P1.30 ON THE QUALITY ASSURANCE OF SURFACE ENERGY FLUX MEASUREMENTS

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1. MOTIVATION

The fact that micrometeorological measurements of energy exchange processes at the surface are often not able to close the energy balance (Foken & Oncley 1995) motivated us to address the issue of quality assurance of these surface energy flux measurements. We concentrated on three parts of this issue: the determination of turbulent heat fluxes with their corrections and quality tests, footprint model based quality assessment for the turbulent heat fluxes, and methods to measure the ground heat flux. All data within this study were measured during the LITFASS-2003 field campaign (Beyrich et al., 2004). Our own work does not go deeper into radiation measurements, but we referred to the BSRN recommendations which represent a good standard (Gilgen et al., 1994).

2. DETERMINATION AND QUALITY ASSURANCE OF TURBULENT HEAT FLUXES

2.1 *Post processing of turbulent fluxes*

The only way to measure turbulent heat fluxes directly is the eddy covariance method. In general, turbulent heat fluxes are calculated as the covariance between the two high frequency time series of vertical wind velocity and a scalar temperature or humidity, measured at one point in time. Inherent to these atmospheric measurements are deficiencies which cause more or less important violations of assumptions to the underlying theory. Therefore, in order to obtain quality assured turbulent fluxes, we at the University of Bayreuth developed a comprehensive software package (http://www.bayceer.uni-bayreuth.de) which is capable of performing all of the post processing of turbulence measurements producing quality assured turbulent fluxes. 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.

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The major components of this quality control system are:

- Identification of spikes after Vickers and Mahrt (1997).
- Determination of the time delay between sensors (e.g. LI-7500 gas analyser and sonic) through the calculation of cross correlations.
- Cross wind correction of the sonic temperature after Liu et al. (2001), if not already implemented in sensor software (e.g. necessary for METEK USA-1).
- Planar Fit method for coordinate transformation (Wilczak et al., 2001).
- Correction of oxygen cross sensitivity of Krypton hygrometers (Tanner et al., 1993; van Dijk et al., 2003).
- 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 of scalar fluxes of H_2O and CO_2 after Webb et al. (1980) and Liebethal & Foken (2003).
- Iteration of the correction steps because of their interacting dependence.
- Spectral analysis and determination of cumulative integral under spectra, the so called ogives (Oncley, 1989).
- Quality control of the calculated fluxes after Foken & Wichura (1996).

The application of this procedure on the data from 15 micrometeorological stations during the LITFASS-2003 campaign allows us to asses the quality of turbulent fluxes. For one selected site (A6), Figure 1 shows the proportion of half hour values of latent heat flux between 06:00 and 20:00 UTC, which were classified as the highest quality, indicating data which can be used for fundamental research. These are the quality classes 1-3 according to Foken et al. (2004).

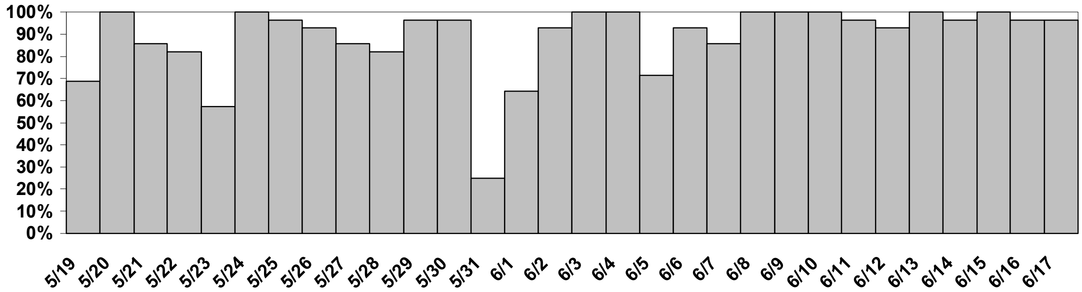

Figure 1: Availability of high quality latent heat flux data in % between 0600 and 2000 UTC. Micrometeorological site LITFASS-2003 A6, corn field in Brandenburg/Germany. Measurement period from May 19th to June 17th 2003

For most of the days during the measurement campaign of LITFASS-2003 more than 90% of high quality latent heat flux data were available on this corn field site A6 during the daytime. Significantly lower percentages on May 19th, May 22nd and June 5th 2003 were mainly caused by rain events. On May 31st and June 1st we suffered data transmission interruptions. Thus, this method is not only able to detect meteorological deficiencies but also technical measurement problems.

2.2 *Intercomparison experiment*

Besides fulfilling the theoretical assumptions of the eddy covariance method, another source of uncertainty in determining turbulent heat fluxes is the instrumentation. To find out about the special characteristics of sonic anemometers and fast response humidity sensors, we operated seven turbulence complexes together side by side within a distance of approx. 8.50 m and at the uniform height of 3.25 m (see Figure 2). This intercomparison of the sensors had been started already one year before the main experiment. The reference measurement complexes consisted of a Campbell CSAT3 sonic anemometer combined with the LI 7500 infrared gas analyser (LiCor Inc.), operated by the University of Bayreuth. Furthermore, the METEK USA-1 sonic anemometer and the Campbell KH20 Krypton hygrometer were used. The different sensors were operated by the following groups: German Meteorological Service, Meteorological Observatory Lindenberg, GKSS Research Centre Geesthacht, the Meteorology Group of the Wageningen University, the University of Hamburg, the Dresden University of Technology, and the University of Bayreuth.

The results for the measurements of statistical moments are only compared for a relatively small wind direction sector of 45° width, where the measurements of all turbulence complexes are undisturbed by each other and are equally influenced by a footprint area representing the same canopy type grassland. We found systematic deviations between the different sensors of up to 5% for the sensible heat flux and up to 25% for the latent heat flux.

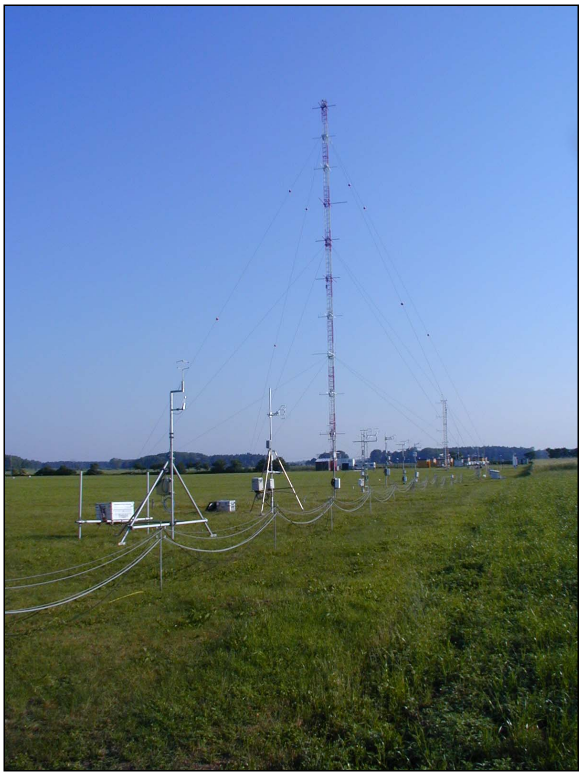

Figure 2: Turbulence intercomparison experiment EVA_GRIPS 2002 at the measurement site of the German Weather Service in Falkenberg/Germany (May 13th to June 7th)

3. FOOTPRINT MODEL BASED QUALITY ASSESSMENT

All sites were investigated for their footprint characteristics and the existence of internal boundary layers. Measurements were excluded if the sensor was not located within the new equilibrium layer of an internal boundary layer δ after a sudden change of the surface characteristics. This is the case after Raabe (1983) and Jegede and Foken (1999) for heights

$$z \le \delta = 0.3 \cdot \sqrt{x} \ . \tag{1}$$

with x: fetch (see Table 1).

To determine the land use composition within the source area of each measurement position, the three dimensional Lagrangian stochastic trajectory model of Langevin type (Thomson, 1987) was used. The parameterization of the flow statistics and the effect of stability on the profiles were in line with those used in Rannik et al. (2003). In the models, particles are dispersed by turbulent diffusion in a vertical direction, along mean wind and cross mean wind directions. They are then carried downwind by horizontal advection. Particles tending downwards are perfectly reflected at the height z_0. In the course of this study, the simulations were performed releasing $5 \cdot 10^4$ particles from a height close to the ground. The particles were then tracked until the upwind distance accounted for approximately 90 percent of the total flux. To save computation time, the flux footprint estimators were pre-calculated for a fixed set of stability classes, roughness lengths, and observation heights, and subsequently stored into tables of weighting factors.

Table 1: Fetch x, height of the new equilibrium layer δ, and percentage of the flux from the target land use area dependent on the wind direction and stability for site A6.

Sector	x	δ	Target land use in [%]		
	[m]	[m]	stable	neutral	unstable
30°	29	1.6	36	51	62
60°	41	1.9	49	63	74
90°	125	3.4	81	90	98
120°	360	5.7	99	100	100
150°	265	4.9	96	100	100
180°	203	4.3	92	98	100
210°	211	4.4	93	98	100
240°	159	3.8	88	95	100
270°	122	3.3	81	90	98
300°	81	2.7	70	82	91
330°	36	1.8	44	59	70
360°	28	1.6	35	50	61

The principle aim of the footprint study was to determine the flux contribution of the target land use area for different sets of wind direction and stability classes in order to check whether the measurements are representative for the specified land use type under different conditions (see Table 1). Flux data were discarded for flux contributions from the target land use (AOI) below 80%.

4. MEASUREMENT OF THE GROUND HEAT FLUX

The third issue we are dealing with is the calculation of the ground heat flux (GHF) from soil data. There are several ways to calculate the GHF from in-situ data of soil temperature, soil moisture, and/or heat flux plate (HFP) measurements. We concentrate on two combination methods: first, a combination of HFP measurements and calorimetry (HFP/c) and second, the combination of fluxes determined from temperature gradients and calorimetry (grad/c). For both methods, a reference depth z_{ref} is chosen, where the soil heat flux is calculated from the gradient approach or from HFP data.

HFP measurements taken at the reference depth are divided by the Philip factor f_{Phil} (Philip, 1961)

$$f_{Phil} = \frac{\lambda_{plate}}{\lambda_{soil} \cdot \left(1 + \left(\frac{\lambda_{plate}}{\lambda_{soil}} - 1\right) \cdot \left(1 - \frac{1.7 \cdot thick_{HFP}}{len_{HFP}}\right)\right)} \tag{2}$$

where λ is the heat conductivity of the HFP or the soil, $thick_{HFP}$ is the thickness of the HFP, and len_{HFP} is the length of the HFP.

For the grad/c approach, the vertical temperature gradient $\frac{\partial T}{\partial z}$ is multiplied by the heat conductivity of the soil to calculate the soil heat flux at the reference depth. For both approaches, the flux at the reference depth ($SHF(z_{ref})$) is extrapolated to the surface by adding the trend of the heat storage between reference depth and surface

$$GHF = SHF\left(z_{ref}\right) + z_{ref} \cdot \frac{\partial\left(\overline{c_v T}\right)}{\partial t} \tag{3}$$

where c_v is the volumetric heat capacity, T is the temperature, and t is time.

The sensitivity analysis aims to determine which of the methods tested is least sensitive to measurement errors. For this purpose, the General Likelihood Uncertainty Estimation (GLUE) approach (Beven and Binley, 1992) is employed: First, the GHF is calculated from the original data set by using the HFP/c as well as the grad/c approach, employing different reference depths (reference results data set). Afterwards, all parameters under consideration are simultaneously modified in the original input data set and all GHF results are recalculated. From the differences ("deltas") between the modified and the reference results, a so called "quality measure" L is calculated (Eq. 4). It compares the variances of the deltas with the variances of the original results. The complete procedure is repeated 10.000 times.

$$L = 1 - \frac{\sigma^2{}_{delts}}{\sigma^2{}_{orig}} \tag{4}$$

The quality measures L calculated in the sensitivity analysis are plotted against the modification of the individual soil parameters. Considering the emerging diagrams, one can draw conclusions about the effect of each soil parameter on the particular method/reference depth combination. As an example, we consider the four sensitivity diagrams in Figure 3. They expose the sensitivity of different grad/c approaches to variations in the soil moisture at 5 cm depth (θ(5 cm)). The scaling of the x-axis from 0 to 1 corresponds to a variation in θ(5 cm) from -30 % to +30 % of the measured value. For the approaches using z_{ref} = 5 cm and z_{ref} = 10 cm, the maximum quality sharply declines from 1 as soon as θ(5 cm) differs from its original value, while the other two approaches (z_{ref} = 15 cm and z_{ref} = 20 cm) still can reach a quality of 1. The minimum quality gets worse for all approaches when θ(5 cm) differs from its original value. The zref = 20 cm approach has the smallest bandwith of quality measures and thus is less affected by variations in θ (5 cm).

From the entire sensitivity study, we can draw the following conclusions:

- Errors in the soil moisture measurements influence the quality of all GHF calculation approaches. Deeper reference depths suffer less from errors in a single moisture sensor.
- Modifying deep temperature sensors causes less loss in GHF quality than modifying shallow sensors. Even for strong modifications of e.g. T(10 cm), all approaches still provide good quality. Altering e.g. T(2 cm) results in worse quality for all approaches.
- Variations in the heat flux plate output do significantly alter the quality of the HFP/c approach, especially for shallow HFPs. However, even with variations of 20 %, quality parameters of L = 1 are still gained.

For the measurement of the GHF, we give the following recommendations:

- GHF calculation procedures using shallow reference or plate depths are more sensitive to errors in the input parameters. Therefore, methods using deeper reference depths should be preferred.
- Sensors installed deeper in the soil alter the quality of GHF calculations less than sensors installed close to the ground. Accordingly, especially sensors in shallow depths should be maintained carefully.
- If these recommendations are met, even greater errors in the input data set will rarely decrease quality below 0.98.

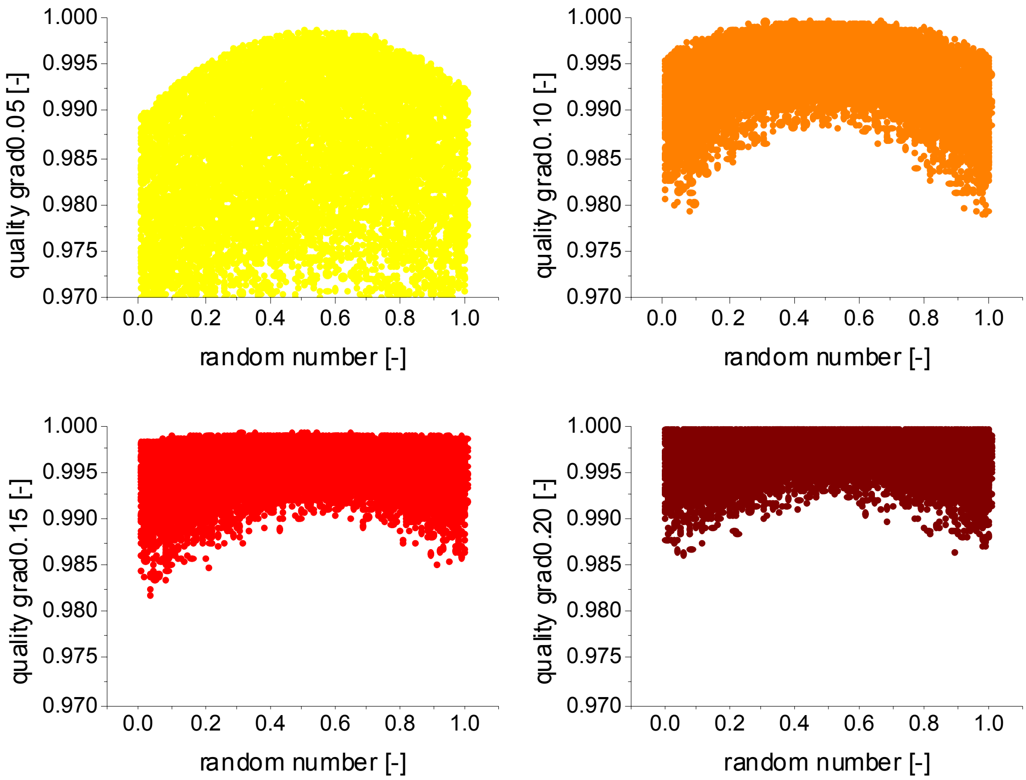

Figure 3: Sensitivity diagrams for different grad/c approaches. The reference depths are 5 cm (upper left), 10 cm (upper right), 15 cm (lower left), and 20 cm (lower right). The scaling of the x-axis (0...1) corresponds to variations in θ (5 cm) of +/- 30 % of its original value.

5. ENERGY BALANCE CLOSURE

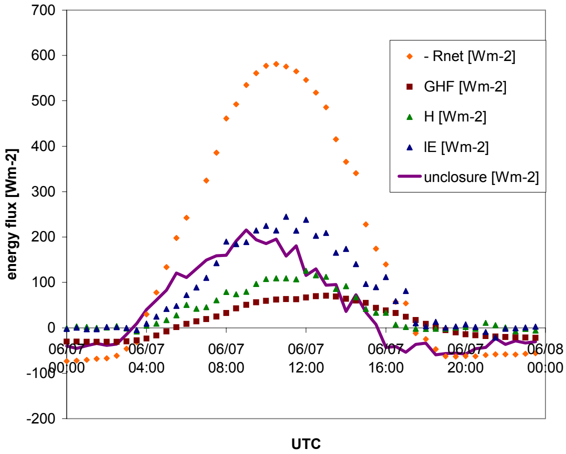

Figure 4: Results of energy flux measurements **without** the application of the presented approaches of **quality assurance and soil heat storage**. Micrometeorological site LITFASS-2003 A6, corn field in Brandenburg/Germany. June 7th 2003.

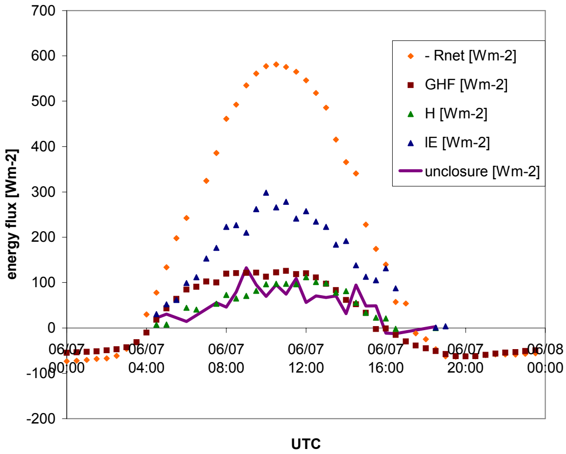

Figure 5: Results of energy flux measurements **with** the application of the presented approaches of **quality assurance and soil heat storage**. Micrometeorological site LITFASS-2003 A6, corn field in Brandenburg/Germany. June 7th 2003.

The three approaches of quality assurance for energy flux measurement, which are presented in this poster, have a significant impact on the results of energy flux measurements (see Figures 4 and 5). The latent turbulent heat flux is increased due to the Moore and WPL correction, whereas the sensible heat flux is decreased mainly as a result of the Schotanus correction. Values of turbulent fluxes, which have bad quality test results or inadequate footprint conditions, are sorted out. These criteria particularly affect nighttime fluxes, when turbulence is not well developed and the footprint area is relatively large. The ground heat flux is almost doubled in amplitude, taking the soil heat storage into account, and the maximum is reached earlier in the day.

6. CONCLUSIONS

The combination of these three approaches of quality assurance for energy flux measurement gives us much more confidence in the results. Furthermore, a significantly better closure of the energy balance can be obtained. Nevertheless, further investigations are necessary because the energy balance still cannot be closed by measurements during the daytime.

7. ACKNOWLEDGMENT

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