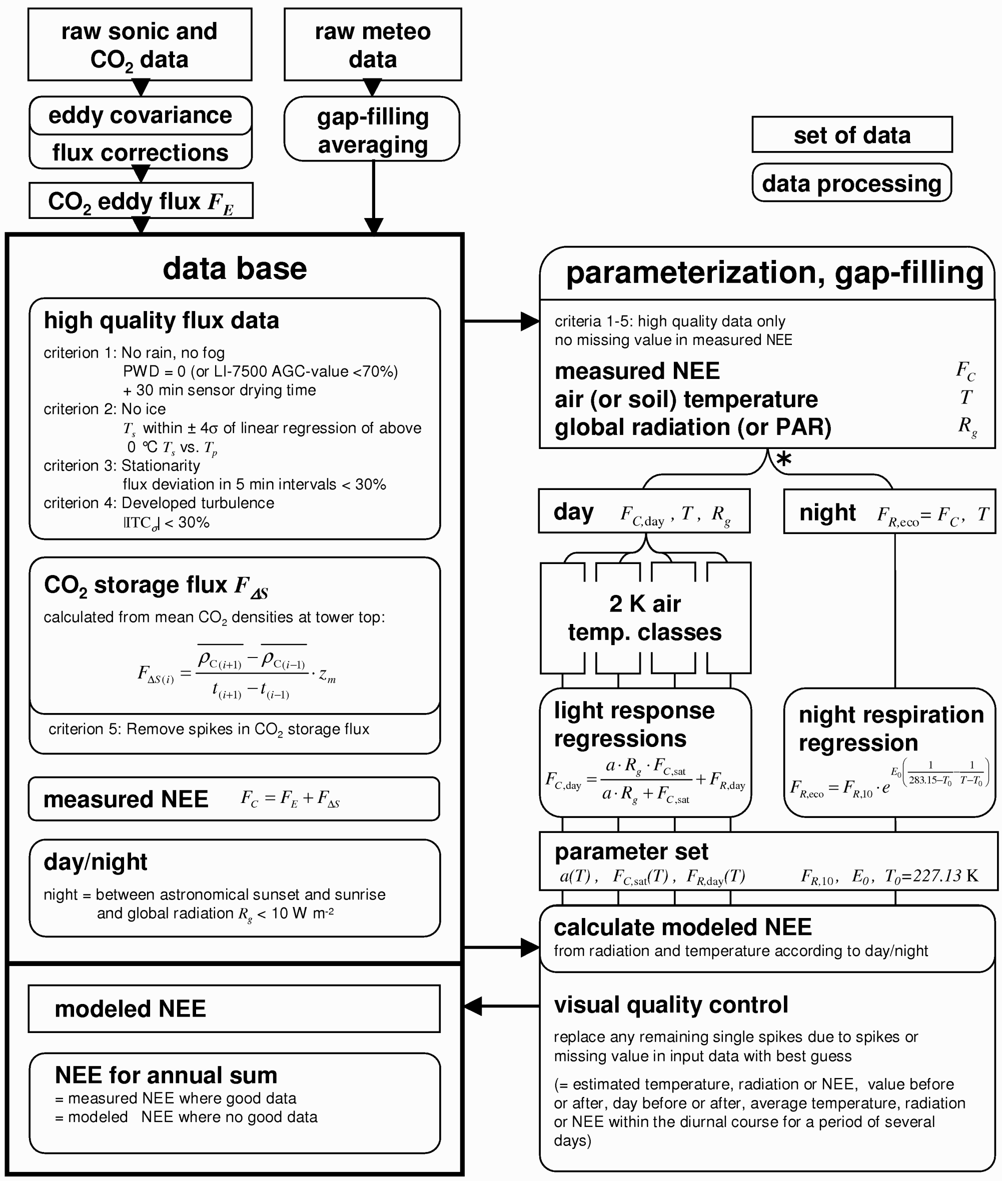

Fig. 1. Scheme of the step by step data handling and processing for the calculation of annual sums of NEE. Rectangular boxes represent sets of data. Rounded boxes represent steps in data processing. From the database, data can easily be selected according to the good data, day/night and 2 K temperature classes for nonlinear regression analysis. Parameterisations based on these subsets are used for gap-filling of missing and bad quality data. Flux corrections applied are described in Section 2.2.

2.3.2 Stationarity and developed turbulence

The tests for stationarity and developed turbulence which form the basis for criteria 3 and 4 (Fig. 1) in this study were suggested by Foken and Wichura (1996) and are discussed in detail in Foken et al. (2004). The stationarity

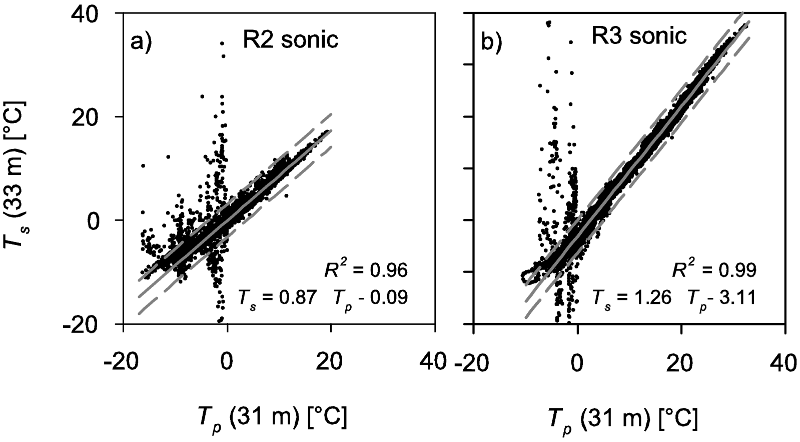

Fig. 2. Platinum wire temperature measured with a ventilated psychrometer at 31 m above ground compared to the sonic temperature recorded with a R2 (a) or R3 (b) sonic anemometer at the FLUXNET-Station Waldstein-Weidenbrunnen in 2003 (dots). The solid lines represent the result of a linear least square regression based on all data above 0 °C. Dashed lines indicate residuals from this fit of plus or minus four standard deviations from the linear regression.

test compares the covariance calculated for a 30 min interval of turbulence measurements to covariances calculated from 5 min subsets of this data. The flux measurement is then rated according to the relative difference by assigning quality flags. In this study only data with relative differences of less than 30% were accepted as high quality measurements (quality flag 1 or 2 after Foken et al., 2004).

The test on developed turbulence is based on the analysis of integral turbulence characteristics. These test parameters are based on the flux-variance similarity and are fundamental characteristics of atmospheric turbulence in the surface layer (Obukhov, 1960; Wyngaard et al., 1971). Integral turbulence characteristics are the ratio of the standard deviation of a turbulent parameter and its turbulent flux, e.g. σ_w/u_*. These are assumed to be nearly constant or a function of certain scaling parameters under the conditions of fully developed and unperturbed turbulence. They can be parameterised empirically as a function of stability (Panofsky et al., 1977; Foken et al., 1991) but also the Coriolis parameter f is discussed as scaling parameters in the literature (Yaglom, 1979; Tennekes, 1982; Högström, 1990). While the test on developed turbulence can be performed on a routine basis for the wind components, the integral turbulence characteristics of scalars have extremely high values under near neutral conditions. Therefore, we restricted the quality assessment for

Table 1
Recommended parameterisations for the integral turbulence characteristics of the vertical wind component (Thomas and Foken, 2002; Foken et al., 2004). ζ: stability parameter $((z_m - d)/L)$, z_+: normalising factor with a value of 1 m, f: Coriolis parameter.

Integral turbulence characteristic	stability ranges $\zeta <$ -0.2	-0.2 $< \zeta <$ 0.4	$\zeta >$ 0.4
σ_w/u_*	$2.0(\zeta)^{1/8}$	$0.21 \ln\left(\frac{z_+ f}{u_*}\right) + 3.1$	$1.3(\zeta)$

developed turbulence on the vertical wind component in this study. The empirical models for normalised standard deviations that we used for the test on developed turbulence are parameterisations presented in Foken et al. (2004, see Tab. 1).

Similar to the test on stationarity, the development of turbulence is rated according to the relative difference between measured and modelled integral turbulence characteristic (1):

$$\mathrm{ITC}_\sigma = \left| \frac{(\sigma_w/u_*)_{\mathrm{model}} - (\sigma_w/u_*)_{\mathrm{measurement}}}{(\sigma_w/u_*)_{\mathrm{model}}} \right| . \tag{1}$$

Only data from periods with well developed turbulence (criterion 4) in which the deviation was within 30 %, i.e. $\mathrm{ITC}_\sigma < 0.3$, were accepted as high quality in this study (quality flag 1 or 2 after Foken et al., 2004).

2.4 *CO_2 storage flux*

A simple method for estimating the CO_2 storage flux $F_{\Delta S}$ from one point CO_2 measurements was suggested by Hollinger et al. (1994). It assumes the same mean CO_2 density $\overline{\rho_C}$ for the entire air column below measurement height (z_m):

$$F_{\Delta S(i)} = \frac{\overline{\rho_{C(i+1)}} - \overline{\rho_{C(i-1)}}}{t_{(i+1)} - t_{(i-1)}} z_m, \tag{2}$$

where i denotes a certain measurement interval and t the time reference of a measurement interval. A comparison of eight level CO_2 profile measurements during summer 2003 at the flux tower as well as studies by Rebmann (2003) showed that this method is able to reflect changes in the canopy storage generally well.

The analysis of the storage flux data indicated that outliers were related to situations in which the open path gas analyser signal showed sudden and unrealistic changes and that these were often related to periods after rain events when the window of the sensor was not yet dried completely. We therefore developed an additional criterion (criterion 5 in Fig. 1) in order to remove spikes in the storage flux.

We analysed the standard error related to the derivation of the storage flux, i.e. determination of the trend in three subsequent CO_2 density measurements. The standard error S_{xy} of a linear regression is defined as:

$$S_{xy} = \sqrt{\frac{1}{n(n-2)}\left[n\sum y^2 - (\sum y)^2 - \frac{[n\sum xy - (\sum x)(\sum y)]^2}{n\sum x^2 - (\sum x)^2}\right]}, \qquad (3)$$

where x in this case is the time reference of the measurement periods t and y is the average CO_2 density $\overline{\rho_C}$. Unlike the coefficient of determination R^2 the standard error of the linear regression S_{xy} is not adjusted to the variability of the CO_2 data. It gives a measure for the residuals expressed in absolute CO_2 density (Fig. 3a) and can therefore indicate periods, in which the storage flux is uncertain because it is calculated from highly fluctuating $\overline{\rho_C}$ with the lack of a clear trend. Such situations occur when one of the three measurements of $\overline{\rho_C}$ used for the calculation of the storage flux is disturbed by measurement failures.

Fig. 3b shows that very large values for the storage flux were related to a high degree of uncertainty due to lack of a clear trend or extremely variable CO_2 densities. We therefore applied a site specific absolute limit ($S_{xy} < 0.1784\,\mathrm{mmol\,m^{-3}} = 4\sigma$) in order to mark these data as bad quality (criterion 5, Fig. 1). Only after removing these data we were able to also identify upper and lower limits of the absolute storage flux ($|F_{\Delta S}| < 0.0053\,\mathrm{mmol\,m^{-2}\,s^{-1}} = 4\sigma$) for the identification and rejection of few remaining outliers.

Valid measurements for the NEE (F_C), i.e. the sum of CO_2 eddy flux and the storage flux, exist when both components are high quality data. By convention all CO_2 fluxes into the atmosphere (upward) and storage increase have a positive sign, while fluxes from the atmosphere into the ecosystem (downward) or storage decrease have a negative sign. A final visual control of the data was performed during the parameterisation procedure, when data is grouped and plotted together with the basic functional dependencies on global radiation and temperature.

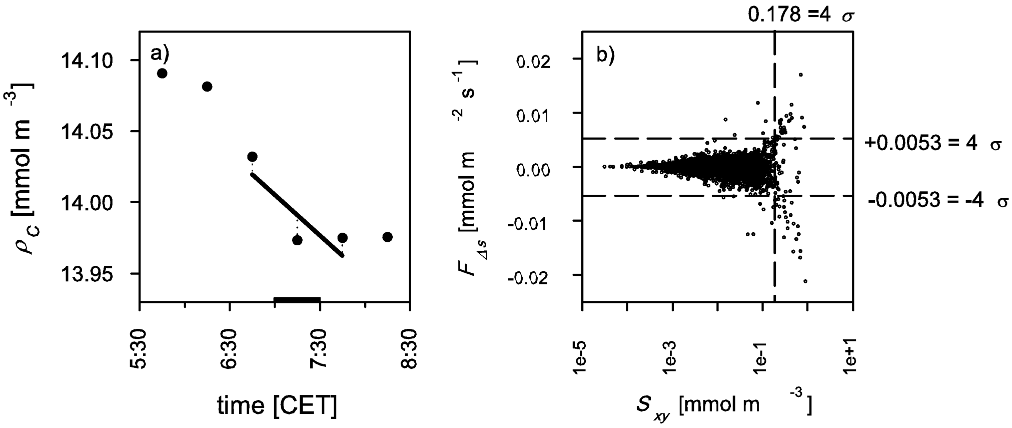

Fig. 3. Estimation of the storage flux from the trend in the CO_2 record obtained with the open-path sensor at tower top (a). The standard error S_{xy} of the linear regression of three adjacent half-hourly average CO_2 values $\overline{\rho_C}$ and the absolute value of the storage flux $F_{\Delta S}$ (b) are the basis for the criterion 5 (Fig. 1). The application of a limit of 4 standard deviations was used in order to flag outliers representing measurement errors or extreme instationarity in the CO_2 record as bad quality. Data was recorded at the FLUXNET-Station Waldstein-Weidenbrunnen in 2003.

2.5 Parameterisation

The regression analysis used as parameterisation scheme for the modelling of NEE and subsequent gap-filling of the measured NEE dataset requires segregating day-time from night-time data. This segregation was done on the basis of (i) calculating astronomical sunrise and sunset for the measurement site and (ii) evaluating measurements of global radiation R_g (Fig. 1). Only when both criteria indicated night-time situation (between astronomical sunset and sunrise and $R_g < 10\,\mathrm{W\,m^{-2}}$) measured data was used for the night-time respiration regression. Time periods during dawn and dusk were grouped with the day-time values, because the light response regression is able to also represent values with low global radiation.

We used *Michaelis-Menten* functions (Michaelis and Menton, 1913; Hollinger et al., 1999; Falge et al., 2001) for the light response regression:

$$F_{C,\mathrm{day}} = \frac{a\,R_g\,F_{C,\mathrm{sat}}}{a\,R_g + F_{C,\mathrm{sat}}} + F_{R,\mathrm{day}}. \tag{4}$$

$F_{C,\mathrm{day}}$ is the NEE during day-time, $F_{C,\mathrm{sat}}$ the saturated NEE rate at $R_g = \infty$ and a is the initial slope of the function. The offset of the function $F_{R,\mathrm{day}}$ represents the respiration rate during day-time. The measured NEE data was grouped in temperature classes and individual light response functions were determined for each class (Rebmann, 2003), in order to reflect temperature dependencies present in the rate of respiration and photosynthesis.

The *Lloyd-Taylor* function (Lloyd and Taylor, 1994; Falge et al., 2001) was used for the regression analysis of night-time ecosystem respiratory flux rates $F_{R,\text{eco}}$:

$$F_{R,\text{eco}} = F_{R,10}\ \mathrm{e}^{E_0\left(\frac{1}{283.15-T_0}-\frac{1}{T-T_0}\right)}\ . \tag{5}$$

Parameters were determined for $F_{R,10}$, the respiration rate at $10\,^oC$ (283.15 K), and E_0, which describes the temperature sensitivity of respiratory fluxes, while T_0 was kept constant with a value of 227.13 K as in Lloyd and Taylor (1994). Because the temperature dependency is represented in the function, data was not segregated into temperature classes for the night respiration regression.

In addition, data can be segregated into temporal classes in order to represent different seasonal and phenological stages more accurately. We tested a method based on the thermal seasons after Rapp and Schönwiese (1994) and Rapp (2000) to objectively split the data according to the annual cycle of air temperature. To smooth the daily variability in air temperature without eliminating the characteristic weather episodes of the corresponding year a low pass filter using a Gaussian weighting function was applied with a filter length of 60 days (Fig. 4). A shorter interval will leave too much variance and a longer interval will result in too much loss of information to distinguish adequate seasons. For 2003, we found an annual temperature maximum of $20.3\,^o$C (1st week of August) and an annual minimum of $-5.2\,^o$C (2nd week of February) for the FLUXNET-Station at Waldstein-Weidenbrunnen based on the smoothed daily means (circles in Fig. 4). The resulting annual temperature amplitude of 25.5 K divided in four equidistant classes leads to the threshold value of $1.2\,^o$C to separate winter and spring (and autumn and winter) and a value of $13.9\,^o$C to separate spring and summer and respectively summer and autumn. A division by four shows the best results to obtain seasons with approximately the same number of valid CO_2-flux data. The seasonal segregation can be integrated into the evaluation scheme at the position indicated with a '*' symbol in Fig. 1.

2.6 Gap-filling

The modelled NEE is calculated from the meteorological data on global radiation and air temperature and the functional dependencies described by the set of parameters. Similar to the measured NEE data, the parameterisations as well as the resulting modelled NEE data should undergo a final visual control

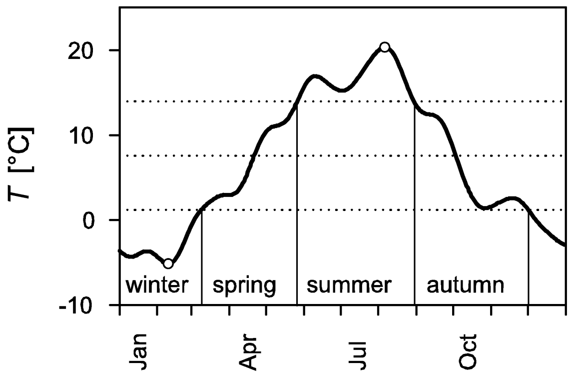

Fig. 4. Method for objectively splitting data in distinguishable seasons. The figure shows daily means of air temperature T measurements (at 31 m a.g.l., tower top) smoothed with a 60 day low pass filter (Gaussian function), FLUXNET-Station Waldstein-Weidenbrunnen, year 2003. The threshold value for 2003 separating winter and spring and respectively autumn and winter is 1.2 ^{o}C, spring and summer and respectively summer and autumn is 13.9 ^{o}C. The 2003 temperature maximum (20.3 ^{o}C) and minimum (-5.2 ^{o}C) are marked as circles.

in order to detect inconsistent data which may result from undetected spikes in the meteorological data or calculation errors during parameterisation or modelling. The complete set of gap-filled NEE data can be achieved by combining the high quality measured NEE data and the modelled NEE data from periods with poor data quality in a database (Fig. 1).

3 Results and Discussion

3.1 Parameterisation and gap-filling

All data rated as high quality according to the criteria 1 to 5 (Fig. 1) were used for the non-linear regression analysis of the light response of photosynthesis and night-time ecosystem respiration.

The night-time NEE data shows large scatter (Fig. 5) similar to results presented by Goulden et al. (1996). Consequently the coefficient of determination R^2 of the least square regression is relatively small when half-hourly data is used for the regression analysis of night-time respiration (Tab. 2). Only after aggregating and averaging half-hourly data in temperature classes the functional dependency is clearly visible and R^2 significantly increases, which corresponds to results by Hollinger et al. (1994). We furthermore found for the

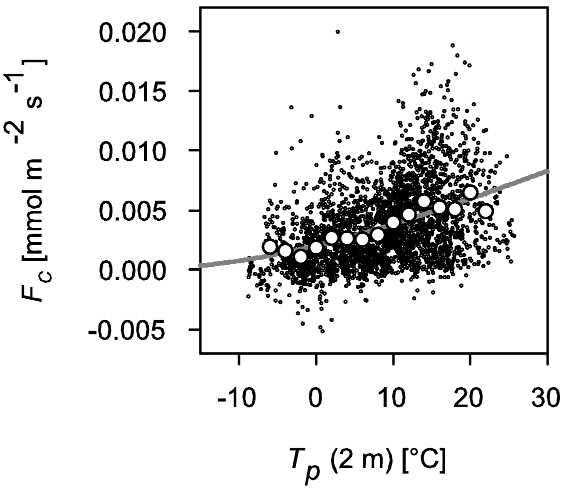

Fig. 5. Regression of night-time NEE F_c with air temperature T_p at 2 m above ground for all high quality half-hourly data (dots) and 2 K bin aggregated data (circles). The grey line indicates the least square fit of the exponential equation proposed by Lloyd and Taylor (1994) to the half-hourly data with variable $F_{R,10}$ and E_0 and fixed $T_0 = 227.13$.

aggregated and also the individual half-hourly data that (i) the Lloyd-Taylor function resulted in better regressions when not only the $F_{R,10}$ parameter but also the temperature sensitivity parameter E_0 was fitted (Tab. 2). Reichstein et al. (2003) suggest that E_0 depends on soil water availability, which may explain the need for its adjustment for a specific site. And (ii) R^2 values were slightly higher when using the air temperature measured at 2 m height for the regression analysis compared to using soil temperature measured at 0.05 m depth, which was also found for data from previous years (Rebmann, 2003). While the use of aggregated data leads to a good fit, it may represent the data less accurately, as each temperature class contains different numbers of data. We therefore preferred to firstly identify a suitable functional dependency for the regression analysis based on the aggregated data, i.e. Eq. (5) using aggregated NEE and 2 m air temperature data leaving out the bordering classes which contain only very few data (Fig. 5 white circles). The resulting coefficients of determination R^2 (0.86 compared to 0.45, Tab. 2) suggest to adjust the E_0 parameter to local sites conditions. Secondly, the final values for the function parameters $F_{R,10}$ and E_0 were determined from the least square regression with half-hourly data (Fig. 5 grey line).

The regression analysis showed a distinct dependence of NEE day-time light response on air temperature, which justifies determination of individual *Michaelis-*

Table 2
Coefficients of determination R^2 from night respiration regressions

	E_0=308.56	E_0 fitted
R^2 (half-hourly data)	0.10	0.18
R^2 (2 K bin aggregated data)	0.45	0.86

Table 3
Coefficients of determination R^2 from light response regressions and high quality NEE data availability for 2 K air temperature classes

2 K air temperature classes:	-6 to 0 ^{o}C	2 to 28 ^{o}C
range of R^2	0.17 to 0.42	0.42 to 0.74
average R^2	0.28	0.61
average number of data	99	267

Menten functions for different temperature classes (Fig. 6). The parameterisation scheme was tested with 1 K, 2 K and 4 K air temperature classes. The 1 K air temperature classes resulted in increased scatter in the temperature dependence of NEE light response due to small numbers of data in the individual classes. The representation of the temperature dependence by 4 K air temperature classes is relatively coarse. Grouping in 2 K air temperature classes was therefore chosen in order to most precisely represent the temperature dependence. The coefficient of determination R^2 of the least square regression indicate that a large degree of the variation in NEE is explained by the *Michaelis-Menten* functions (Tab. 3). Reduced R^2 for temperature classes from -6 to 0 ^{o}C correspond to larger scatter and smaller numbers of available high quality NEE data under freezing conditions.

Additional segregation of data into seasonal classes (Fig. 4) did not result in significantly different functional dependencies during the regression analysis. This unexpected result may be explained by two reasons: (i) the temperature information included in both the night respiration regression and in the light response regression by determining individual functions for 2 K temperature classes already contain a certain degree of information on seasonality (Kramer and Kozlowski, 1979; Hollinger et al., 1999; Suni et al., 2003), which therefore is incorporated in the regression analysis indirectly, (ii) the evergreen spruce forest lacks a distinct additional pattern of seasonality, which is found for deciduous forest due to plant physiological processes. Also, in periods with harsh weather conditions during wintertime, the soil is protected from frost by a snow cover on the forest floor at Waldstein-Weidenbrunnen for most of the time. The parameters only differed significantly for the bordering temperature ranges of the different seasons. These temperature ranges are, how-

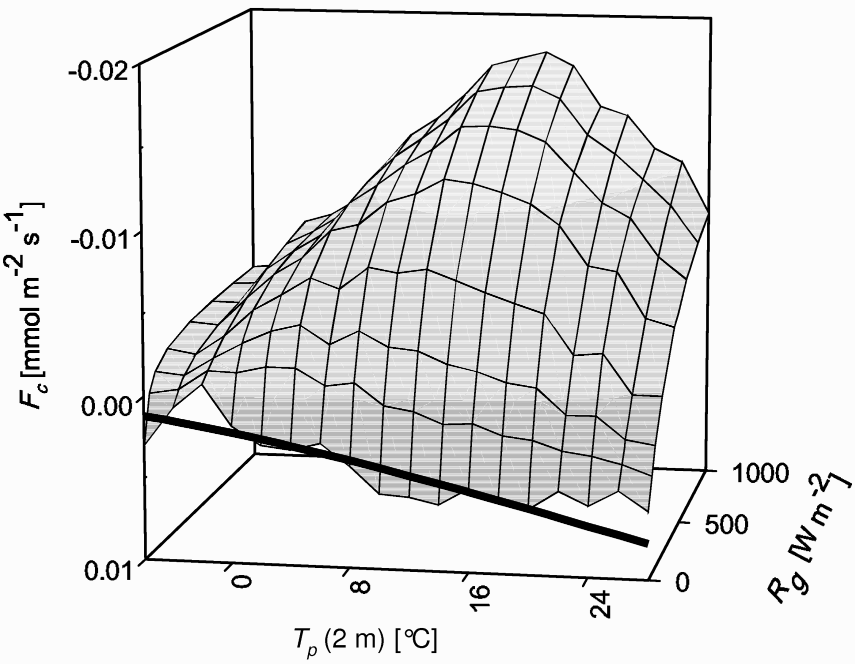

Fig. 6. Day-time NEE (surface) and night-time NEE (black line) at the FLUXNET-Station Waldstein-Weidenbrunnen in dependence of air temperature T_p (2 m a.g.l.) and global radiation R_g modelled with parameters from the regression analysis using *Michaelis-Menten* functions (1913) for the light response regression and the *Lloyd-Taylor* function (1994) for the regression of night-time ecosystem respiratory fluxes.

ever, poorly represented by a small number of data. This is an effect of the seasonal segregation, which results in representation of limited temperature ranges and reduced data availability. Based on these results we decided not to use additional seasonal segregation within the parameterisation scheme for the determination of the annual NEE at the Waldstein-Weidenbrunnen site. As confirmation, an analysis of the residual NEE, i.e. the difference between measured NEE and NEE modelled based on the parameterisation scheme without seasonal classes, did not show distinct seasonal dependencies. Additional segregation into seasonal classes may be required for other sites. The segregation can then be integrated at the beginning of the parameterisation scheme marked with a '*' symbol in Fig. 1. Other environmental variables controlling NEE, e.g. soil water availability, could potentially be used in similar fashion like described in Section 2.5 in order to define seasons on the basis of objective criteria. However, with seasonal segregation the regression analysis, especially the night-time respiration can lack statistically robustness due to the large scatter in half-hourly NEE data, limited temperature ranges and the reduced number of data in each seasonal class.

3.2 Flux data quality assessment

A large number of measured high quality data is desired in general for the determination of the annual sum of NEE and the parameterisations used for gap-filling. For the assessment of the scheme of quality control we compared the application of the criteria 3 and 4 (stationarity and developed turbulence) to filtering the dataset with a threshold criterion of $u_* > 0.3\,\mathrm{m\,s^{-1}}$ for low turbulent conditions. This threshold value is intermediate of threshold values commonly applied to respiration measurements at forest sites (Goulden et al., 1996; Greco and Baldocchi, 1996; Lindroth et al., 1998; Carrara et al., 2003; Griffis et al., 2003; Rebmann et al., 2004; Gu et al., 2005). Fig. 7 clearly shows that the data availability for night-time measurements significantly differs in its pattern. Criteria 3 and 4 tend to reject data in the early morning and late afternoon hours during which frequently extremely instationary conditions are observed. Data gaps during night-time and day-time show less systematic scatter and significant numbers of data are rated as high quality also during night-time. Compared to this pattern, the rejection of data by the u_* threshold criterion is much more systematic. Large proportions of the available night-time data fall below the u_* threshold criterion. This pattern increases the chance for *selective systematic error* in the annual sum of NEE (Moncrieff et al., 1996). At the same time, the availability of night-time data is much more limited with the use of the u_* threshold criterion. The selection of high quality data based on the tests of stationarity and developed turbulence as prerequisites for the eddy-covariance method (criteria 3 and 4) increases overall night-time data availability by +9 % throughout the year. This effect is even more pronounced during the summer, +26 %, when nights are shorter, respiration rates are higher and robust data is especially needed. Only when the u_* threshold value is decreased to $0.16\,\mathrm{m\,s^{-1}}$, similar amounts of data from summer night-time measurements become available.

The frequency distribution of overall quality flags after Foken et al. (2004) ranging from 1 high quality to 9 low quality in dependence of u_* is presented in Fig. 8. The quality flag is derived by combining the test on stationarity and developed turbulence. The definitions of the criteria 3 and 4 (Section 2.3.2) correspond to accepting data with quality flag 1 or 2 as high quality. A correlation of low and medium quality ratings with low u_* is apparent for half-hourly flux data at u_* below $0.25\,\mathrm{m\,s^{-1}}$. However, only at a u_* of $\leq 0.15\,\mathrm{m\,s^{-1}}$ more than 50 % of the data is rated as medium or low quality (quality flag $\geq$ 3), which means that these data do not meet the criteria 3 or 4.

There is also a significant number of half-hourly periods, which exhibit instationarity in fluxes or poorly developed or disturbed turbulent conditions, in combination with fairly high values of u_* (Fig. 9a and 9b). During these periods, u_* seems to be insufficient for rating the quality of the flux measurements. High values of u_* can occur under the presence of gravity waves. Gravity waves

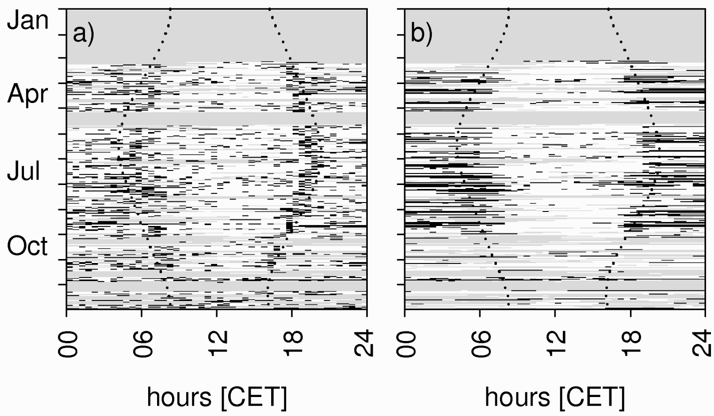

Fig. 7. Eddy flux quality assessment at the FLUXNET-Station Waldstein-Weidenbrunnen for the year 2003 using (a) criteria based on the stationarity test and the test of integral turbulence characteristics in order to check for the validity of the eddy-covariance method and well developed turbulent conditions (criteria 3 and 4). In comparison, the use of $u_* < 0.3\,\mathrm{m\,s^{-1}}$ (b) as criterion to indicate poor turbulence conditions leads to rejection of a large proportion of the night-time data especially during the summer. White areas represent accepted and black rejected data. Grey areas indicate missing data due to rain, fog, ice (criteria 1 and 2) or general instrument failure. The dotted lines indicate astronomical sunrise and sunset.

often result in strong correlation of scalar values and vertical wind velocity, which is not related to significant turbulent exchange (Foken and Wichura, 1996; Thomas and Foken, 2005c). Consequently, the calculated covariances are often unrealistically high. The covariances during these periods tend to show extreme instationarity and the ratio of σ_w/u_*, i.e. the integral turbulence characteristic, is increased. The tests on instationarity and developed turbulence (criteria 3 and 4) therefore provide means to reject periods with the presence of gravity waves and to check for the prerequisites of the eddy-covariance method more precisely than the use of a u_* threshold criterion.

The analysis of the Waldstein-Weidenbrunnen data from 2003 shows that in general the u_* threshold criterion is not sufficient to detect all periods, in which the prerequisites for the eddy-covariance method are violated. Only for the summer night-time measurements (Fig. 9c), the use of a very low u_* threshold criterion of $0.15\,\mathrm{m\,s^{-1}}$ could potentially indicate poor data quality in a manner comparable to the criteria 3 and 4. The use of data down to relatively low values of u_* during summer ($\leq 0.16\,\mathrm{m\,s^{-1}}$) is in general supported by an analysis applying objective methods for the determination of critical u_* thresholds (Gu et al., 2005). The determination of a critical threshold of u_* would require a well defined plateau in NEE plotted against u_* (Goulden et al., 1996; Gu et al., 2005), which is analysed in the following Section.

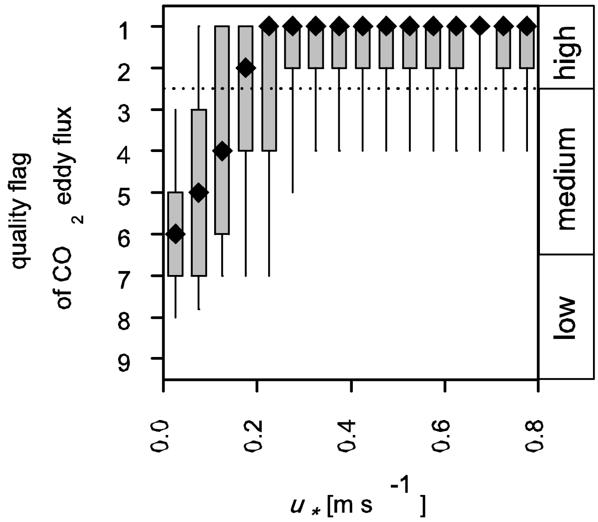

Fig. 8. Frequency distribution of quality flags after Foken et al. (2004) for the CO_2 eddy flux data at the FLUXNET-station Waldstein-Weidenbrunnen in dependence of u_* aggregated in $0.05\,\mathrm{m\,s^{-1}}$ bins. Diamonds indicate the median, box boarders the 25 % and 75 % percentile and lines the 10 % and 90 % percentile. With the new method of quality assessment applied in this study all data with high quality (quality flag 1 or 2, i.e. data above the dotted line which meet the criteria 3 and 4 in Fig. 1) were accepted for the regression analysis and derivation of the annual sum. With the old method based on an absolute u_* threshold criterion of $0.3\,\mathrm{m\,s^{-1}}$ all data right of the dashed line are accepted.

3.3 Systematic dependence of night-time NEE from u_*

Another reason for the use of a u_* threshold criterion in many studies is the observation of systematically reduced flux rates measured above canopy under conditions of low turbulent mixing. Generally, a systematic scaling of CO_2 fluxes with u_* should be expected from K-theory (Massman and Lee, 2002). However, biological source strength during night-time is assumed to be independent of turbulent mixing (Goulden et al., 1996). The deficit should then be explained either by storage accumulation below measurement hight or CO_2 leaving the forest in ways that are not adequately accounted for, e.g. by advection. In order to assess the relationship between u_* and night-time NEE after rejection of medium and low quality data (criteria 1 to 5), remaining summer night-time eddy covariance flux F_C data was plotted in dependence of u_* (Fig. 10a, dashed line). It shows the expected scaling of CO_2 fluxes with u_*, also after the application of the criteria 1 to 5. The storage flux $F_{\Delta S}$ (dash-dotted line) used for the derivation of NEE in Fig. 10a (solid line) and Fig. 10b (dots) is calculated from measurements performed with the eight

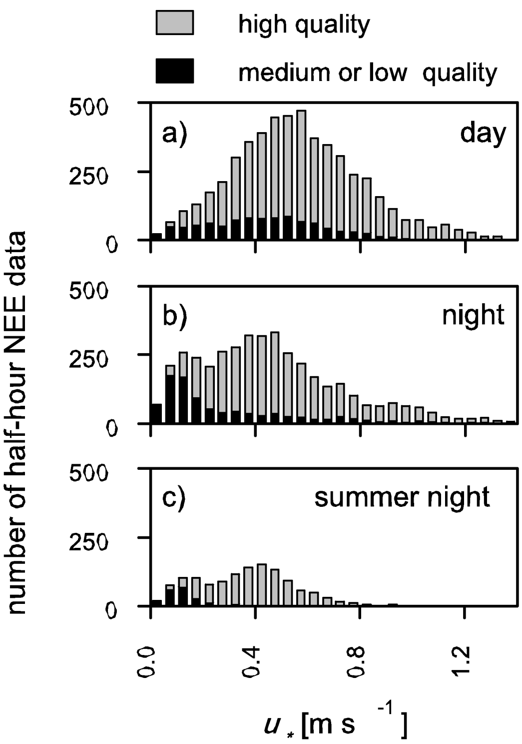

Fig. 9. Histogram of day-time (a) and night-time (b) half-hourly NEE data at the FLUXNET-station Waldstein-Weidenbrunnen during the year 2003 for $0.05\,\mathrm{m\,s^{-1}}$ bins of u_*. Plot c) indicates the availability of night-time data from the summer season 2003 (Fig. 4). The grey part of the bars represents data rated as high quality according to the criteria 1 to 5 (Fig. 1), while the black part of the bar represents medium or poor quality data.

point profile system (0.03 m to 33 m a.g.l.). Therefore it represents the canopy storage changes more accurately than the storage flux derived from the CO_2 measurements at tower top (Section 2.4).

From the 2003 data (Fig. 10a) as well as from previous years data (Station Bayreuth data presented in Aubinet et al., 2000) there is no indication of systematic accumulation of CO_2 in the forest canopy during conditions with low turbulent mixing. Consequently, also for storage corrected night-time NEE a typical scaling with u_* measured above canopy is found at the FLUXNET-station Waldstein-Weidenbrunnen. Fig. 10a and Fig. 10b show the lack of a plateau in NEE. The levelling of bin aggregated NEE (Fig. 10a) is rather an effect of significantly reduced numbers of representative data left above a value of $u_* = 0.6\ \mathrm{m\,s^{-1}}$ (Fig. 9c) than of saturation in NEE. Therefore, the use of a critical u_* threshold lacks justification also during summer nights.

For the summer night-time data (Fig. 10a) we can not attribute the pattern to inadequate vertical profile resolution within the canopy space like suggested

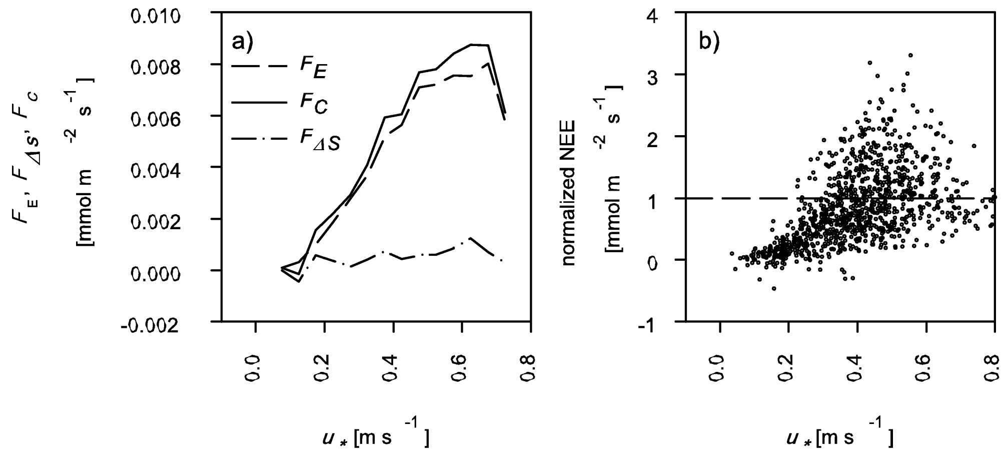

Fig. 10. Correlation of night-time CO_2 flux components and u_* for high quality data during summer 2003 (June, July, August) at the FLUXNET-Station Waldstein-Weidenbrunnen (F_E: corrected eddy flux, F_C: CO_2 NEE and $F_{\Delta S}$: storage flux). The storage flux component was determined more precisely from eight level CO_2 profile measurements between the forest floor (0.03 m) and tower top (33 m). The data in plot a) was aggregated in 0.05 m s^{-1} bins of u_*. The NEE data in plot b) was normalised by NEE modelled with parameters from the night-time regression analysis with air temperature.

in Gu et al. (2005). However, measurements at 0.03 m and 0.30 m indicated a moderate accumulation of CO_2 very close to the forest floor in periods with very low u_*. These measurements represent only a very small volume of the canopy air so that this accumulation does not compensate the reduction of the CO_2 flux observed above canopy at low values of u_*. Still, they indicate, that respired CO_2 is accumulated at the forest floor and likely even more within the litter and top soil. Adequate representation of such storage components below the canopy space would require to (i) extent CO_2 mixing ratio measurements into the forest floor (Rayment and Jarvis, 2000; Tang et al., 2003) and to (ii) assure sufficient horizontal representation of these measurements in order to reduce effects of small scale heterogeneity in the ecosystem (Buchmann, 2000; Gu et al., 2005).

The lack of any significant CO_2 storage accumulation in the overall forest canopy measured with an eight point profile system during low turbulent conditions (Fig. 10a) could be explained either by significantly reduced CO_2 release from the soil or very efficient horizontal transport. The latter was tested by measurements of horizontal CO_2 gradients, which were performed during the WALDATEM-2003 experiment. The exemplary analysis of CO_2 gradients in very stable nights with very low u_* which showed downhill katabatic air flows did not indicate significant horizontal advection which could explain the significantly reduced values in NEE.

Patterns similar to those found for absolute NEE data in Fig. 10a and for normalised half-hourly NEE data in Fig. 10b from the FLUXNET-Station Waldstein-Weidenbrunnen were reported for other sites by Massman and Lee (2002) and Gu et al. (2005). These were named as examples for situations in which no critical threshold in u_* exists and in which likely the effect of 'pressure pumping' is contributing to the observed pattern. Pressure pumping means, that the release of CO_2 from the soil into the canopy air-space is controlled to a large extend by strong exchange events like coherent structures which penetrate the forest canopy and change the pressure field at the soil surface. Such effects of pressure pumping during night-time at the FLUXNET-station Waldstein-Weidenbrunnen are likely related to a night-time secondary wind maximum (Lüers et al., 2005), which is a typical finding for stations in the mountains. Presuming the existence of pressure pumping, the systematic rejection of low NEE values at low values of u_* would most likely introduce 'double accounting' of respiratory fluxes into the annual sum of NEE (Aubinet et al., 2000), because night-time respired CO_2 is then released from the soil predominantly during periods of vigorous turbulence in which normally the prerequisites for eddy covariance measurements are given. The corresponding night-time respiration of CO_2 is then adequately accounted for later during the morning.

The significance of such complex exchange effects at the site is further supported by the finding that frequently exchange processes above the canopy and within the canopy are decoupled during night (Thomas and Foken, 2005c). The subsequent re-coupling of exchange processes within the canopy often takes place only late in the morning at 9-11 h CET. This is much later than suggested by increasing values of u_* measured above the canopy during the early morning. Effects of complete decoupling during the early morning hours and relatively late re-coupling are also visible in the CO_2 profile measurements (Ruppert, 2005). The study by Thomas and Foken (2005c) suggests that the use of measurements from above the canopy is not sufficient to assess complex exchange processes like potential decoupling within the canopy. This means that neither the test on developed turbulence (Section 2.3.2) nor u_*, both derived form data measured above the canopy, should be used to assess potential decoupling within the canopy space at forest sites.

Especially for flux measurements above tall vegetation, any systematic rejection of data beyond the assessment of flux measurement quality (criteria 1 to 5) should therefore be justified by more precise measurements or parameters describing exchange processes. There should be clear evidence for CO_2 leaving the forest by ways that are not accounted for in order to prevent the risk of double accounting of fluxes from systematic rejection. Based on the relation between summer night-time NEE and u_* and indication for the effect of pressure pumping contributing to the release of CO_2 from the soil at the

FLUXNET-station Waldstein-Weidenbrunnen we decided not to apply a u_* threshold criterion additional to the criteria 1 to 5. The application of criteria 3 and 4 makes the use of u_* for the assessment of the quality of the turbulent flux measurements by the eddy covariance method obsolete.

The annual sum of NEE calculated by applying the complete data processing scheme presented in Fig. 1 and using the criteria 1 to 5 for the quality assessment was determined with -398 $\mathrm{gC\,m^{-2}}$. Likewise for many other flux stations we find that the use of a u_* threshold criterion would significantly change the annual sum of NEE. The change amounted to +51 $\mathrm{gC\,m^{-2}}$ (annual sum of NEE: -347 $\mathrm{gC\,m^{-2}}$) when rejecting all measured data with $u_* < 0.3\,\mathrm{m\,s^{-1}}$.

4 Conclusions

The combination of data quality criteria presented in this study provides means to efficiently select high quality flux data based on the fundamental prerequisites of the eddy-covariance method. The data selection forms the basis for subsequent parameterisation and gap-filling of NEE measurements for the derivation of annual sums of NEE.

Flux data quality assessment with tests on stationarity of fluxes and on developed turbulence (criteria 3 and 4) lead to a less systematic distribution of data gaps compared to the use of a u_* threshold criterion of $0.3\,\mathrm{m\,s^{-1}}$. It may therefore help to reduce the risk of *selective systematic error* in the annual sum of NEE. At the same time it significantly increased the number of available high quality night-time measurements, especially during summer, giving a more robust basis for the parameterisation of respiratory fluxes and for the derivation of the annual sum. Data rated as low quality at higher values of u_* indicate, that the u_* criterion is not sufficient for the assessment of the prerequisites of the eddy-covariance method.

From the remaining positive correlation between summer night-time NEE and u_*, which was hardly altered by storage changes measured with an eight point profile and from which no critical u_* threshold criterion could be determined, we conclude that the degree to which turbulent mixing penetrates the forest canopy is an important factor for the release of respired CO_2 from the forest floor (pressure pumping) at the FLUXNET-station Waldstein-Weidenbrunnen. The determination of temperature dependent light response functions integrates information on seasonality so that further segregation of data into seasonal classes does not significantly improve the parameterisation scheme used for this evergreen forest site.

Within the framework of the proposed evaluation scheme the criteria 1 and 2 identified poor quality measurements due to meteorological conditions, i.e.

measurement problems due to rain, fog or ice in winter time. The use of the criteria 3 and 4 provide fundamental and robust quality assessment of turbulent flux data. Especially above forest sites, any further rejection of data related to the dependence of night-time NEE on turbulent mixing or decoupling within the canopy should use more specific information than u_* measured above the canopy in order to prevent the risk of double accounting of respiratory fluxes. Extended CO_2 concentration measurements at the forest floor could provide more detailed insight into characteristic patterns of CO_2 exchange from below the canopy.

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References

Aubinet, M., Clement, R., Elbers, J. A., Foken, T., Grelle, A., Ibrom, A., Moncrieff, J., Pilegaard, K., Rannik, U., Rebmann, C., 2003. Methodlogogy for data acquisition, storage and treatment. In: Valentini, R. (Ed.), Fluxes of Carbon, Water, Energy of European Forests. Vol. 163 of Ecological Studies. Springer, Heidelberg, pp. 9–35.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, 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. In: Advances in Ecological Research. Vol. 30. Academic Press, San Diego, pp. 113–175.

Baldocchi, D., Falge, E., Gu, L. H., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X. H., Malhi, Y., Meyers, T., Munger, W., Oechel, W., U, K. T. P., Pilegaard, K., Schmid, H. P., 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 vapor, and energy flux densities. Bull. Amer. Met. Soc. 82, 2415–2434.

Buchmann, N., 2000. Biotic and abiotic factors controlling soil respiration rates in Picea abies stands. Soil Biol. Biochem. 32, 1625–1635.

Carrara, A., Kowalski, A. S., Neirynck, J., Janssens, I. A., Yuste, J. C., Ceulemans, R., 2003. Net ecosystem CO_2 exchange of mixed forest in Belgium over 5 years. Agric. For. Meteorol. 119, 209–227.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grunwald, T., Hollinger, D., Jensen, N. O., Katul, G., Keronen, P., Kowalski, A., Lai, C. T., Law, B. E., Meyers, T., Moncrieff, H., Moors, E., Munger, J. W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agric. For. Meteorol. 107, 43–69.

Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B., Munger, W., 2004. Post-field data qualtiy control. In: Lee, X., Massman, W., Law, B. E. (Eds.), Handbook of Micrometeorology. Kluwer, Dordrecht, pp. 181–208.

Foken, T., Skeib, G., Richter, S., 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.

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: A German case study. Vol. 172 of Ecological Studies. Springer, Heidelberg, pp. 15–41.

Goulden, M. L., Munger, J. W., Fan, S.-M., Daube, B. C., Wofsy, S. C., 1996. "measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy". Global Change Biol. 2, 169–182.

Greco, S., Baldocchi, D., 1996. Seasonal variations of CO_2 and water vapour exchange rates over a temperate deciduous forest. Global Change Biol. 2, 183–197.

Griffis, T. J., Black, T. A., Morgenstern, K., Barr, A. G., Nesic, Z., Drewitt, G. B., Gaumont-Guay, D., McCaughey, J. H., 2003. Ecophysiological controls on the carbon balances of three southern boreal forests. Agric. For. Meteorol. 117, 53–71.

Gu, L., Falge, E. M., Boden, T., Baldocchi, D. D., Black, T., Saleska, S. R., Suni, T., Verma, S. B., Vesala, T., Wofsy, S. C., Xu, L., 2005. Objective threshold determination for nighttime eddy flux filtering. Agric. For. Meteorol. 128, 179–197.

Högström, U., 1990. Analysis of turbulence structure in the surface layer with a modified similarity formulation for near neutral conditions. J. Atm. Sci. 47, 1949–1972.

Højstrup, J., 1981. A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux. Boundary-Layer Meteorol. 21, 341–356.

Højstrup, J., 1993. A statistical data screening procedure. Measuring Science Technology 4, 153–157.

Hollinger, D. Y., Goltz, S. M., Davidson, E. A., Lee, J. T., Tu, K., Valentine, H. T., 1999. Seasonal patterns and environmental control of carbon dioxide and water vapour exchange in an ecotonal boreal forest. Global Change Biol. 5, 891–902.

Hollinger, D. Y., Kelliher, F. M., Byers, J. N., Hunt, J. E., McSeveny, T. M., Weir, P. L., 1994. Carbon dioxide exchange between an undisturbed old-growth temperate forest and the atmosphere. Ecology 75, 134–150.

Hui, D. F., Wan, S. Q., Su, B., Katul, G., Monson, R., Luo, Y. Q., 2004. Gap-filling missing data in eddy covariance measurements using multiple imputation (MI) for annual estimations. Agric. For. Meteorol. 121, 93–111.

Kaimal, J. C., Wyngaard, J. C., Izumi, Y., Coté, O. R., 1972. Spectral characteristics of surface-layer turbulence. Quart. J. Roy. Meteor. Soc. 98, 563–589.

Kramer, P., Kozlowski, T., 1979. Enzymes, energetics, and respiration. In: Physiology of Woody Plants. Academic Press, New York, pp. 223–257.

Lee, X., Massman, W., Law, B. E. (Eds.), 2004. Handbook of micrometeorology. A guide for surface flux measurement and analysis. Kluwer, Dordrecht.

Lindroth, A., Grelle, A., Moren, A.-S. a., 1998. Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity. Global Change Biol. 4, 443–450.

Liu, H. P., 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, J., 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8, 315–323.

Lüers, J., Klemm, O., Foken, T., 2005. Klimatologie und Deposition von Luftschadstoffen im Fichtelgebirge, Climatology and deposition of airborne pollutents in the Fichtelgebirge. In: Foken, T. (Ed.), Klimatologische und mikrometeorologische Froschungen im Rahmen des Bayreuther Institutes für terrestrische Ökosystemforschung (BITÖK) 1998 - 2004. Vol. 29 of Arbeitsergebnisse. Universität Bayreuth, Abt. Mikrometeorologie, Bayreuth, Germany. Print, ISSN 1614-8916, pp. 7–46.

Massman, W. J., Lee, X., 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. Agric. For. Meteorol. 113, 121–144.

Mauder, M., Foken, T., 2004. Documentation and instruction manual of the eddy covariance software package TK2. Arbeitsergebnisse 26, Universität Bayreuth, Abt. Mikrometeorologie, Bayreuth, Germany. Print, ISSN 1614-8916.

Michaelis, L., Menton, M. L., 1913. Die kinetik der invertinwirkung, kinetics of the invertin reaction. Biochem. Z. 49, 333.

Moncrieff, J. B., Malhi, Y., Leuning, R., 1996. The propagation of errors in long-term measurements of land-atmosphere fluxes of carbon and water. Global Change Biol. 2, 231–240.

Moore, C. J., 1986. Frequency response corrections for eddy correlation sys-

tems. Boundary-Layer Meteorol. 37, 17–35.
Obukhov, A. M., 1960. O strukture temperaturnogo polja i polja skorostej v uslovijach konvekcii. Izvestia AN SSSR, seria Geofizika, 1392–1396.
Panofsky, H. A., Tennekes, H., Lenschow, D. H., Wyngaard, J. C., 1977. The characteristics of turbulent velocity components in the surface layer under convective conditions. Boundary-Layer Meteorol. 11, 355–361.
Rapp, J., 2000. Konzeption, Problematik und Ergebnisse klimatologischer Trendanalysen für Eruopa und Deutschland, Concept, problems and results of climatological trend analysis for Europe and Germany. Berichte des Deutschen Wetterdienstes Nr. 212. Tech. rep., German Meteorological Service, Offenbach a. M., Germany.
Rapp, J., Schönwiese, C.-D., 1994. Thermische Jahreszeiten als anschauliche Charakteristik klimatischer Trends, Thermal Seasons as descriptive characteristic of climatological trends. Meteorol. Z. 3, 91–94.
Rayment, M. B., Jarvis, P. G., 2000. Temporal and spatial variation of soil co2 efflux in a canadian boreal forest. Soil Biol. Biochem. 32, 35–45.
Rebmann, C., 2003. Kohlendioxid-, Wasserdampf und Energieaustausch eines Fichtenwaldes in Mittelgebirgslage in Nordostbayern, Carbon dioxide, water vapor and energy exchange of a spruce forest in midrange mountains in North-East Bavaria. Phd thesis, University of Bayreuth.
Rebmann, C., Anthoni, P., Falge, E., Göckede, M., Mangold, A., Subke, J. A., Thomas, C., Wichura, B., Schulze, E. D., Tenhunen, J. D., Foken, T., 2004. Carbon budget of a spruce forest ecosystem. In: Matzner, E. (Ed.), Biogeochemistry of Forested Catchments in a Changing Environment: A german case study. Vol. 172 of Ecological Studies. Springer, Heidelberg, pp. 143–159.
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., Granier, A., Grünwald, T., Guyon, D., Havrankova, K., Heinesch, B., Knohl, A., Laurila, T., Longdoz, B., Marcolla, B., Markkanen, T., Miglietta, F., Moncrieff, H., Montagnani, L., Moors, E., Nardino, M., Ourcvial, J.-M., Rambal, S., Rannik, U., 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.
Reichstein, M., Rey, A., Freibauer, A., Tenhunen, J., Valentini, R., Banza, J., Casals, P., Cheng, Y., Grünzweig, J. M., Irvine, J., Joffre, R., Law, B. E., Loustau, D., Miglietta, F., Oechel, W., Ourcival, J.-M., Pereira, J. S., Peressotti, A., Ponti, F., Qi, Y., Rambal, S., Rayment, M., Romanya, J., Rossi, F., Tedeschi, V., Tirone, G., Xu, M., Yakir, D., 2003. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature and vegetation productivity indices. Global Biogeochemical Cycles 17, 1104, doi:10.1029/2003GB002035.
Ruppert, J., 2005. Messung turbulenter Flüsse von Kohlendioxid und stabilem Kohlenstoffisotop ^{13}C über Pflanzenbeständen mit Hilfe der Relaxed Eddy Accumulation Methode, Measurements of turbulent fluxes of carbon dioxide and stable carbon isotopes ^{13}C above plant canopies using the re-

laxed eddy accumulation method. In: Foken, T. (Ed.), Klimatologische und mikrometeorologische Froschungen im Rahmen des Bayreuther Institutes für terrestrische Ökosystemforschung (BITÖK) 1998 - 2004. Vol. 29 of Arbeitsergebnisse. Universität Bayreuth, Abt. Mikrometeorologie, Bayreuth, Germany. Print, ISSN 1614-8916, pp. 83–106.

Schotanus, P., Nieuwstadt, F. T. M., DeBruin, H. A. R., 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluctuations. Boundary-Layer Meteorol. 26, 81–93.

Suni, T., Berninger, F., Vesala, T., Markkanen, T., Hari, P., Makela, A., Ilvesniemi, H., Hanninen, H., Nikinmaa, E., Huttula, T., Laurila, T., Aurela, M., Grelle, A., Lindroth, A., Arneth, A., Shibistova, O., Lloyd, J., 2003. Air temperature triggers the recovery of evergreen boreal forest photosynthesis in spring. Global Change Biol. 9, 1410–1426.

Tang, J. W., Baldocchi, D. D., Qi, Y., Xu, L. K., 2003. Assessing soil co2 efflux using continuous measurements of co2 profiles in soils with small solid-state sensors. Agric. For. Meteorol. 118, 207–220.

Tennekes, H., 1982. Similarity relations, scaling laws and spectral dynamics. In: Nieuwstadt, F., Van Dop, H. (Eds.), Atmospheric turbulence and air pollution modelling. D. Reidel Publishing Company, Dordrecht, Boston, London, pp. 37– 68.

Thomas, C., Foken, T., 2002. Re-evaluation of integral turbulence characteristics and their parameterisations. In: 15th Symposium on Boundary Layers and Turbulence. Am.Meteorol.Soc., Wageningen, The Netherlands, pp. 129–132.

Thomas, C., Foken, T., 2005a. Coherent structures in a tall spruce canopy: Temporal scales, structure spacing and terrain effects. Boundary-Layer Meteorol., submitted.

Thomas, C., Foken, T., 2005b. Detection of long-term coherent exchange over spruce forest using wavelet analysis. Theor. Appl. Climatol. 80, 91–104.

Thomas, C., Foken, T., 2005c. Flux contribution of coherent structures and its implications for the exchange of energy and matter in a tall spruce canopy. Boundary-Layer Meteorol., submitted.

Thomas, C., Ruppert, J., Lüers, J., Schröter, J., Mayer, J., Bertolini, T., May 2004 2004. Documentation of the WALDATEM-2003 Experiment, 28.4.-3.8.2003. Arbeitsergebnisse 24, Universität Bayreuth, Abt. Mikrometeorologie, Bayreuth, Germany. Print, ISSN 1614-8916.

Vickers, D., Mahrt, L., 1997. Quality control and flux sampling problems for tower and aircraft data. J. Atmos. Ocean. Tech. 14, 512–526.

Webb, E. K., Pearman, G. I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quart. J. Roy. Meteor. Soc. 106, 85–100.

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

WMO, 1995. Manual on codes - International codes VOLUME I.1, Annex II to WMO technical regulations, Part A - Alphanumeric codes. WMO-No. 306, World Meteorological Organization, Geneve.

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.
Yaglom, A., 1979. Similarity laws for constant-pressure and pressure-gradient turbulent wall flows. Annu. Rev. Fluid Mech. 11, 505– 540.

Erklärung

Hiermit erkläre ich, dass ich die Arbeit selbständig verfasst und keine anderen als die angegebenen Hilfsmittel verwendet habe.

Weiterhin erkläre ich, dass ich nicht anderweitig mit oder ohne Erfolg versucht habe, eine Dissertation einzureichen oder mich einer Doktorprüfung zu unterziehen.

Bayreuth, den 24.01.2006

Matthias Mauder