1.11 ATTEMPT TO CLOSE THE ENERGY BALANCE FOR THE LITFASS-2003 EXPERIMENT

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1. INTRODUCTION

During the late 1980s it became obvious that the energy balance at the earth's surface could not be closed with experimental data if all its components were measured individually. The available energy, i.e. the sum of the net radiation ($-Q_s^*$) and the ground heat flux (Q_G)

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

was found in most cases to be larger than the sum of the turbulent fluxes of sensible (Q_H) and latent (Q_E) heat. This closure problem was a main topic of a workshop held in 1994 in Grenoble (Foken and Oncley, 1995). In most of the land surface experiments (Bolle et al., 1993; Kanemasu et al., 1992; Tsvang et al., 1991), as well as in the carbon dioxide flux networks (Aubinet et al., 2000; Wilson et al., 2002), a closure of the energy balance of approximately 80% was found. An experiment designed to investigate this problem, the EBEX- 2000, took place in the summer of 2000 near Fresno, California. Its results are now submitted for publication (Oncley et al., 2006). They confirm these findings In recent papers it was found that time-averaged fluxes (Finnigan et al., 2003) or space-averaged fluxes (Kanda et al., 2004) can close the energy balance. To verify these recent results, the data set of the LITFASS-2003 experiment (Beyrich and Mengelkamp, 2006), which includes also area-averaged flux measurements, was used to attempt to close the energy balance.

2. EXPERIMENTAL SETUP

During the LITFASS-2003 experiment, which took place in a 20x20 km^2 area near the Meteorological Observatory Lindenberg, Germany, in May and June of 2003, turbulent fluxes of momentum, sensible, and latent heat were measured at nine agricultural sites, two grassland sites, one forest site, two lake sites, and at two levels of a 100 m tower (see Beyrich et al., the conference paper 5.3, Beyrich et al., 2006).

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For the present study, only the agricultural part of the study area with eleven flux towers over agricultural and grassland were used. The fluxes measured at these stations were combined to a so-called flux composite, taking into account the data quality of the individual measurements and the relative occurrence frequency of the different types of low vegetation (Beyrich et al., 2006) in relation to the typical footprint area. The footprint analysis was done with a Lagrangian footprint model (Rannik et al., 2000; Rannik et al., 2003) combined with an averaging concept for land use parameters (Göckede et al., 2006; Göckede et al., 2004). Possible internal boundary layers were indicated according to a former study by Jegede and Foken (1999) for these sites.

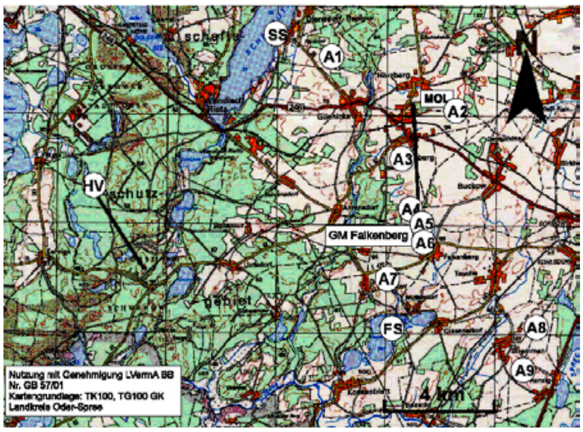


Figure 1: The area of investigation of the LITFASS-2003 experiment near the Meteorological Observatory Lindenberg (MOL), with the Boundary layer field site (GM Falkenberg) and flux tower sites. For details see Beyrich et al. (2006).

The area-averaging measurement systems were a Large Aperture Scintillometer (LAS) for the sensible heat flux (Beyrich et al., 2002a; Meijninger et al., 2002b) and a microwave scintillometer (MWS) for the latent heat flux (Meijninger et al., 2006) with a path length over approximately 5 km between the boundary layer field site Falkenberg (GM Falkenberg) and the

Meteorological Observatory Lindenberg (MOL), see Figure 1. Airborne measurements with the Helipod, a turbulence probe carried by a helicopter (Bange et al., 2006b), were performed on several days of the LITFASS-2003 experiment. One flight leg during each flight was usually oriented parallel to the LAS-MWS path.

In order to investigate the findings by Kanda et al. (2004), LES simulations for this area with the model by Raasch and Schröter (2001) were also applied to this area.

For this first study we used data from May 25, 2003. On this day the weather was cloud-free until around noon and data from both the LAS and MWS were available. Unfortunately, the MWS broke down on May 29. For the comparison with the LES results, data from May 30 was used; this day was characterised by nearly clear sky over the whole day.

3. INVESTIGATION OF SURFACE FLUXES

The most common point of discussion of the energy balance closure problem was measurement errors, especially those of the eddy-covariance technique, which cause a systematic underestimation of the turbulent fluxes. Improvements in the sensors, as well as in the correction methods, and the application of a more stringent determination of the data quality have made this method much more reliable over the past ten years (Mauder et al., 2006c; Moncrieff, 2004).

Because of different reference levels and of different sampling scales between the diverse measuring methods (for net radiation, turbulent fluxes, and soil heat flux), the energy storage in the canopy and in the soil was often discussed as one reason for the unclosed energy balance. Most of these energy storages are not significant to the problem (Oncley et al., 2006), with the exception of the heat storage in the soil.

The non-closure of the energy balance was also explained by the heterogeneity of the land surface (Panin et al., 1998). The authors assumed that the heterogeneities generate eddies at larger time scales than eddies measured with the eddy-covariance method. This problem is also closely connected with advection and fluxes due to longer wavelengths (Finnigan et al., 2003). Obviously, this problem may be the key to the solution.

3.1. Fluxes of Sensible and Latent Heat

Based on former experiments at this site (Beyrich et al., 2002b), and the EBEX-2000 experiment (Mauder et al., 2006c), the data from all surface flux towers were carefully analysed (Mauder et al., 2006b) by the University of Bayreuth in a uniform way using the comprehensive turbulence software package TK2 (Mauder and Foken, 2004). It includes quality tests of the raw data and necessary corrections of the covariances, as well as quality tests for the resulting turbulent fluxes. The major components of this quality control system are:

- Identification of spikes after Vickers and Mahrt (1997).
- Determination of the time delay of all additional sensors (e.g. LI-7500 gas analyser) through the calculation of cross correlations.
- Cross wind correction of the sonic temperature according to Liu et al. (2001), if not already implemented in sensor software (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 according to 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 according to Schotanus et al. (1983).
- Density correction of scalar fluxes of H_2O and CO_2 following Webb et al. (1980) and Liebethal and Foken (2003; 2004).

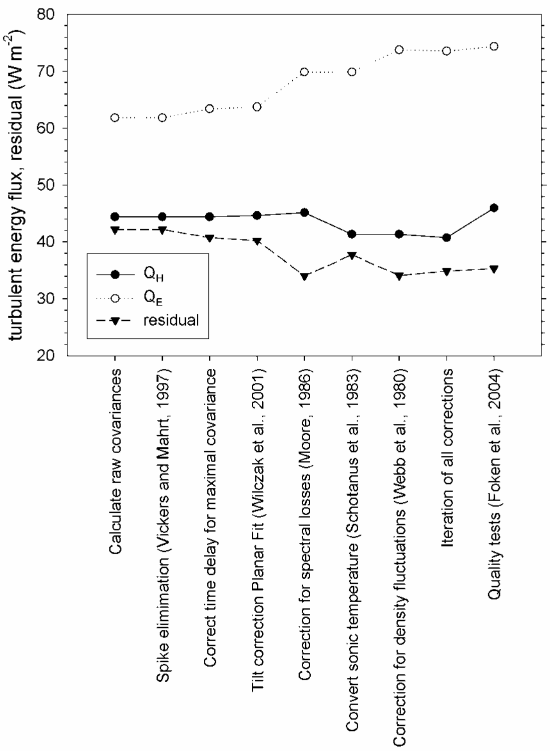


Figure 2: Influence of the different data correction steps for the sensible (green) and latent (blue) heat flux and the residual of the energy balance closure (all in W m^{-2}) for site A6 (maize) of the whole LITFASS-2003 period (Mauder and Foken, 2006).

- Iteration of the correction steps because of their interacting dependence.
- Data quality analysis according to Foken and Wichura (1996) in the updated version by Foken et al. (2004).

In the following remarks, only the effect of the different steps of data processing on the closure of the energy balance will be discussed.

The most significant changes of the heat fluxes are the transformation from the buoyancy flux into the 'exact' sensible heat flux (Schotanus et al., 1983), corrections for spectral losses and the effect of density fluctuations on the latent heat flux (Webb et al., 1980). The effect of the data quality analysis (Foken et al., 2004) is caused by the rejection of very small fluxes with a low data quality. Overall, a careful data correction reduces the residual of the energy balance closure by about 10 – 20 %, but flux corrections can not explain the magnitude of the residual.

The sensors, mainly the fast response humidity sensors, were calibrated and compared during a pre-experiment.

3.2 Net Radiation and Ground Heat Flux

For the LITFASS-2003 experiment the net radiation measurements should not be a source of errors. The sensors were well compared against the standards of the BSRN station (Ohmura et al., 1998) of the Meteorological Observatory Lindenberg and also partly during EBEX-2000 (Kohsiek et al., 2006a) and during a pre-experiment (Mauder et al., 2006b). Therefore, the accuracy of the shortwave components is better than 2 % and of the long wave components better than 5 W m^{-2} (Kohsiek et al., 2006a).

Two main factors influence the role of the ground heat flux for the energy balance and its closure: firstly, the magnitude of the flux and secondly, the mode of its determination.

The magnitude of the ground heat flux (amount of energy entering or leaving the soil through the soil surface) at a specific site strongly depends on the density of the vegetation. While at densely vegetated sites the ground heat flux will play a minor role in the energy balance, its role will be considerable at sparesely vegetated or bare soil sites (Heusinkveld et al., 2004). Then In the case of sparse or no vegetation, the ground heat flux may become larger than each of the turbulent energy fluxes and errors in its determination can strongly influence the energy balance closure. For the LITFASS-2003 experiment this was partly the case for one plot grown with short grass and for the other sites, as long as vegetation was minimal.

According to a sensitivity analysis by Liebethal et al. (2005), the most reliable method to determine the ground heat flux for the LITFASS-2003 data recorded over a maize field turned out to be a combination of two methods. The gradient approach was applied at a depth of 0.20 m and the change in the heat storage in the soil layer above this reference level was added to it. Even with this high quality data set for the ground heat flux, the energy balance can only be closed within the error margins of flux determination during nighttime (Figure 3). During daytime, still a considerable residual of several tens to over 100 W m^{-2} exists (Liebethal et al., 2006). Due to missing data, the complete reliability analysis could not be done for all of the LITFASS-2003 ground heat flux data sets. However, there is no reason, why the situation should be fundamentally different for other agricultural sites.

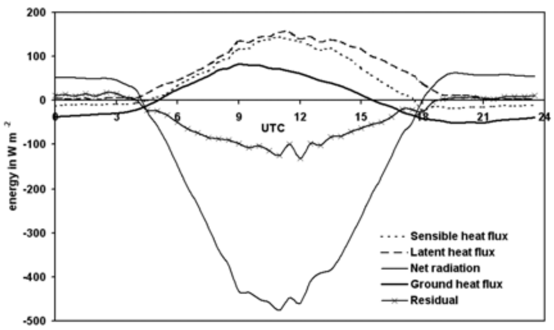


Figure 3: Mean diurnal cycle of all energy balance components for site A6 (maize) during the LITFASS-2003 period (Liebethal et al., 2006).

4. FLUXES DUE TO LONGER WAVELENGTHS

About 15 years ago the ogive function was introduced into the investigation of turbulent fluxes (Desjardins et al., 1989; Friehe, 1991; Oncley et al., 1990). This function was proposed as a test to check if all low frequency parts are included in the turbulent flux measured with the eddy-covariance method (Foken et al., 1995; Foken et al., 2004). The ogive is the cumulative integral of the co-spectrum starting with the highest frequencies

$$og_{w,x}\left(f_0\right)=\int\limits_{\infty}^{f_0} Co_{w,x}\left(f\right)df \qquad (2)$$

with $Co_{w,x}$: co-spectrum of a turbulent flux, w: vertical wind component, x: horizontal wind component or scalar, f: frequency. In this study, co-spectra for all relevant combinations of time series were calculated over integration times of up to four hours. Though only frequency values higher than approx. 1.39 10^{-4} Hz that correspond to periods of two hours and shorter were used for the test (Foken et al., 2006), an underlying interval of four hours improves the statistical significance. Longer periods were not investigated due to non-stationary conditions related to the diurnal cycle of the fluxes and high non-steady state conditions. Because the ogive test must be applied to time series without any gaps, only 121 series for the whole experiment were available. The convergence of the ogive was analysed as follows:

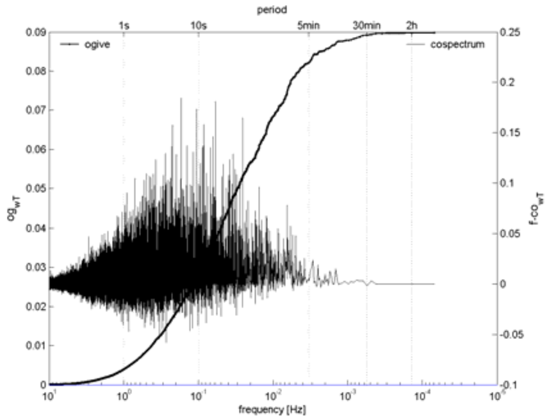
In the ideal convergent case, the ogive function increases during the integration from high frequencies to low frequencies until a certain value is reached and remains on a more or less constant plateau before a 30-minute integration time. If this condition is fulfilled, the 30-minute covariance is a 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). Figure 4a 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, Figure 4b) or that the ogive function doesn't show a plateau but increases throughout (Case 3, Figure 4c). Ogive functions corresponding to Case 2 or 3 indicate that a 30-minute flux estimate is possibly inadequate.

An overview of the number of measuring series compliant with these cases is given in Table 1. It can be concluded that a 30-minute averaging interval appears to be sufficient to cover all relevant flux contributions in roughly 5 out of 6 cases (85 %). For the remaining cases the eddy-covariance method does not measure the total flux within the 30-minute interval in all cases. The 30-minute flux may be reduced because the flux in one direction was already reached in a shorter time period (Case 2) and an integration of up to 30 minutes reduces the fluxes due to non-steady state conditions or long wave trends, or because significant flux contribution can be found for integration periods larger than 30 minutes (Case 3).

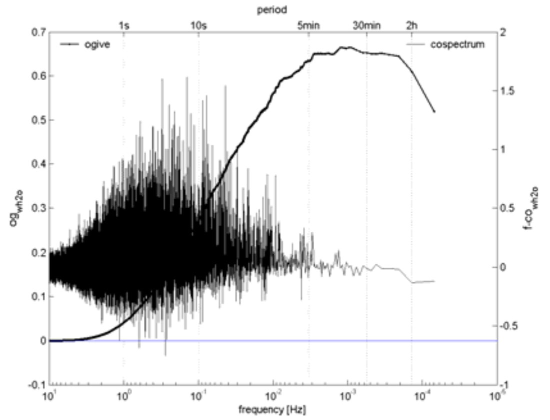
It must be assumed that a reduction of the turbulent fluxes also occurs if the ogive function has an extreme value for time periods less than 30 minutes and decreases for longer integration times (Case 2). Reasons for that are non-steady state conditions and trends, which either cannot entirely or at least not sufficiently be found with the relevant tests (Foken and Wichura, 1996; Vickers and Mahrt, 1997), or advective conditions. Furthermore, the flux is underestimated in the 30-minute integration time if energy is also transported with low frequency eddies (Case 3). These findings explain the fact that turbulent fluxes are always underestimated. A simplified correction of the turbulent fluxes by the ratio of the ogive function for 30 minutes and the maximum ogive function (extreme or convergence) shows a reduced residual by 5-10 %.

Table 1. Number of convergent ogives (Case 1), ogives with an extreme value (Case 2), non-convergent ogives (Case 3) of momentum (og_{uw}), sensible heat (og_{wT}), latent heat (og_{wa}) flux. The numbers in brackets are for the whole period the percentages of the data set of 121 series (Foken et al., 2006).

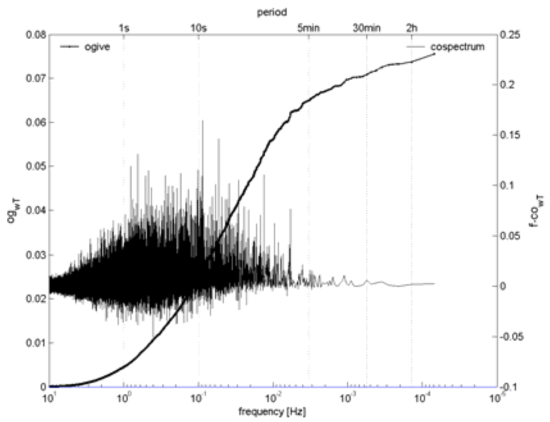
	Case 1	Case 2	Case 3
og_{uw}	103 (85 %)	13 (11 %)	5 (4 %)
og_{wT}	100 (83 %)	14 (12 %)	7 (6 %)
og_{wa}	100 (83 %)	17 (14 %)	4 (3 %)



a)



b)



c)

Figure 4: Typical ogive functions (og) and cospectrum (Co) of the sensible heat flux(a,c, units ogive: Kms^{-1}, fCo: Kms^{-2}) and latent heat flux (b, units ogive: mmol $m^{-2}s^{-1}$, fCo: mmol $m^{-2}s^{-2}$) measured during the LITFASS-2003 experiment (Foken et al., 2006), a) Ogiven converges within 30 minutes (Case 1), b) Ogive with a distinct maximal value (extreme) and a decline for longer integration periods (Case 2), c) Ogive not convergent within 30 minutes (Case 3).

Therefore, an increase of the averaging time of up to 2 hours has no significant effect on the closure problem, because most of the Cases 2 and 3 occur in the morning and late afternoon hours. Finnigan et al. (2003) proposed a site specific extension of the averaging time of up to several hours to close the energy balance. This was also done for the LITFASS-2003 experiment (Figure 5). This underlines the finding that in the first hours the effect is small. If the averaging over longer time periods is from the statistical point of view acceptable, the energy balance can be closed over 24 hours for this data set mainly due to an increase of the sensible heat flux. Probably larger turbulent structures are responsible for the closure problem.

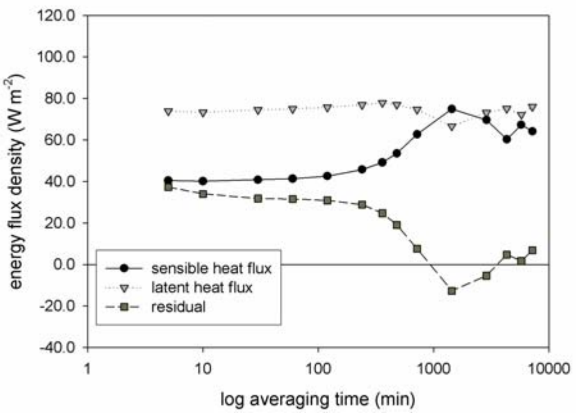


Figure 5: Influence of averaging time on the sensible (red) and latent (blue) heat flux and the residual of the energy balance closure (all in W m^{-2}) for site A6 (maize) of the whole LITFASS-2003 period (Mauder and Foken, 2006)

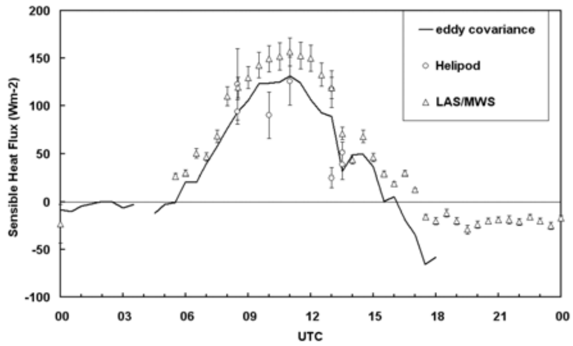
5. AREA-AVERAGING MEASURING SYSTEMS

As mentioned above, two area integrated scintillometers and the airborne measuring system Helipod were used to measure area-averaged fluxes along the approx. 5 km path between the GM Falkenberg and MOL sites.

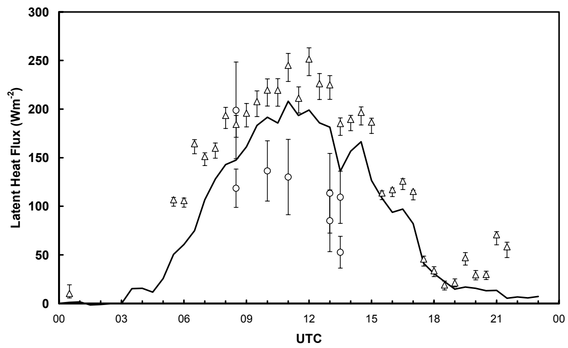
Helipod measured during LITFASS-2003 over 15 times 15 square kilometres, the composite ground-based measurement covered the entires site of 20 times 20 square kilometres. Additionally flights above homogeneous sub-areas (like agricultural land) - so-called catalogue flights - were performed to obtain the individual surface fluxes of these surface types (Bange et al., 2006a). These flights were performed quite low, usually at about 80 m above ground level altitude.

The combination of a (near-infrared) LAS and a (94 GHz) microwave scintillometer (known as the two-wavelength method) make it possible to measure the fluxes of sensible heat and latent heat flux directly at scales of several kilometres (Meijninger et al., 2002a; Meijninger et al., 2006). Applying Obukhov's similarity relations (Obukhov, 1960), the surface fluxes can be derived from the path-averaged structure parameter data (C_n^2). A footprint analysis of the set-up performed by Meijninger et al. (2006) showed that more than 85% of the source area of the scintillometer represents farmland (for all wind directions).

For May 25, 2003, the area-averaged fluxes were compared with the composite of the surface layer fluxes (Figure 6). The sensible and latent heat fluxes estimated with the scintillometer are approx. 20-50 W m^{-2} larger than the eddy-covariance data and can nearly compensate the residual with a maximum of approx. 100 W m^{-2}.



a)



b)

Figure 6: Comparison of eddy-covariance measurements (solid line) and scintillometer measurements of the sensible (a) and latent (b) heat flux as well as Helipod measurements, May 25, 2003 (Beyrich et al., 2006)

The Helipod data are not directly comparable because they are related to a height of approx. 50 m. Only at noon, when the thickness of the surface layer is in this order, are the fluxes similar. From Figure 6 it follows that the Helipod data are in a good agreement with the scintillometer measurements.

6. LARGE EDDY SIMULATION

The PArallelized LES Model PALM (Raasch and Schröter, 2001) was applied to investigate the fluxes at approx. 40 m height for May 30, 2003; unfortunately, it was a day where the microwave scintillometer did not work. The model is based on the filtered non-hydrostatic Boussinesq equations and uses a one-and-a-half-order subgrid closure scheme (Deardorff, 1980). For the adaptation of the heterogeneous land use, we used the CORINE-dataset from the European Environment Agency with a resolution of 100 m. The numerical grid was composed of 320 * 400 * 84 gridpoints. At the lower boundary, the temporal development of the surface sensible and latent heat flux was prescribed for the different classes of landuse as given by representative measurements from the corresponding energy balance stations. One major goal of the simulations was to detect the secondary circulations (Raasch and Harbusch, 2001; Shen and Leclerc, 1995) caused by the heterogeneities. The SC have an even stronger effect on the flow than the turbulent organized structures discussed by Kanda et al. (2004) as a reason for the unclosed energy balance. The secondary circulations have been determined by averaging the flow field over an ensemble of eight identical LES runs, each started with different initial random perturbations. The flow field of each run was additionally averaged over one hour before the ensemble average was applied.

As a result of the model, Figure 7 was generated, which shows the secondary circulations for May 30, 2003, a day with weak mean horizontal wind. The secondary circulation structures were found to be very stable in relation to the underlying surface. For stronger winds, these structures are generally much weaker and aligned in bands parallel to the mean wind.

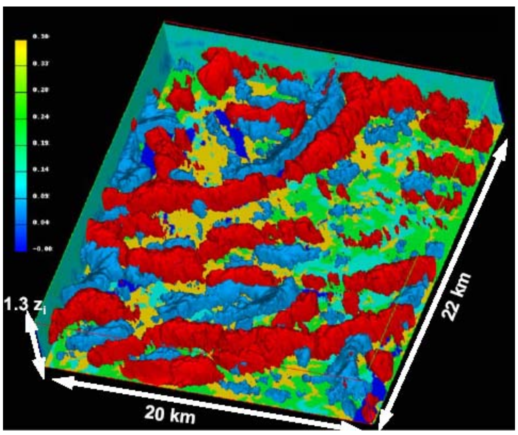


Figure 7: LES simulation for secondary circulations for May 30, 2006 over the LITFASS area

Along the investigated path 40 virtual towers of 40 m height were built up with the LES model. The data of the LES simulation of these towers with a sampling frequency of 2 Hz were used for an eddy-covariance calculation in two ways: determination of the fluxes of all towers and averaging of these fluxes and spatial calculation of the fluxes (similar to an aircraft flight along the towers). The results are given in Figure 8. The spatial calculated flux is approx. 20 W m^{-2} larger than the averaging of the fluxes of the towers but significantly larger than the measured fluxes of the flux stations, and partly larger than those of the scintillometer as well.

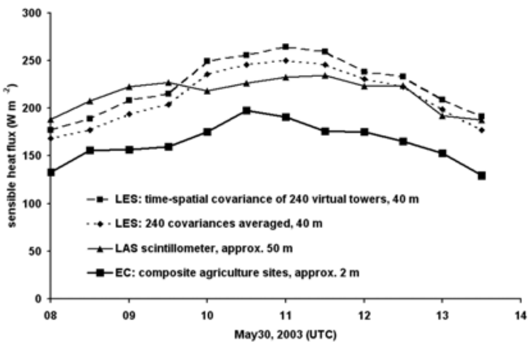


Figure 8: Comparison of the sensible heat fluxes measured with the eddy-covariance systems, the scintillometer (LAS date were corrected for saturation, Kohsiek et al., 2006b) and simulated with the LES model for May 30, 2003 over the agricultural path of the LITFASS area.

7. CONCLUSIONS

Due to recent sensor developments and comprehensive correction methods, the turbulent fluxes measured with the eddy-covariance method nowadays have an accuracy of approximately 5-10 % or 10-20 W m^{-2} (Mauder et al., 2006b), which is much better than ten years ago and cannot explain the residual. Additionally, the net radiation has a high accuracy with top quality sensors, but also some types of sensors in the lower price segment have an accuracy of about 20 W m^{-2} (Kohsiek et al., 2006a, not the single components). Determining the ground heat flux incorrectly can alter the energy balance closure considerably and often leads to an additional residual. Using the highest quality and most accurate data for the ground heat flux can only close the energy balance during nighttime, but often leaves a residual during daytime.

It must be assumed that on the small scale of typical energy balance measurements with no internal boundary layers and ideal footprint conditions the energy balance cannot be closed in a heterogeneous landscape. For homogeneous landscapes, the closure was demonstrated (Heusinkveld et al., 2004; Mauder et al., 2006a). Therefore, the radiation energy must be transferred in another way. It has been reported that additional fluxes are generated at forest edges (Klaassen et al., 2002). Also secondary circulations may transport the surplus of energy. Because these secondary circulations do not touch the surface or are steady state over the same structures of heterogeneity, the eddy- covariance method is unable to measure these fluxes. Only the movement of secondary circulations during the daily cycle can be indicated with the long term integration.

It was shown that spatial averaging measuring systems calcute additional flux contributions, which are probably connected with secondary circulations, which were indicated with large eddy simulations. For the selected cases it could be shown that on the landscape scale the energy balance can be closed with spatially averaging methods..

Therefore, the energy balance closure problem is apparently connected with a scale problem. If the landscape scale is very heterogeneous, the balance can not be closed on small scales of typical flux measurements but only on the landscape scale as the LITFASS area of 20 x 20 km^2. This means that earlier studies of the heterogeneity aspect (Finnigan et al., 2003; Panin et al., 1998) of this reason showed the right direction, but these investigations basically suggested an influence of the heterogeneities in the immediate neighbourhood of the measurement site The new aspect is turbulent structures within the boundary layer over a heterogeneous landscape. Further conclusions and consequences of this problem are given by Foken (2006).

8. ACKNOWLEDGMENT

This project is funded by the Federal Ministry of Education, Science, Research and Technology (DEKLIM, project EVA-GRIPS). Participation of the Wageningen group in LITFASS-2003 was based on the funding and support of the Dutch Science Foundation (NWO, project number 813.03.007). LES runs were performed on the NEC-SX6 of the German High Performance Computing Centre for Climate- and Earth System Research (DKRZ), Hamburg.

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