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

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With 8 Figures

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Summary

Measuring turbulent fluxes with the eddy covariance method has become a widely accepted and powerful tool for the determination of long term data sets for the exchange of momentum, sensible and latent heat, and trace gases such as CO_2 between the atmosphere and the underlying surface. Several flux networks developed continuous measurements above complex terrain, e.g. AmeriFlux and EUROFLUX, with a strong focus on the net exchange of

CO_2 between the atmosphere and the underlying surface. Under many conditions basic assumptions for the eddy covariance method in its simplified form, such as stationarity of the flow, homogeneity of the surface and fully developed turbulence of the flow field, are not fulfilled. To deal with non-ideal conditions which are common at many FLUXNET sites, quality tests have been developed to check if these basic theoretical assumptions are valid.

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

1. Introduction

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

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

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

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

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

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

2. Methodology for site characterisation

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

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

2.1 Quality assessment

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.2 Footprint modelling

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

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

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

2.3 Source weight synthesis

To produce the cumulative characterisation of the flux data quality for a specific site, the results of the footprint calculations were connected with the quality assessment of turbulent flux data. The products of the procedure are two-dimensional matrices. These matrices show, for example, the dominating data quality class for each of the grid cells of the matrix surrounding the tower, and can be combined with its contribution to the total flux.

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

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

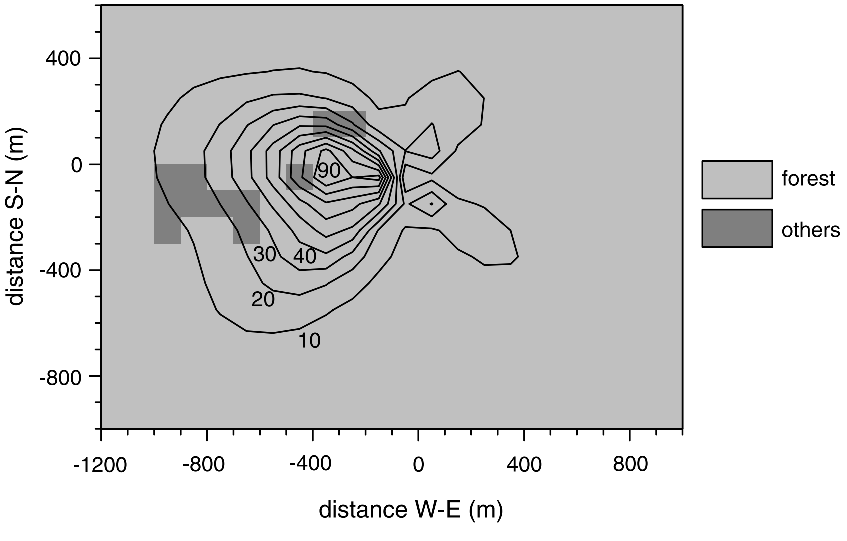

Fig. 1. The relative flux contribution determined with the analytic footprint model for DE-Wei (Waldstein Weidenbrunnen) for the period May 1st–Aug 31st, 1998, including all stratification regimes ($-2.0 \leq \zeta \leq 0.4$). Original size of grid cells for the calculations: 100 m. The grid cell with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

each quality feature is determined by the median of the distribution of summed weighting factors.

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

3. Footprint modelling and quality checks applied on CARBOEUROFLUX data

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

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

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

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

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

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

4. Results

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

For the sites for which we performed the additional model runs with z_0-values depending on canopy height, generally less stable and unstable cases could be calculated by the FSAM-routine. This resulted from restrictions of the model to certain intervals of the ratios of measurement height and roughness length, measurement height and Obukhov length, and standard deviation of

Table 3. Characteristics of the participating flux measuring sites

Site code	Site name	Type of orography	Elevation (m)	Measuring height (m)	Canopy height (m)	Type of land use intended to be observed (AOI)	Period with data available for footprint calculations	Period for which quality tests were performed	Citation
BE-Vie	Vielsalm	gently sloping	450	40.0	27/35	Fagus sylvatica, Pseudotsuga menziesii	01.05.–31.08.2000	01.05.–31.08.2000	Aubinet et al. (2002)
BE-Bra	Brasschaat	flat	16	41.0	22	Pinus sylvestris, Quercus robur	31.05.–01.09.2000	31.05.–17.08., 23.08.–31.08.2000	Carrara et al. (2003)
CZ-BKr1	Bily Kriz	strong slope	900	12.0	8	Picea abies	01.07.–30.09.2000	01.07.–30.09.2000	Spunda et al. (1998)
FI-Hyy	Hyytiälä	gently sloping	181	23.3	14	Pinus sylvestris, Picea abies	01.05.–31.08.2001	07.05.–15.07.2001	Vesala et al. (1998)
FI-Sod	Sodankylä	flat	179	23.5	10–18	Pinus sylvestris	01.05.–30.09.2001	02.06.–18.07.2001	Laurila et al. (2003)
FI-Kaa	Kaamanen	flat	155	5.0	0.5	Wetland	01.05.–30.09.2000	07.06.–22.08.2000	Aurela et al. (2002)
FR-Hes	Hesse	flat/hilly	300	22.0	13	Fagus sylvatica	17.04.–31.12.2000	01.06.–28.08.2000	Granier et al. (2000)
FR-LBr	LeBray	flat	60	41.5	20	Pinus pinaster	07.05.–31.08.2000	01.07.–31.08.2000	Berbigier et al. (2001)
FR-Pue	Puechabon	flat	270	12.2	6.5	Quercus ilex	03.05.–31.07.2001	03.05.–03.06.2001	Joffre et al. (2003)
DE-Wei	Waldstein	hilly	780	32.0	19	Picea abies	01.05.–31.08.1998	01.05.–31.08.1998	Rebmann et al. (2004)
DE-Tha	Tharandt	flat/hilly	380	42.0	29	Picea abies	31.05.–30.08.2000	01.06.–30.06.2000	Bernhofer et al. (2003)
DE-Hai	Hainich	gently sloping	438	43.5	33	Fagus sylvatica	01.06.–31.08.2001	01.06.–31.08.2001	Knohl et al. (2003)
IL-Yat	Yatir	hilly	630	18.8	10	Pinus halepensis	01.01.–31.03.2001	01.01.–31.03.2001	Grünzweig et al. (2003)
IT-Ren	Renon	hilly, alpine	1730	40.0	28	Picea abies	05.10.–05.12.2001	04.10.–03.12.2001	Montagnani (1999)
IT-Non	Nonantola	flat	40	13.0	7	Quercus robur	01.04.–31.07.2001	01.06.–30.06.2001	Nardino et al. (2002)
IT-Lav	Lavarone	hilly, alpine	1370	33.0	28	Mixed: Abies alba, Picea abies, Fagus sylvatica	22.05.–30.09.2001	22.05.–30.09.2001	Marcolla et al. (2003)
NL-Loo	Loobos	flat	25	27.0	15.5	Pinus sylvestris	31.05.–30.08.2000	02.06.–14.07.2000	Dolman et al. (2002)
UK-Gri	Griffin	hilly	340	15.4	10	Picea sitchensis	09.01.–06.12.2000	18.06.–08.07.2000	

the crosswind velocity and friction velocity, respectively (see Göckede et al., 2004). Consequences concerning the quality features are minor.

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

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

4.1 Land use classification

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

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

In the example shown in Fig. 2a, for the period from Jan 9th through Dec 6th, 2000, all investigated half-hourly fluxes (7062) originated with more than 80% from the land use intended to be observed. The two peaks with the highest flux contribution are almost totally influenced by the land use intended to be observed. Only small areas with flux contributions of less than 40% are influenced by different land uses than forest.

For seven sites the land use intended to be observed contributes for more than 90% of all cases with more than 80% to the measured fluxes (FI-Kaa, FR-LBr, DE-Hai, IT-Ren, IT-Non, IT-Lav, NL-Loo, see Table 4). For the sites where the land use matrices were determined from remote sensing data (FI-Hyy, FI-Sod, FI-Kaa, FR-Hes and DE-Tha), the results generally look worse, because of the higher spatial resolution (20–25 m) and the enhanced differentiation of the land use classes compared to the sites where the matrices were determined from topographical maps. The exception is FI-Kaa, Kaamanen,

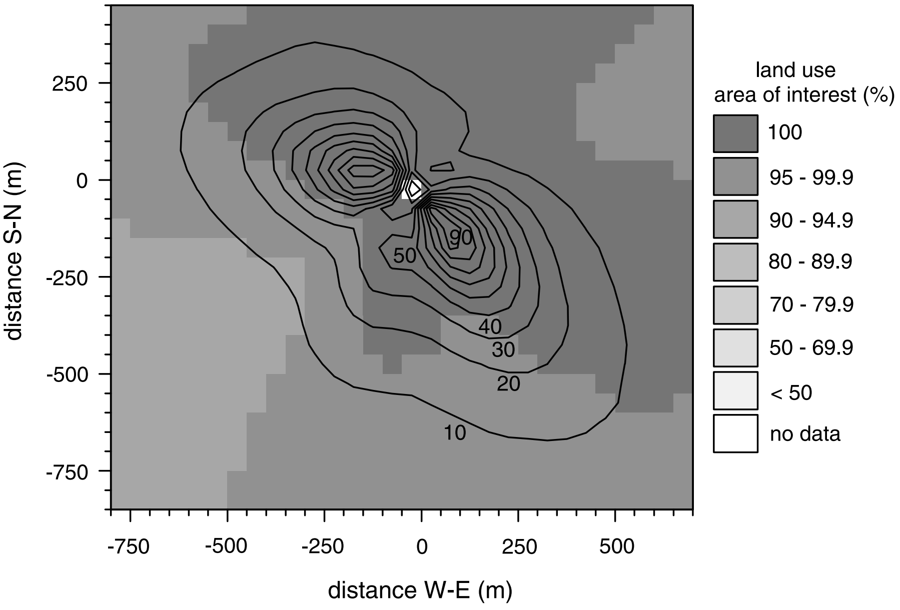

Fig. 2a. Representation of the land use classification with the relative flux contribution for UK-Gri (Griffin) for the period Jan 9th–Dec 6th, 2000, including all stratification regimes. Original size of grid cells for the calculations: 50 m. Dark greyscales indicate high contribution from the area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

Table 4. Land use classification (AOI is area of interest, meaning the land use type intended to be observed) and quality tests for the fluxes of momentum (including integral turbulence characteristics), sensible heat H, latent heat λE and carbon dioxide flux F_{CO_2} (only stationarity) and vertical wind component $|\bar{w}|$. Numbers are relative to the total number of investigated cases for each site in %

Site	AOI > 80%	τ flag 1–2	H stflag 1	λE stflag 1	F_{CO_2} stflag 1	$\lvert\bar{w}\rvert < 0.35\,\mathrm{m\,s^{-1}}$
BE-Vie	79	90	84	54	83	100
BE-Bra	60	83	82	76	76	100
CZ-BKr1	100	84	82	53	85	53
FI-Hyy	70	92	86	73	93	100
FI-Sod	59	93	89	86	86	100
FI-Kaa	94	92	92	96	89	93
FR-Hes	32	86	80	64	72	99
FR-LBr	93	72	74	62	79	93
FR-Pue	100	87	91	82	84	100
DE-Wei	86	91	87	51	80	98
DE-Tha	80	85	86	81	87	99
DE-Hai	97	93	90	71	87	100
IL-Yat	100	89	85	58	90	92
IT-Ren	98	51	60	40	52	90
IT-Non	90	81	74	85	78	100
IT-Lav	99	95	79	79	41	98
NL-Loo	96	94	87	49	87	100
UK-Gri	100	91	86	63	92	97
average	85	86	83	68	80	95

where the land use intended to be observed is wetland and the measuring height is only 5 m. The low measuring height results in small footprints relatively close to the tower and hence, areas with different land use do not strongly influence the measurements. But also sites for which the land use matrices were provided with a resolution of 50, 100 or 150 m are partly strongly influenced by land use types different from the land use intended to be observed (BE-Vie, BE-Bra, DE-Wei). For BE-Vie, Vielsalm, two different forest types are intended to be observed: coniferous (Douglas fir, Silver fir, Norway spruce and Scots pine) and deciduous (beech) forest (Aubinet et al., 2002). If only the subplots conifers are taken as the species of interest, only 11% of the measured fluxes originate with more than 80% from the land use intended to be observed, and 20% for the deciduous species, respectively. ‘Mixed forest’ (both forest types combined) as land use intended to be observed contributes in 79% of all cases with more than 80% to the measured fluxes. For the conifers (deciduous) 66% (53%) of all cases have flux contributions of less than 50% from the area intended to be observed. These strong influences of land uses different from the forest type of interest is shown in Fig. 2b and 2c for the period May 1st until August 31st, 2000, with 2851 half-hourly values contributing to the graphs. The sector between 330 and 60° is favourable for the conifers, but has only small flux contribution. Westerly wind directions are more favourable for the deciduous forest, especially under unstable conditions.

4.2 *Quality tests*

Momentum flux τ: As explained earlier, the quality of the momentum flux is derived from a combination of stationarity of the covariance and the integral turbulence characteristics of the wind components u and w. Most sites (17 out of 18) show a high data quality in the momentum flux, with more than 72% of all investigated cases flagged 1 and 2. Most of this classification is due to stationarity as the integral turbulence characteristics of the wind components agree mostly with the parameterisations. On average over all sites, 86% of the data are of high quality concerning the momentum flux (86% of the data are flagged 1 and 2 if integral turbulence characteristics are also taken into account, see Table 4). Cases with lower quality

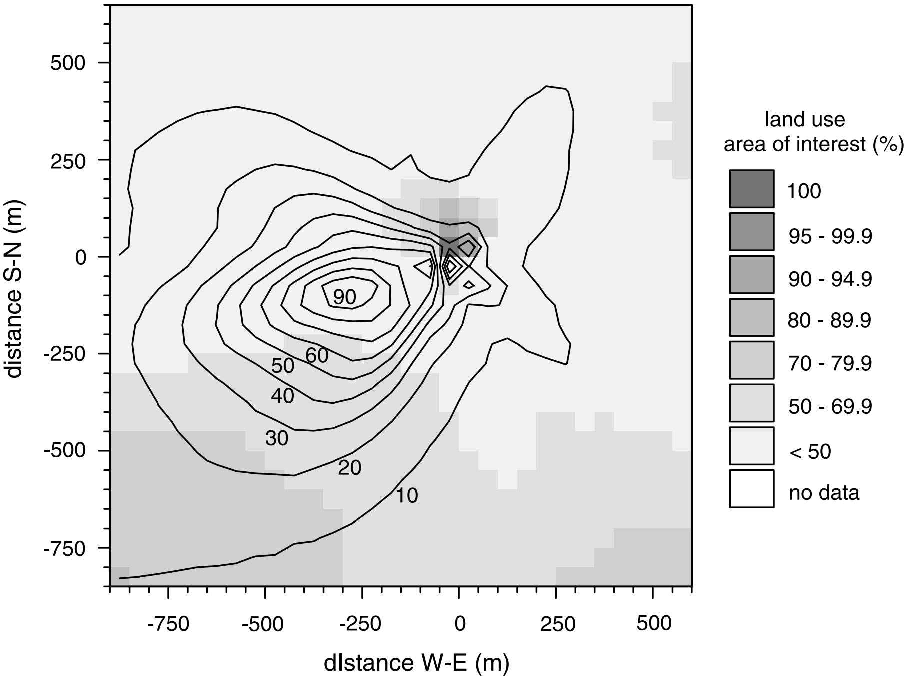

Fig. 2b. Representation of the land use classification with the relative flux contribution for BE-Vie (Vielsalm), with coniferous forest as area of interest for the period May 1st–Aug 31st, 2000, including all stratification regimes. Original size of grid cells for the calculations: 50 m. Dark greyscales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

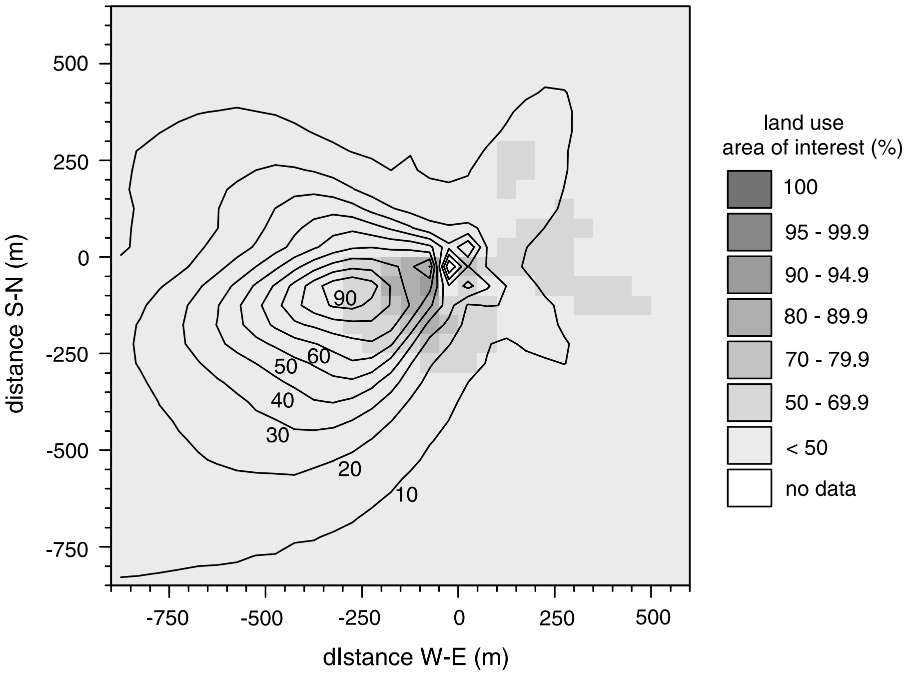

Fig. 2c. Representation of the land use classification with the relative flux contribution for BE-Vie (Vielsalm), with deciduous forest as area of interest for the period May 1st–Aug 31st, 2000, including all stratification regimes. Original size of grid cells for the calculations: 50 m. Dark greyscales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

can mostly be attributed to distinct areas, often having a different land use than that intended to be measured, but also with lower flux contributions (BE-Bra, FR-Hes, FR-LBr, FR-Pue, DE-Tha, IT-Lav). Only one site has more cases with quality flags 3 to 5 (48% of all data). But the supplied data for this site were from a period in autumn and winter with generally lower fluxes and more frequent stable conditions (IT-Ren). This results in more frequent cases with non-stationary conditions.

As an example, the aerial representation of quality flags for the momentum flux is shown for FR-Hes (Hesse) in Fig. 3 for the period

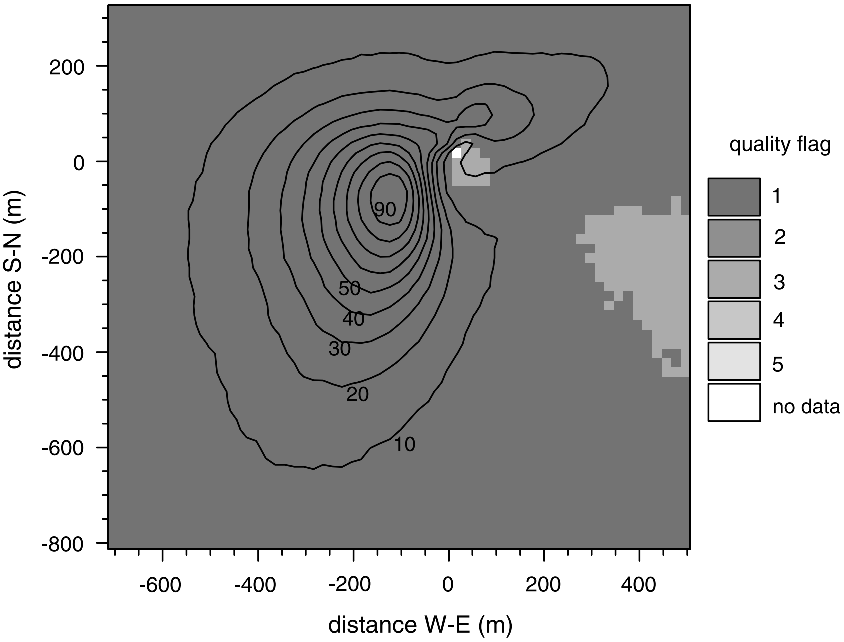

Fig. 3. Spatial distribution of stationarity flags for momentum fluxes τ with relative flux contribution for FR-Hes (Hesse) for the period Jun 1st–Aug 28th, 2000, including all stratification regimes. Original size of grid cells for the calculations: 20 m. The darkest grey indicates the highest quality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

June 1st–August 28th together with the relative flux contribution determined with the footprint model. 2032 half-hourly fluxes are contributing to this graph. Most of the grid cells are assigned to the highest quality class, except an area east of the tower of lower quality, which has only a small contribution to the fluxes (less than 10%). Only a small area north-east of the tower shows some grid elements flagged more often 3 to 5, having slightly higher flux contribution.

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

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

Latent heat flux λE: The quality flags are derived from a combination of stationarity of the covariance and the integral turbulence characteristic of the wind component *w*. We will focus here only on stationarity, as the integral turbulence characteristic of *w* is seldom negatively influenced and

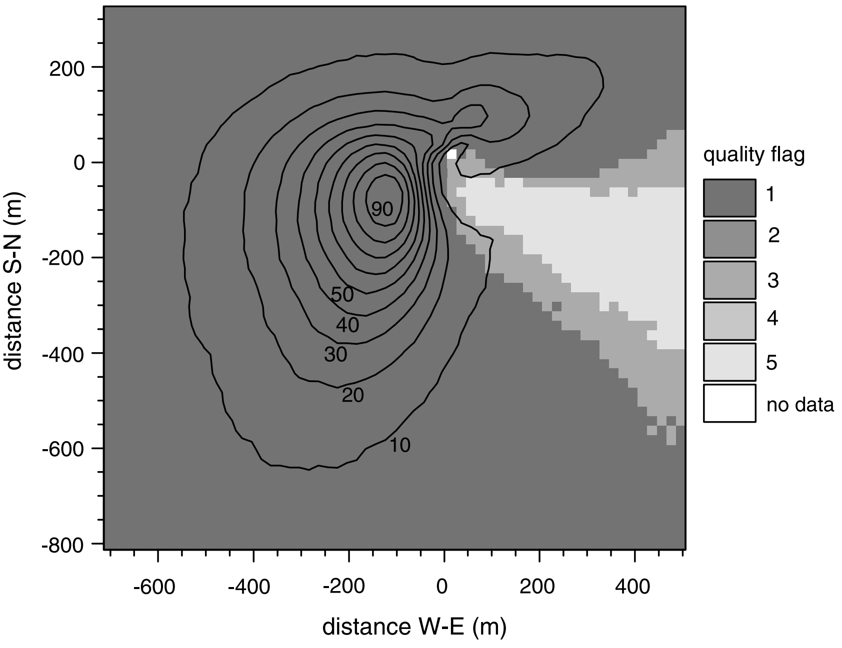

Fig. 4. Spatial distribution of stationarity flags for sensible heat fluxes H with relative flux contribution for FR-Hes (Hesse) for the period Jun 1st–Aug 28th, 2000, including all stratification regimes. Original size of grid cells for the calculations: 20 m. The darkest grey indicates the highest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

was already investigated with the momentum flux. On average over all sites, 68% of all investigated cases are in the highest quality class. Only for two sites (NL-Loo, IT-Ren), less than 50% of the measured H_2O-fluxes are flagged 1, and one site (FI-Kaa) has more than 95% of the data in this quality class. Almost all grid cells are assigned to quality class 1 as well for FI-Sod, where 86% of all measured latent heat fluxes got this quality flag. This means that at this site no wind direction or specific area causes instationarities per se. Lower quality in the latent heat flux may be attributed partly to the closed path system. Weather conditions with high air humidities or fog strongly influence the time lags between the vertical wind component and the water vapour concentration in the tubing (BE-Vie, CZ-BKr1, GE-Wei, IL-Yat). This also results in a more frequent occurrence of instationarities in the water vapour flux. This is demonstrated in Fig. 5 for CZ-BKr1, Bílý Kříž (1041 cases contributing to the graph). Higher uncertainty of the latent heat flux data is caused by the cases when the site is covered with clouds,

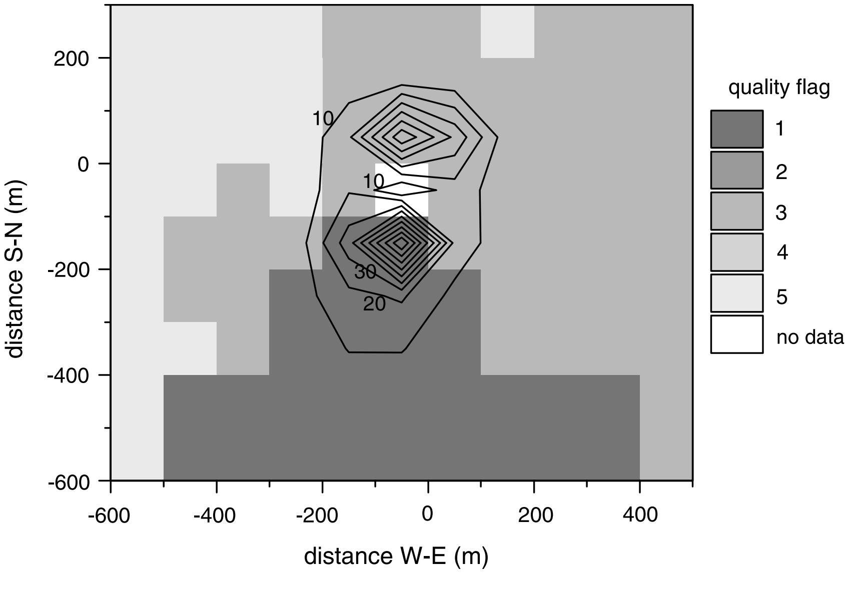

Fig. 5. Spatial distribution of stationarity flags for latent heat fluxes λE with relative flux contribution for CZ-BKr1 (Bílý Kříž) for the period Aug 17th–Sep 30th, 2000, including all stratification regimes. Original size of grid cells for the calculations: 100 m. The darkest grey indicates the highest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

sometimes accompanied by rain. Although southerly flow generally dominates at the site, more than 50% of the cloud episodes are characterised by northerly wind directions. This explains why flags 3 and 5 in Fig. 5 are associated mostly with the northern sector.

Areas with lower quality assignment are generally often in western and southern directions from the towers, where low pressure events with moist conditions usually originate in Europe. Some sites also show distinct areas with higher frequencies of instationarities apart from the latter that may be attributed to the surrounding land use (BE-Bra, FI-Hyy, FR-Hes, FR-Pue, DE-Tha, DE-Hai, IT-Non, IT-Lav, NL-Loo). The results for the sites which have been measuring with open-path systems (IT-Ren, IT-Lav) show clearly that water vapour fluxes are less often marked by instationarity if not influenced by the tubing. 6% more data are assigned to the highest quality class for the open path-system compared to the closed-path system (IT-Ren).

Carbon dioxide flux F_{CO_2}: The quality flags are derived from a combination of stationarity of the covariance and the integral turbulence characteristic of the wind component *w*. As for the latent heat flux, we will focus only on stationarity here. On average, 80% of all data are flagged 1. CO_2-fluxes are less influenced by the closed-path system compared to the water vapour fluxes. Two flux sites (FI-Hyy, UK-Gri) had more than 90% of the CO_2-fluxes assigned stationary (flag 1). For ten sites, more than 80% of the fluxes were flagged 1 (BE-Vie, CZ-BKr1, DE-Wei, DE-Tha, DE-Hai, FI-Sod, FI-Kaa, FR-Pue, IL-Yat, NL-Loo), and only small areas, if any, generally having low flux contribution, show less measurement certainties. If not flagged 1, areas are usually flagged 3, which means the deviation is less than 50% and, according to Foken and Wichura (1996), still acceptable for long-term measurements, which is the goal in the CARBOEUROFLUX project.

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

The general high quality of carbon dioxide fluxes may also result from the fact that the turbulence structures are different for scalars compared to the wind components (Katul et al.,

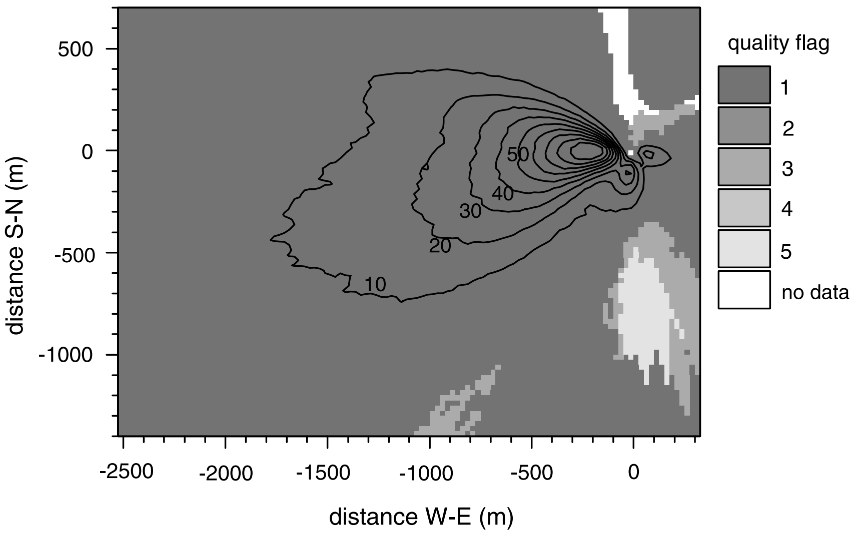

Fig. 6. Spatial distribution of stationarity flags for carbon dioxide fluxes F_{CO_2} with relative flux contribution for DE-Tha (Tharandt) for the period Jun 1st–Jun 30th, 2000, including all stratification regimes. Original size of grid cells for the calculations: 25 m. The darkest grey indicates the highest quality class. Relative flux contribution, dimension of area and isopleths according to Fig. 1

1996; Wichura et al., 2002). High frequency structures are not present and thus quality tests should be refined.

4.3 Vertical wind component *w*

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

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

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

4.4 Overall quality assessment

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

Figure 8 demonstrates the overall distribution of the relative numbers of quality flags for the fluxes of momentum τ, sensible and latent heat (H and λE), and the carbon dioxide flux $F_{\mathrm{CO_2}}$. Figure 8a represents quality flags including integral turbulence characteristics and stationarity tests, whereas Fig. 8b shows only stationarity flags.

For the momentum flux, on average over all sites 70% of the data are in the highest quality class. 27% of the data are still flagged 2 and 3 and only 3% of the data are flagged 4 and 5. Cases in classes 2 and 4 are attributed to the integral turbulence characteristics of w and u, whereas flags 1, 3 and 5 are due to stationarity, as can be seen by comparing the top left panels of Fig. 8a and 8b. The quality flags for the sensible heat flux are clearly influenced by the parameterisations of the integral turbulence characteristic of the temperature T, which are not valid for neutral and stable conditions and thus leading frequently to flag assignments of 2, 4 and 5. Stationarity per se shows most of the data flagged 1 (83%). For the latent heat flux, 65% of the fluxes are flagged 1 and only 10% are in classes 4 and 5. The average quality assessment for the carbon dioxide flux shows that 77% of all data are flagged 1 and only 5% of the data are assigned to stationarity class 5.

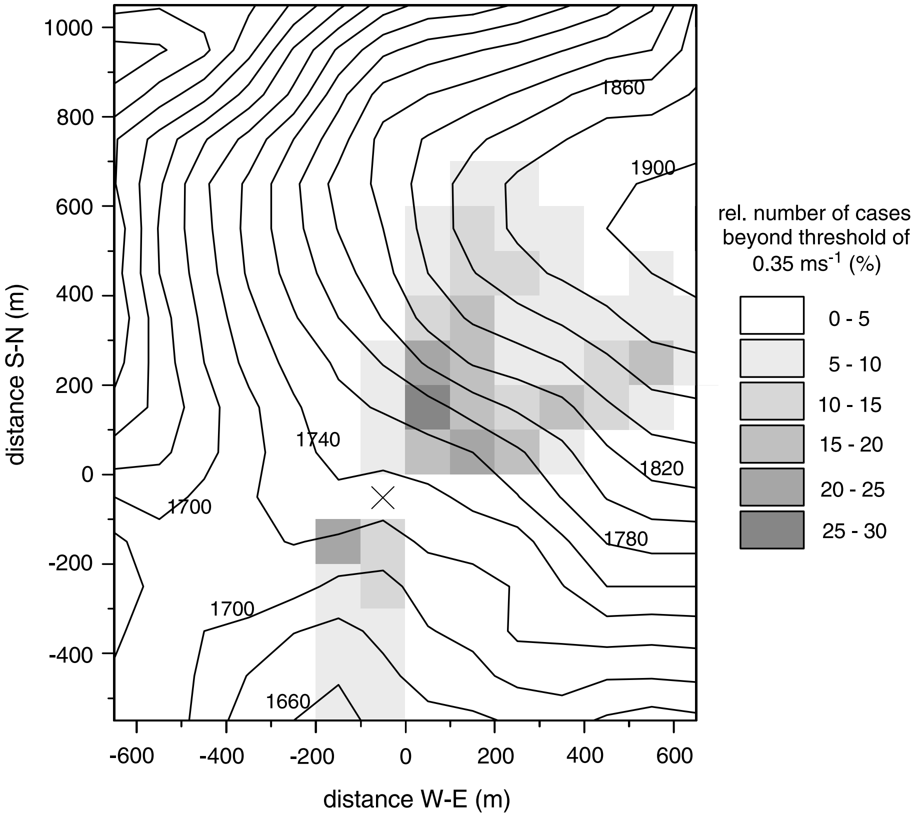

Fig. 7a. Spatial distribution of quality flags for the vertical wind component *w* with topography (isopleths: m asl) for IT-Ren (Renon) for the period Oct 4th–Dec 3rd, 2001, including all stratification regimes. Original size of grid cells for the calculations: 100 m. The tower grid is marked with a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

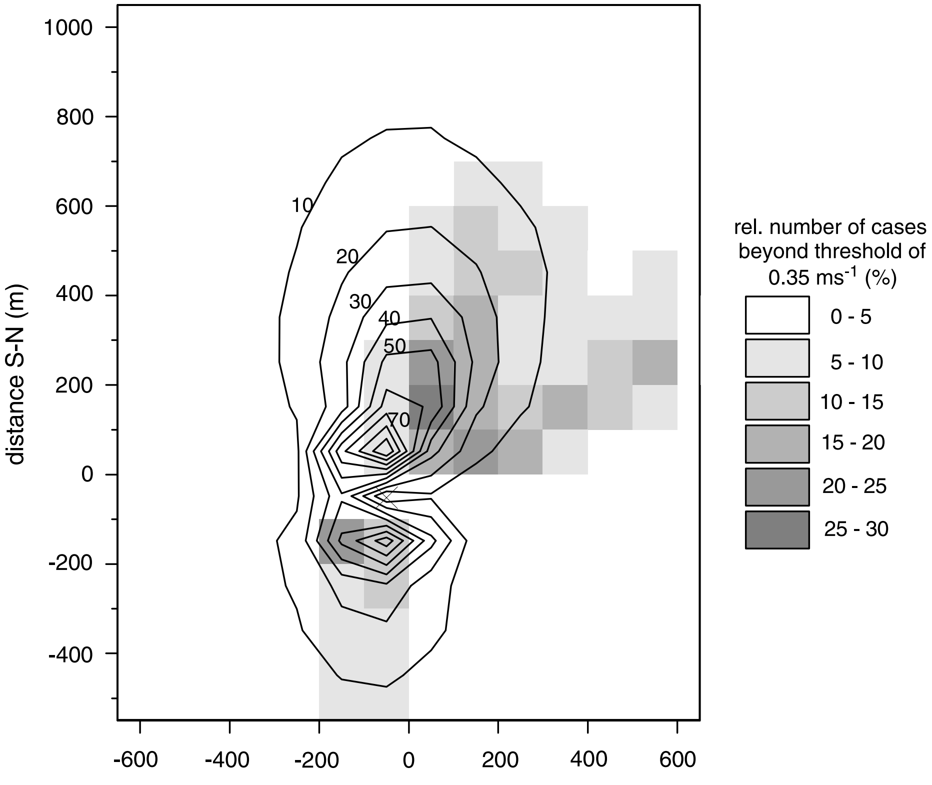

Fig. 7b. Spatial distribution of quality flags for the vertical wind component *w* with relative flux contribution (isopleths: flux contribution in %) for IT-Ren (Renon) for the period Oct 4th–Dec 3rd, 2001, including all stratification regimes. Size of the area and all other features as in Fig. 7a

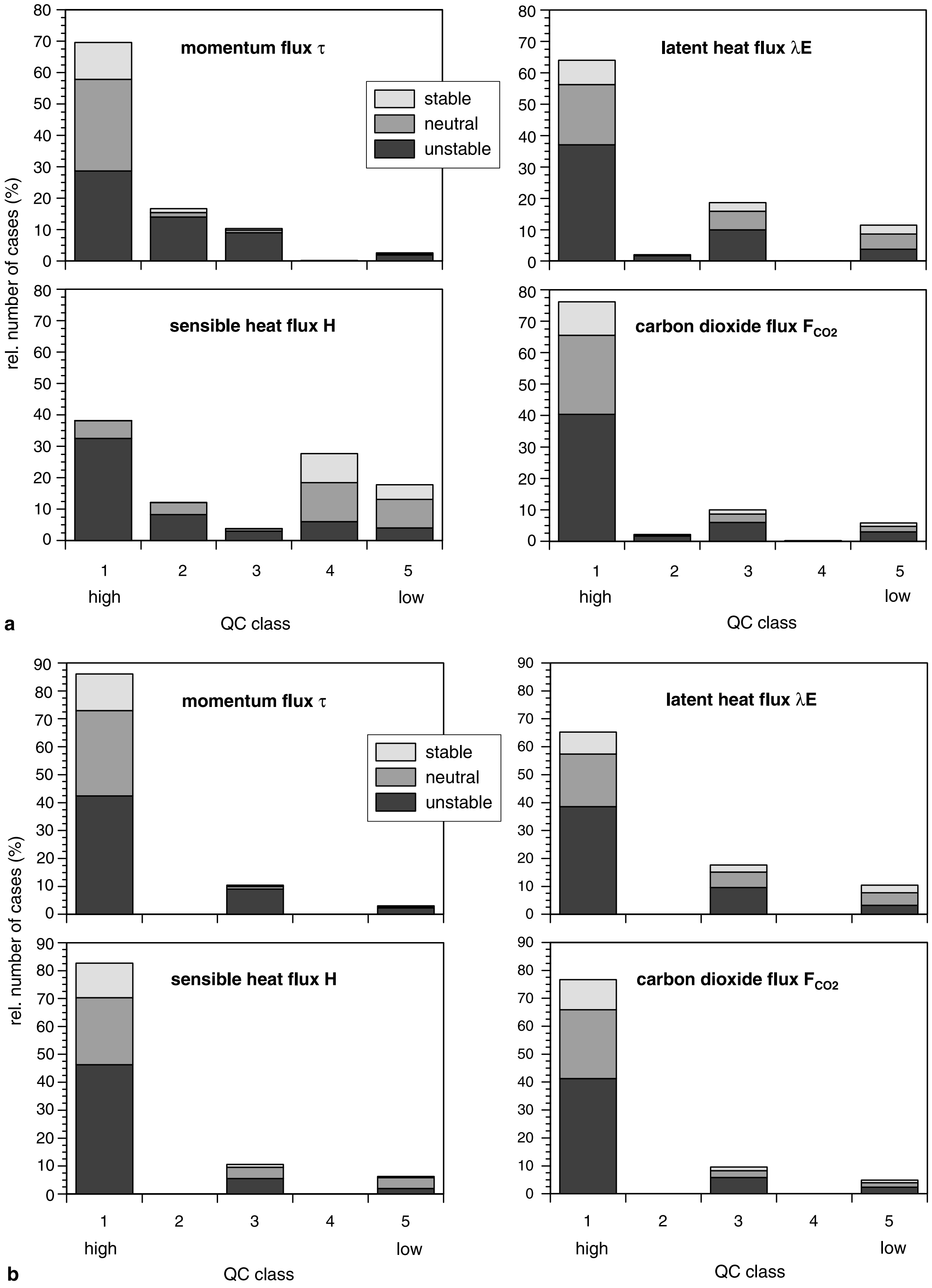

Fig. 8. Frequency distribution of quality flags relative to the number of cases per site for the fluxes of momentum τ, sensible heat H, latent heat λE and carbon dioxide F_{CO_2} as averages over all sites. **a**) Stationarity and integral turbulence characteristics, **b**) only stationarity

5. Discussion

Comparisons with Lagrangian footprint models have shown that results obtained with the analytical model of Schmid (1997) overestimate the longitudinal extension of the footprint areas, and thus provide a 'worst case' scenario concerning source area dimensions (Rannik et al., 2000; Schmid, 2002; Kljun et al., 2002). Smaller footprints with peaks closer to the tower would result in fluxes more frequently originating from the area intended to be measured as was determined in this presentation. One of the shortcomings of the analysis is that situations under strongly stable conditions ($\zeta > 0.4$) cannot by calculated by the footprint model, but these conditions are out of the range of the validity of the Monin-Obukhov similarity theory. Nevertheless, the results presented here include all meaningful stratification conditions, even though the picture is slightly biased concerning the frequency distribution of atmospheric stability. Both effects, the overestimation of the footprint dimensions and the relative low number of cases of stable conditions, probably cancel out each other if all stratification regimes are regarded together. Furthermore, the applied quality tests are not valid for very stable conditions anyhow, and fluxes occurring under low turbulence conditions are omitted when determining the net ecosystem exchange of carbon dioxide (NEE). Thus the bias in the analysis caused by less stable cases compared to neutral and unstable cases does not have a large influence on the results obtained with the footprint model. In general fluxes of low measurement certainty are more frequent under neutral and stable conditions, and if they originate from areas more far away from the tower. This is clear for example for the latent heat flux which is close to zero at night and the stationarity test is not reasonable under this conditions.

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

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

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

6. Conclusions

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

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

Acknowledgements

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