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ORIGINAL PAPER

Energy balance closure for the LITFASS-2003 experiment

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Abstract In the first part, this paper synthesises the main results from a series of previous studies on the closure of the local energy balance at low-vegetation sites during the LITFASS-2003 experiment. A residual of up to 25% of the available energy has been found which cannot be fully explained either by the measurement uncertainty of the single components of the surface energy balance or by the length of the flux-averaging period. In the second part, secondary circulations due to heterogeneities in the surface characteristics (roughness, thermal and moisture properties) are discussed as a possible cause for the observed energy balance non-closure. This hypothesis seems to be supported from the fluxes derived from area-averaging measurement techniques (scintillometers, aircraft).

1 Introduction

During the late 1980s, it became obvious that the energy balance at the earth's surface could often not be closed with

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experimental data if all its components were measured individually with state of the art sensors. The available energy, i.e. the sum of the net radiation ($-Q_s^*$) and the ground heat flux (Q_G)

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

was found in most cases to be larger than the sum of the turbulent fluxes of sensible (Q_H) and latent (Q_E) heat. Therefore, the missing energy is included in Eq. 1 as a residual:

$$\mathrm{Res} = Q_s^* - (Q_H + Q_E + Q_G), \tag{2}$$

In most of the land-surface experiments (Bolle et al. 1993; Kanemasu et al. 1992; Laubach and Teichmann 1996; Oliphant et al. 2004; Oncley et al. 2007; Tsvang et al. 1991) and also 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 specifically designed to investigate this problem, the Energy Balance Experiment 2000 (EBEX-2000), took place in the summer of 2000 near Fresno, CA. The results from EBEX-2000 have been published recently (Kohsiek et al. 2007; Mauder et al. 2007b; Oncley et al. 2007). Although the terrain, vegetation and site characteristics for EBEX-2000 were carefully chosen to avoid complex settings and the sensor operation and data analysis followed state-of-the-art standards, a closure gap of about 15% was obtained for the local energy-balance measurements. In contrast to many other experiments, the horizontal advection could be calculated for EBEX-2000; otherwise, the closure gap would have been approximately 25% of the available energy. Overviews on the energy balance closure (EBC) problem and a discussion of possible reasons were recently given by Culf et al. (2004) and Foken (2008).

In the past, the most common point of discussion with respect to the energy balance closure problem was measurement errors, especially those of the eddy-covariance technique which were assumed to 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 accurate over the past 10 years (Foken et al. 2004; Mauder and Foken 2006; Mauder et al. 2007b; Moncrieff 2004).

Different reference levels and different sampling scales of the measuring methods for net radiation, turbulent fluxes and soil heat flux were often seen as another possible reason for the lack of energy-balance closure. Moreover, the role of energy storage in the canopy and in the soil was discussed by several authors. Most of these energy storages appear to be not significant to the problem for low vegetation canopies (Oncley et al. 2007) with the exception of the heat storage in the soil (see, e.g. Culf et al. 2004; Foken 2008; Heusinkveld et al. 2004; Meyers and Hollinger 2004).

The non-closure of the energy balance was also explained by the heterogeneity of the land surface (Panin et al. 1998). These authors assumed that the heterogeneity in the vicinity of a flux-measurement site generates eddies at larger time scales, but such turbulent structures generated by heterogeneities close to the measuring tower can be measured with the eddy-covariance method (Thomas and Foken 2007; Zhang et al. 2007). This problem is also closely connected with advection and fluxes associated with longer wavelengths (Finnigan et al. 2003).

Also in recent studies, it was found that fluxes averaged over long time periods (Finnigan et al. 2003; Mauder and Foken 2006; Sakai et al. 2001) or spatially averaged fluxes (Inagaki et al. 2006; Kanda et al. 2004; Steinfeld et al. 2007) could close the energy balance. These hypotheses were not investigated during EBEX-2000. To verify these results, the data set of the LITFASS-2003 experiment (Beyrich and Mengelkamp 2006; Mengelkamp et al. 2006) was used in the present study. In contrast to EBEX-2000, this data set also includes area averaged flux measurements. Some aspects relevant for the energy balance closure discussion were already published, such as the quality of the flux data based on eddy-covariance measurements (Mauder et al. 2006), the effect of the corrections of the turbulent fluxes (Mauder and Foken 2006), investigations of the low-frequency part of the spectra (Foken et al. 2006b) and the area averaging of fluxes (Meijninger et al. 2006). Combining these previous investigations and adding other relevant aspects, this paper attempts to give a synthetic picture of the closure of the energy balance for the LITFASS-2003 data set.

2 Experimental setup

The LITFASS-2003 experiment (for a summary see, e.g. Beyrich and Mengelkamp 2006) took place in May and June 2003 in a 20×20-km^2 area around the Meteorological Observatory Lindenberg (MOL) of the German Meteorological Service (Deutscher Wetterdienst, DWD). Turbulent fluxes of momentum, sensible and latent heat were measured at nine agricultural sites, two grassland stations, one forest site, two lake sites and at two levels of a 100-m tower. The grassland and tower measurements were performed at the boundary layer field site (in German: Grenzschichtmessfeld) GM Falkenberg of the MOL. The distribution of these flux sites over the study area is shown in Fig. 1.

For the present study, only the agricultural part of the study area with 11 flux stations over agricultural farmland

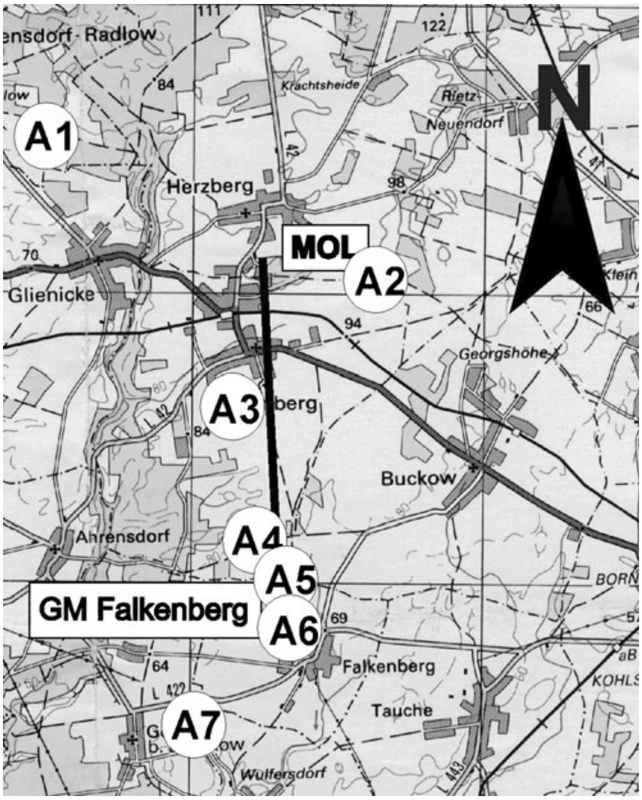

Fig. 1 The study area of the LITFASS-2003 experiment near the Meteorological Observatory Lindenberg, with the MOL, the GM Falkenberg, and the scintillometer path between the two (*black line*). *A1* to *A7* indicates the farmland flux stations; four additional stations were on the GM Falkenberg. This *figure* is based on the topographic maps TK100 and TG 100 GK by LVermA BB; reproduction has been kindly permitted under Ref.-No. GB 57/01

and over grass will be considered. The sites were equipped with two types of sonic anemometers (either CSAT3, Campbell Sci. Inc., or USA-1, METEK GmbH) and two types of fast-response hygrometers (either LiCor-7500, LiCor Inc., or KH20, Campbell Sci. Inc.) and state-of-the-art radiation-measuring systems (CM 11, CM 21, CNR 1, Kipp and Zonen, PIR, Eppley). Details about the instrumentation, the data calculation and the post-field data quality control of the flux, radiation, soil heat flux and scintillometer measurements are given by Beyrich et al. (2006) and Mauder et al. (2006).

Each of the sites was characterised with respect to the micrometeorological site conditions. A footprint analysis was performed using a Lagrangian footprint model (Rannik et al. 2003, 2000) combined with an averaging concept for land use parameters (Göckede et al. 2004, 2006). Possible internal boundary layers were indicated according to a former study by Jegede and Foken (1999).

The fluxes measured at these stations were combined to yield a so-called farmland 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). The area averaging flux measurements included the operation of a large aperture scintillometer (LAS) and a microwave scintillometer (MWS) over a path of about 5 km with an averaged path height of 45 m (Beyrich et al. 2002a) for the determination of the sensible and latent heat fluxes (Meijninger et al. 2006). Airborne measurements with the Helipod were performed on several days of the LITFASS-2003 experiment. The Helipod is an autonomous turbulence probe attached to a 15-m-long rope and carried by a helicopter (Bange et al. 2006b). It is equipped with high-precision, fast-response sensors for the measurement of the turbulent fluctuations of wind, temperature and humidity. One flight leg during each flight was usually oriented parallel to the LAS–MWS path. These flights were performed quite low, typically at about 80 m above ground level.

Large-eddy simulations (LES) for the LITFASS-2003 study area were performed with the parallelised LES model (PALM; Raasch and Schröter 2001) in order to investigate the boundary-layer structure. PALM is based on the filtered non-hydrostatic Boussinesq equations and uses a one-and-a-half-order sub-grid closure scheme (Deardorff 1972). For the adaptation of the heterogeneous land use, we used the Coordinated Information on the European Environment (CORINE) dataset from the European Environment Agency at a resolution of 100 m. The numerical grid was composed of $320\times400\times84$ grid points ($x/y/z$) with a horizontal grid spacing of 100 m and a vertical spacing of 50 m. At the lower boundary, the temporal development of the surface sensible and latent heat fluxes was prescribed for the different classes of land use as given by representative measurements from the corresponding energy balance stations. A more detailed explanation of the simulations is given in Uhlenbrock et al. (2004).

The results of these simulations were used to further investigate the findings by Kanda et al. (2004) and Inagaki et al. (2006) with respect to the possible occurrence of organised mesoscale circulations when real-terrain heterogeneous forcing is applied to the LES. For the present study, we focused on data from 2 days, namely May 25 and 30, 2003 for the LES and LAS studies. On the first day, the sky was cloud free until around noon, and data from both the LAS and MWS were available. Unfortunately, the MWS broke down on May 29. May 30, for which LES results are available, was characterised by nearly clear sky over the whole day.

3 Local surface fluxes

Previous studies on the local energy balance at the LITFASS-2003 flux measurement sites focused on the

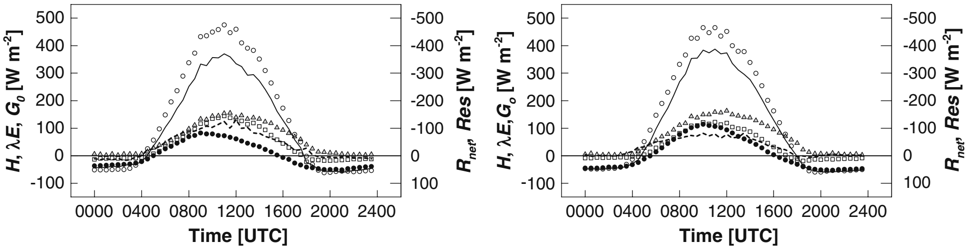

Fig. 2 Components of the energy balance during LITFASS-2003 averaged over the experiment duration for a corn site (*left graph*) and for a grassland site (*right graph*). Sensible and latent heat flux (H—*squares* and λE—*grey triangles*) as well as ground heat flux (G_0—*black circles*) are plotted on the *left ordinate*; net radiation (R_{net}—*white circles*) and residual (*Res*—*dashed line*) are plotted on the *right ordinate*

sparsely vegetated sites at the GM Falkenberg (grassland) and a nearby corn field, for which a particularly careful determination of the soil heat flux was performed based on multi-level soil temperature, soil moisture and soil heat flux measurements (see Section 3.2). Both data sets feature a large residual (Res) during daytime. At the corn site, the average Res amounts to −125 W m^{-2} around solar noon (Fig. 2). Maxima of the Res exceed −220 W m^{-2} (Fig. 3). The EBC, given as the sum of the turbulent fluxes divided by the available energy, scatters around 0.70 during daytime. During nighttime, the average residual is close to zero with a small positive offset (between 10 and 15 W m^{-2} on the average) which reaches its maximum in the early morning hours. EBC values are not representative during nighttime because fluxes are generally small. For the grassland site, the diurnal pattern of Res and EBC is similar although closure is generally better (Figs. 2 and 3). The average Res around noon is only −100 W m^{-2} (maximum values around −150 W m^{-2}) and EBC is higher than 75%. During nighttime, average Res is close to zero. The closure gap in the energy balance was found, in spite of a very careful data analysis which was performed as described in the sections below.

3.1 Fluxes of sensible and latent heat

Based on the experiences from former experiments at the LITFASS site (Beyrich et al. 2002b) and on the EBEX-2000 experiment (Mauder et al. 2007b), much effort was spent on the quality assurance and quality control of the eddy-covariance measurements. The fast responding humidity sensors were calibrated before and after the experiment, and an inter-comparison of different turbulence measurement systems and sensor setups had been performed during a pre-experiment in summer 2002. Moreover, a careful analysis of the data from all surface flux stations was done by Mauder et al. (2006) in a uniform way using the comprehensive turbulence software package TK2 (Mauder and Foken 2004) which was compared with most of the internationally available eddy-covariance software packages (Mauder et al. 2008). It includes quality tests of the raw data and the 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 according to Vickers and Mahrt (1997)

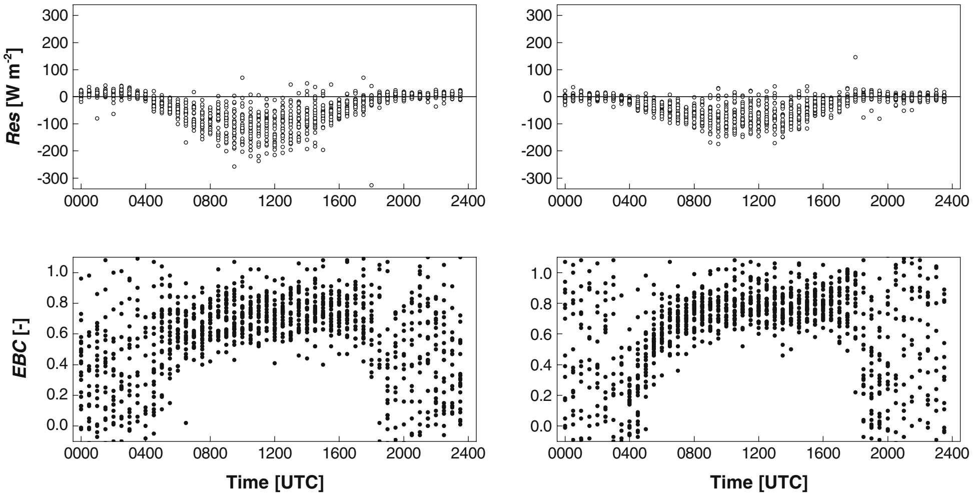

Fig. 3 Residual of the energy balance (*Res*; *upper graphs*) and energy balance closure (*EBC*; *lower graphs*) for a corn site (*left graphs*) and for a grassland site (*right graphs*) during the LITFASS-2003 experiment. All measuring series of the LITFASS-experiment form May 19 to June 17, 2003 are shown

- Determination of the time delay of all additional sensors (e.g. LI-7500 gas analyser) compared to the sonic anemometer by the calculation and maximisation 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)
- Application of the planar fit method for coordinate rotation (Wilczak et al. 2001)
- Correction of oxygen cross sensitivity for 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) except for the longitudinal separation which is accounted for by the maximisation of the covariances
- 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 as suggested by Webb et al. (1980) and Liebethal and Foken (2003, 2004)
- Iteration of the correction steps due to their interdependence (Mauder and Foken 2006)
- Data quality analysis according to Foken and Wichura (1996) in the updated version by Foken et al. (2004)

An angle of attack correction (Nakai et al. 2006; van der Molen et al. 2004) was not made as used by Cava et al. (2008), because this correction is usually determined in the wind tunnel for 'laminar flow' and overestimates the fluxes in the turbulent atmosphere (Högström and Smedman 2004).

The effect of the different steps of data processing on the closure of the energy balance was discussed by Mauder and Foken (2006). In their study, they analysed the data set of the whole LITFASS-2003 period for one agricultural site (A6, corn). The most significant changes of the heat fluxes are due to the transformation from the buoyancy flux into the 'exact' sensible heat flux (Schotanus et al. 1983), to the consideration of the effect of density fluctuations on the latent heat flux (Webb et al. 1980)—both not real corrections—and to the corrections for spectral losses (Moore 1986). The Schotanus conversion increases the mean residual by 11%, whilst the correction for density effects decreases the residual by 11%, and the Moore correction leads to 15% lower residuals on average. An effect of the data-quality analysis (Foken et al. 2004) on the mean residual 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 for this data set by 17%; this means that the overall residual of 20–30% of the available energy would be about 5% smaller compared to the uncorrected data. However, it becomes obvious that the flux corrections cannot explain the magnitude of the residual.

Special efforts were made by Foken et al. (2006b) to analyse the effects of the long-wave part of the turbulence spectra by the use of the ogive function (Desjardins et al. 1989; Friehe 1991; Oncley et al. 1990). This function was proposed in order to test whether all low frequency parts are included in the turbulent flux calculated with the eddy-covariance method (Foken et al. 1995, 2004). The ogive is the cumulative integral of the co-spectrum starting with the highest frequencies.

In the ideal converging case, the ogive function increases whilst integrating from high frequencies to low frequencies until a certain value is reached, and it remains at a more or less constant plateau before a 30-min integration time is reached. If this condition is fulfilled, it can be assumed that the whole turbulent spectrum is covered by the 30-min averaging interval and that there are only negligible flux contributions from longer wavelengths. This implies that the 30-min covariance gives a reliable estimate for the turbulent flux. Alternatively, it may occur that the ogive function reaches a maximum value at shorter averaging times and decreases again towards lower frequencies or that the ogive function does not approach a constant level but increases throughout. Ogive functions corresponding to the latter cases indicate that a 30-min averaging time might be inadequate for the flux calculation. For the LITFASS-2003 data set, it was found (Foken et al. 2006b) that a 30-min averaging interval appears to be sufficient to cover all relevant flux contributions in 85% of the cases.

For the remaining 15%, the eddy-covariance method does not provide the correct total flux within the 30-min averaging interval. It should be remarked that most of these cases occur in the morning and late afternoon hours when the absolute values of the fluxes are small. The ogive method was applied to adjust the averaging interval in order to maximise the absolute value of the eddy-covariance fluxes. The length of the averaging interval, ranging from 1 to 120 min, was set equal to the wavelength where the ogive function has its maximum absolute value. Thereby, the turbulent fluxes increase for these 15% of the investigated period and the overall residual is reduced by about 7%. For more details, see Foken et al. (2006b).

Therefore, a general increase of the averaging time up to 2 h has no significant effect on the mean energy-balance closure. The latent heat flux is slightly reduced, but the sensible heat flux is increased. This tendency is in agreement with the investigations (Mauder and Foken 2006) of a long-time integration. Such a long-term integration was proposed by Finnigan et al. (2003) with a site-specific extension of the averaging time up to several hours to close the energy balance. If the averaging over longer time periods appears to be acceptable from the statistical point of view, the energy balance can be closed over the diurnal cycle of 24 h for this data set mainly due to an increase of the sensible heat flux (Fig. 4). Mauder and Foken (2006) also selected periods of 5 days with nearly identical diurnal cycles. These cycles fulfilled typical steady-state criteria (Vickers and Mahrt 1997), and the flux integration over those 5-day time periods also fulfilled the energy balance equation.

3.2 Net radiation and ground heat flux

Radiation sensors operated during LITFASS-2003 were carefully compared against the standards of the Basic Surface Radiation Network station (Ohmura et al. 1998) at the MOL. Additional inter-comparisons of some of the sensors were performed during EBEX-2000 (Kohsiek et al. 2006) and during a LITFASS-2003 pre-experiment (Mauder et al. 2006) on clear days. The accuracy of the shortwave components was found to be better than 2% and of the longwave components better than 5 W m^{-2}. Because of these findings, the radiation fluxes are not considered as factors contributing significantly to the energy balance non-closure for the LITFASS-2003 experiment, in contrast to findings by, e.g. Culf et al. (2004).

To determine the ground heat flux, all sites were equipped with additional soil sensors. According to the sensitivity analysis by Liebethal et al. (2005), the most reliable way to determine the ground heat flux turned out to be a combination of two methods, namely the gradient approach and the calorimetry. The soil heat flux at a so-called reference depth of about 0.20 m is determined from the vertical soil temperature gradient and soil thermal conductivity at that depth according to Fourier's law of heat conduction. The extrapolation of ground heat flux to the surface is done by adding the temporal change in the heat storage in the soil layer between the reference depth and the surface. The necessary volumetric soil heat capacity was calculated from the volumetric fractions of soil constituents according to De Vries (1963), where organic compounds are neglected as the soils were estimated to contain not more than 3% of organic compounds (Liebethal 2006).

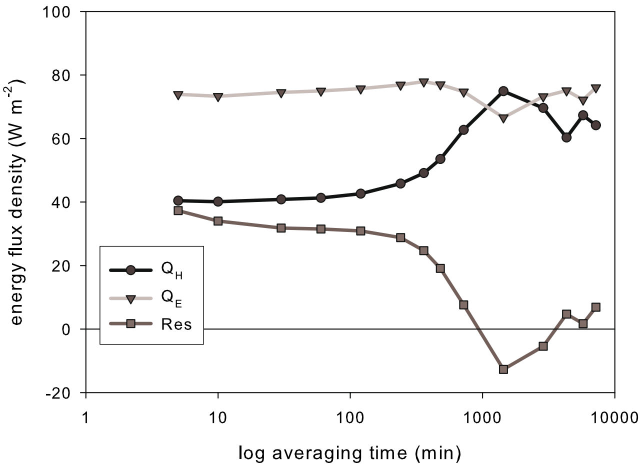

Fig. 4 Influence of log-transformed averaging time (originally measured in minutes) on the sensible and latent heat flux and the residual of the energy balance closure (all in watts per square metre) for the corn site of the whole LITFASS-2003 period (Mauder and Foken 2006)

When applying the maximum measurement errors assumed by Liebethal et al. (2005) for the LITFASS-2003 data sets, the error of the resulting ground heat flux at the surface is smaller than 15 W m^{-2} for most of the 30 min data. Based on the above results, we are convinced that measurement errors or uncertainties in the determination of the net radiation, the ground heat flux and the turbulent fluxes are not the reason for the energy imbalance in our data sets. Other sources of the imbalance due to heterogeneity effects will be discussed in the section below.

4 Regional aspects of the energy balance closure

Based on the discussion above, heterogeneity effects are considered as one possible cause of the unclosed local energy balance. Therefore, area-averaging measurement methods were analysed.

4.1 Scintillometer and airborne measurements

Two scintillometers and the Helipod system were used to estimate area averaged fluxes along the approximately 5 km path between the GM Falkenberg and MOL sites. The combination of a (near-infrared) LAS and a (94-GHz) microwave scintillometer (known as the two-wavelength method) makes it possible to determine the fluxes of sensible heat and latent heat directly at scales of several kilometres from the path-averaged structure parameter data (C_n^2) applying similarity relationships (Meijninger et al. 2002, 2006). A footprint analysis of the setup performed by Meijninger et al. (2006) showed that more than 85% of the source area of the scintillometers represents farmland (for all wind directions).

For May 25, 2003, a comparison of the area-averaged fluxes with the composite of the surface-layer fluxes from the eddy-covariance stations is shown in Fig. 5 (Beyrich et al. 2006). The sensible and latent heat fluxes estimated from the scintillometer measurements are both approximately 20–50 W m^{-2} larger than the surface flux composite and can nearly compensate the residual with a maximum of approximately 100 W m^{-2}. Analysing the 10-day data set of the period from 19 to 29 May, for which days both H and LE were available from the LAS and MWS systems,

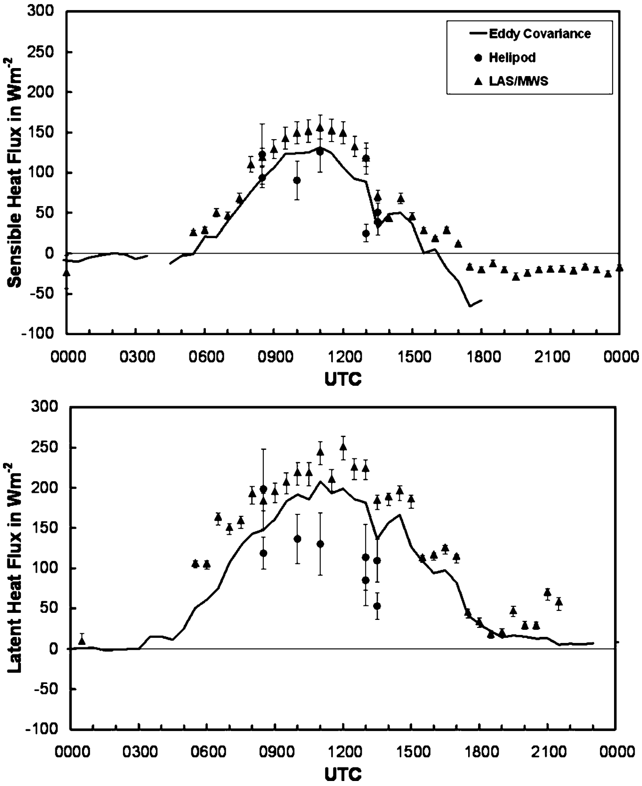

Fig. 5 Diurnal cycle of the sensible (*upper panel*) and latent (*lower panel*) heat fluxes on May 25, 2003, over the farmland part of the LITFASS area as derived from eddy-covariance, scintillometer (LAS date were corrected for saturation, Kohsiek et al. 2006) and Helipod measurements (Beyrich et al. 2006)

Meijninger et al. (2006) have demonstrated that the scintillometer-based fluxes are about 7% (H) and 25% (LE) higher than the aggregated eddy-covariance fluxes.

It should be remarked that the scintillometer data evaluation method uses similarity equations where the vertical profiles of the structure parameters (C_T^2, C_q^2) scales with the surface fluxes. Hence, it is a surface flux which is derived from the scintillometer measurements. On the other hand, the scintillometer sees the scintillations caused by turbulence at some elevated level, and if part of this turbulence was due to secondary structures which do not touch the surface, this might result in enhanced flux estimates. In this case, the scintillometer might be better able to close the surface energy balance than measurements close to the surface.

On 25 May, 2003, Helipod measurements were performed for three different flight patterns (see also Bange et al. 2006a). Turbulent fluxes along each of the flight legs were calculated using the eddy-covariance method. For the comparisons with the LAS, only flight legs parallel and close to the scintillometer path were used (Fig. 5).

The vertical turbulent fluxes of sensible and latent heat measured along these flights could not be extrapolated to the surface. The well-known box method (linear extrapolation using flux measurements at several flight levels) leads to large systematic errors (Bange et al. 2006b). The low-level flight and inverse modelling method (see also Bange et al. 2006b) could not be applied to this data set, since the horizontal and temporal dependence of air temperature and humidity cannot be detected from single flight legs in general. Thus, the flux measurements at the individual flight levels (between 80 and 100 m above the surface) were plotted in Fig. 5. Since in the lower part of a convective boundary layer the fluxes can be assumed to decrease linearly with height, it is expected that the surface fluxes are under-estimated by the airborne measurements in the order of 10% or less given that the boundary layer height was around 1,000 m during the first flight and around 2,000 m during the last flight.

Additional deviations between the Helipod and LAS measurements have to be expected since:

- The scintillometer weights the turbulent fluctuations along the path and fluctuations in the centre of the path have a larger influence on the resulting flux than fluctuations in the areas at both ends of the path
- The Helipod flights were not precisely located along the LAS path but with a horizontal displacement in the order of 1 km
- The LAS fluxes are half-hour averages whilst a Helipod flight along a 5-km leg takes about 5–6 min

Thus, taking into account the surface heterogeneity of the experimental site, the agreement between LAS and Helipod measurements shown in Fig. 5 can be considered as quite good for the sensible heat flux whilst larger differences were found for the latent heat flux. The statistical errors of latent heat flux measurements are larger in general, as shown by several other investigations (Bange et al. 2006b; Flamant et al. 1997; Linne et al. 2006).

4.2 Large-eddy simulations

The PALM (Raasch and Schröter 2001) was used to study the turbulent flow and fluxes over the LITFASS area. The simulations were (heterogeneously) driven by the surface sensible and latent heat fluxes as observed at the energy balance stations. Here, the original measurements have been used which still include the residual. Using corrected fluxes would have given slightly stronger secondary circulations, because the differential heating and hence the horizontal temperature gradients would have been larger. 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. In addition, the flow field of each run was averaged over 1 h before the ensemble average was applied. Figure 6 shows the spatial structure of the vertical velocity field for May 30th, a

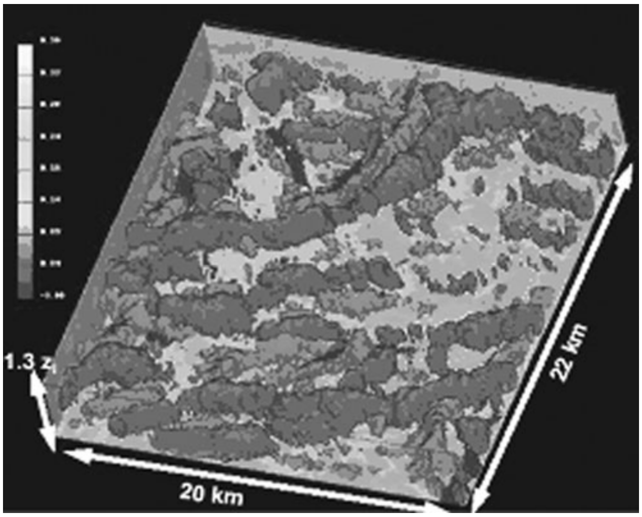

Fig. 6 Spatial structure of the vertical velocity field from LES for May 30, 2003 over the LITFASS area (Uhlenbrock et al. 2004). The different levels of *grey colour* show updrafts (*dark grey*) and downdrafts (*light grey*). The lakes in the area are shown in *black*

day with weak mean horizontal wind. Secondary circulations are visible in particular in the western part of the area around the lake 'Scharmützelsee' and over the forested region. These 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.

Secondary circulations over heterogeneous terrain have a similar effect on the vertical fluxes as the organised turbulent structures over terrain with homogeneous heat flux discussed by Kanda et al. (2004) and Steinfeld et al. (2007) who also used PALM for carrying out virtual EC measurements. Inagaki et al. (2006) extended this method to heterogeneous surface heating. All these papers have shown that the secondary circulations seriously affect the eddy correlation flux measurements and thus may contribute to the unclosed energy balance. However, as shown by Steinfeld et al. (2007), the effect of the secondary circulations decreases with decreasing observation height. For an observation height of 100 m, the vertical eddy-covariance heat flux is about 18% less than the 'true' flux, but for a height of 20 m, the deficit already reduces to about 6%. It can be estimated that at the 2-m level (the typical height for flux measurements with energy balance stations), the deficit will be less than 1%.

Therefore, the larger-scale secondary circulations are probably not responsible for the unclosed energy balance. However, smaller-scale heterogeneities with diameters much smaller than the boundary layer height or flow singularities such as forest edges may have a similar near surface effect. An LES study for such small scale heterogeneities and a virtual measurement height of 2 m would require a grid spacing of at least 1 m or less.

For May 30, we also carried out a high-resolution LES run using 960 × 800 × 244 grid points (*x*/*y*/*z*) with a horizontal grid spacing of 20 m and a vertical spacing of 10 m. 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: Firstly, a determination of the fluxes for all virtual towers and an averaging of these fluxes over the whole path were performed, and secondly, a spatial calculation of the fluxes was carried out similar to an aircraft flight along the towers. The results are given in Fig. 7. The spatially calculated flux is approximately 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 also than those of the scintillometer.

5 Conclusions

A detailed analysis of the energy balance closure was performed for two sparsely vegetated flux sites using data from the LITFASS-2003 experiment. A residual of about 20–30% of the available energy was found during daytime, although all energy fluxes were measured with (calibrated) research-type sensors and a comprehensive quality assurance and control scheme was applied. We are thus convinced that the non-closure of the energy balance cannot be attributed to measurement errors or uncertainties of the different energy fluxes. Due to recent sensor developments and elaborated correction methods, the turbulent fluxes determined with the eddy-covariance method nowadays have an accuracy of approximately 5–10% or ±10–20 W m^{-2} (Mauder et al. 2006) which is much

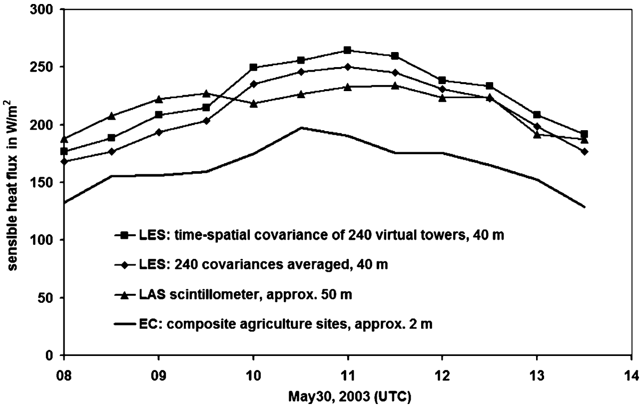

Fig. 7 Daytime evolution of the sensible heat fluxes derived from the measurements with the eddy-covariance systems and from the LAS surface flux measurements and simulated with the LES model for May 30, 2003 over the agricultural part of the LITFASS area (Foken et al. 2006a)

better than 10 years ago. Also, the net radiation has a high accuracy with best quality sensors, and even some types of sensors in the lower price segment have an accuracy of about ±20 W m^{-2} (Kohsiek et al. 2006, not the single components). Using the highest quality and most accurate data for the ground heat flux can close the energy balance during nighttime, but often leaves a residual during daytime. However, uncertainties in the determination of the soil heat flux can explain not more than about 25% to 30% of the residual.

It must therefore be assumed that on the local 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 due to deficits of measurement concepts and methodologies. Since energy balance closure could be demonstrated for sites with relatively homogeneous surroundings (Heusinkveld et al. 2004; Mauder et al. 2007a), it is assumed that terrain heterogeneity causes the transfer of energy by other mechanisms than just non-organised turbulent motions. 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 (Inagaki et al. 2006). Because these secondary circulations either do not touch the surface or are stationary over the same terrain structures, the eddy-covariance method is unable to measure these fluxes.

It was shown that spatially averaging measurement systems provide higher turbulent fluxes than the aggregation of locally determined eddy-covariance data. These might be connected with secondary circulations which were indicated with large eddy simulations (e.g. Inagaki et al. 2006). For the selected cases, it could be shown that on the landscape scale, there is a tendency to close the energy balance with spatially averaging methods. This is in agreement with other investigations about aircraft measurements (Mauder et al. 2007c).

It is therefore concluded that the energy balance closure problem is apparently connected with the interaction of scales and terrain heterogeneity. If the landscape is very heterogeneous at a relevant scale, the budget cannot be closed at the small scales of typical local flux measurements but only at the landscape scale. This means that earlier studies of the heterogeneity aspect (Finnigan et al. 2003; Panin et al. 1998) showed the right direction, but these investigations basically suggested an influence of the heterogeneities in the immediate neighbourhood of the measurement site and not a contribution from larger heterogeneities at the landscape scale, which are necessary for the generation of secondary circulations.

A conceptual picture considering the land surface–atmosphere interaction at different scales was shown by Foken (2008). This is also based on numerical studies which have shown that at steps of heterogeneities the fluxes are significantly larger than over more homogeneous areas (e.g. Schmid and Bünzli 1995a, b). This was underlined by the experiments by Klaassen et al. (2002). If the size of the heterogeneities or the differences of the characteristic heterogeneities (e.g. roughness, heat fluxes) are too small, this effect disappears (Friedrich et al. 2000).

The energy balance equation can be written with the sensible and latent heat fluxes for smaller and for larger eddies, where the smaller have a random character or are coherent structures with short time scales and the larger are more organised as secondary circulations. It is assumed that the net radiation does not differ for smaller and larger scales significantly on average and the ground heat flux is also assumed as identical. Near the surface, the smaller eddies are measured with micrometeorological methods and the long-wave part is not available (Steinfeld et al. 2007). Such a possible scheme is illustrated in Fig. 8. The transfer of the energy from the surface to the larger eddies happens mainly at significant heterogeneities and is not uniformly distributed over the area. Coherent structures near the surface can be to a large extent measured with the eddy-covariance technique (Thomas and Foken 2007); other turbulent structures probably have a contribution to larger eddies. The transfer of energy from the entire areas to the roughness changes is caused by advection, as probably measured in a specially designed experiment by Oncley et al. (2007). A long-term eddy-covariance averaging of the turbulent fluxes can nearly close the energy balance over a daily cycle (Finnigan et al. 2003; Mauder and Foken 2006) because of the non-steady state character of the advection.

The different approaches to investigate the energy balance closure of LITFASS-2003 presented in this paper provide some indications of what kind of transport

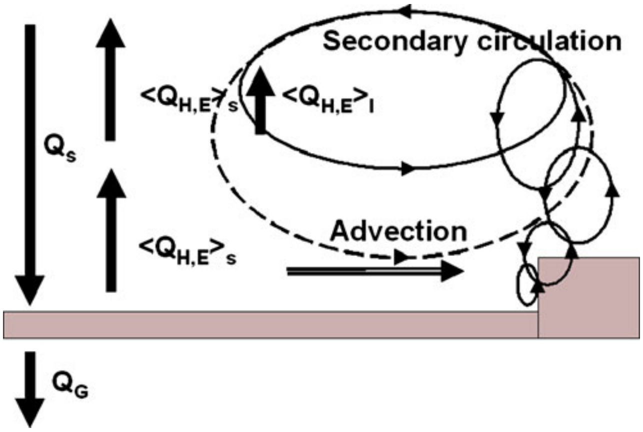

Fig. 8 Schematic figure of the generation of secondary circulations and the hypothesis of turbulent fluxes of sensible (Q_H) and latent (Q_E) heat in different scales based on small eddies (*s*) and large eddies (*l*) after Foken (2008), published with kind permission of the American Ecological Society

processes may be responsible for the missing energy flux. However, the results are not yet fully conclusive. This may partly be attributed to overlaying measurement uncertainties, partly to current limitations of LES and partly to the fact that we did not measure all required parameters, e.g. horizontal and vertical advection and horizontal and vertical eddy flux divergence, or spatially averaged fluxes from multiple towers etc. According to our results and exclusion of all other possibilities, we conclude that the missing energy is most likely transported into the atmosphere by processes that cannot be captured by a single-station eddy-covariance measurement. This can either be due to very large-scale structures that have a longer wavelength than the 30-min averaging time or due to quasi-stationary circulations that are not transported with the mean wind.

If only the fluxes can be measured with the eddy-covariance technique and other measuring methods or LES simulations for are not available for typical experiments, the question remains how to determine the fluxes from large eddies and secondary circulations. It should be mentioned that the contribution of such circulations to the sensible and latent heat flux may be different, because turbulent fluxes are not similar for all scalars, especially in the long-wave part (Ruppert et al. 2006). This paper might be also understood as a suggestion to include area averaging surface flux measurement techniques (such as scintillometry) and modelling efforts into future land surface and boundary-layer experiments.

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