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AREA-AVERAGED SURFACE FLUXES OVER THE LITFASS REGION BASED ON EDDY-COVARIANCE MEASUREMENTS

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Abstract. Micrometeorological measurements (including eddy-covariance measurements of the surface fluxes of sensible and latent heat) were performed during the LITFASS-2003 experiment at 13 field sites over different types of land use (forest, lake, grassland, various agricultural crops) in a $20 \times 20\,\mathrm{km}^2$ area around the Meteorological Observatory Lindenberg (MOL) of the German Meteorological Service (Deutscher Wetterdienst, DWD). Significant differences in the energy fluxes could be found between the major land surface types (forest, farmland, water), but also between the different agricultural crops (cereals, rape, maize). Flux ratios between the different surfaces changed during the course of the experiment as a result of increased water temperature of the lake, changing soil moisture, and of the vegetation development at the farmland sites. The measurements over grass performed at the boundary-layer field site Falkenberg of the MOL were shown to be quite representative for the farmland part of the area. Measurements from the 13 sites were composed into a time series of the area-averaged surface flux by taking into account the data quality of the single flux values from the different sites and the relative occurrence of each surface type in the area. Such composite fluxes could be determined for about 80% of the whole measurement time during the LITFASS-2003 experiment. Comparison of these aggregated surface fluxes with area-averaged fluxes from long-range scintillometer measurements and from airborne measurements showed good agreement.

Keywords: Eddy covariance, Flux aggregation, Heterogeneous land surface, LITFASS-2003, Scintillometer.

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1. Introduction

An important aspect in numerical weather prediction (NWP) and climate modelling is the adequate description of the interaction between the atmosphere and the underlying surface using sophisticated parameterisation schemes. Relevant processes to describe in the models comprise the exchange of momentum, energy, and trace gases, including water vapour. The development and validation of such parameterisations is usually based on measurements performed over homogeneous land surfaces. While the assumption of homogeneity might be justified at the local (patch) scale (orders of $10^1 \ldots 10^3$ m), it is often violated at the scale of the grid resolution of current regional atmospheric models (about 10^4 m), especially over Europe. Techniques are therefore needed to achieve a matching of the scales of atmospheric measurements and models. In numerical models an "artificial" typical land surface may be introduced by determining effective surface parameters, or the dominant land use may be assumed to be the one governing the area-averaged exchange conditions. Alternatively, subgrid-scale variability may be taken into account by the mosaic or tile approach (see, e.g., Avissar, 1991; Mahrt, 1996; Giorgi and Avissar, 1997; Mölders, 2001; Heinemann and Kerschgens, 2005). On the other side measurements can provide averaged fluxes at model grid scale if special aggregation rules for local flux measurements are applied or if spatially integrating measurement or data analysis techniques are used (see, e.g., Gottschalk et al., 1999; Mahrt et al., 2001; Gioli et al., 2004). In addition to numerical modelling, area-averaged fluxes are required as a ground-truth for satellite data at the image's pixel resolution scale (e.g., Berger, 2001; van den Hurk, 2001). Moreover, knowledge of the area-averaged evaporation at the field or watershed scale is of interest for hydrological studies and for irrigation management (e.g., Kite and Droogers, 2000).

Several field experiments have been performed over heterogeneous land surfaces in different geographical and climate regions of the earth over the last 15–20 years (e.g., André et al., 1988, 1990; Tsvang et al., 1991; Doran et al., 1992; Sellers et al., 1997; Halldin et al., 1999; LeMone et al., 2000). Within field programmes, the experimental determination of the energy budget over a locally "homogeneous" surface is usually based on micrometeorological measurements and modelling techniques (for a summary, see, e.g., Kaimal and Finnigan, 1994; Arya, 2001). It should be remarked that "homogeneous" typically means a sufficiently large area of a certain soil or vegetation type thereby neglecting the microscale variability of soil and vegetation parameters. Data from local micrometeorological measurements performed at a number of sites and covering all representative surface types have been suitably aggregated in order to determine an area-average of the surface fluxes in a number of studies (e.g., Gottschalk et al., 1999;

Chen et al., 2003). Direct measurements of the area-averaged fluxes are possible with aircraft only (e.g., Mahrt and Ek, 1993; Desjardins et al., 1997; Frech and Jochum, 1999; Mahrt et al., 2001). In addition, alternative methods based on optical path measurements of turbulence properties using a scintillometer (e.g., De Bruin et al., 1995; Green et al., 2001; Meijninger et al., 2002a, b) or based on the measurements of mean mixed-layer variables and budget considerations (e.g., Barr et al., 1997; Gryning and Batchvarova, 1999; Cleugh et al., 2004) have been applied successfully to determine area-representative flux values. Also, flux (profile) measurements made on tall towers above a potential blending height inside the atmospheric boundary layer or with the help of ground-based remote sensing instruments are assumed to represent regionally averaged conditions and they might be used to give an estimate of the area-averaged surface flux.

Initial studies of area-averaged fluxes in the region around the Meteorological Observatory Lindenberg (MOL) of the German Meteorological Service (Deutscher Wetterdienst, DWD) were performed during the LITFASS-98 experiment with a limited number of ground stations and a large-aperture scintillometer (Beyrich et al., 2002). A case study during LITFASS-98 included both the analysis of simultaneous airborne measurements with a DO-128 research aircraft and with the Helipod, a turbulence probe carried by a helicopter, and the derivation of flux profiles from wind profiler radar/RASS measurements (Bange et al., 2002; Engelbart and Bange, 2002). The experiences from LITFASS-98 formed the basis for the design of the LITFASS-2003 experiment (Beyrich and Mengelkamp, 2006). The considerably extended flux measurement programme comprised micrometeorological measurements at 13 sites, more than 20 Helipod flights, the operation of several long-range scintillometers and flux-profile measurements from a combination of two lidars (a water vapour DIAL and a Doppler wind lidar).

With the measurement set-up of the LITFASS-2003 experiment we attempted to overcome a number of limitations that previous field experiments suffered from with respect to the determination of area-averaged fluxes, as discussed, e.g., in Mahrt et al. (2001). These limitations include, analysis problems with tower and aircraft eddy-covariance measurements (in particular under weak wind nocturnal conditions); data gaps in flux time series that prevent the calculation of area-averaged fluxes; the absence of tower measurements over some of the relevant types of land use (especially over lakes); or inappropriate coverage of the study area by aircraft measurements.

The present study is specifically devoted to the analysis of local flux measurements made over different types of the underlying surface using micrometeorological techniques. Details of the scintillometer, Helipod, and lidar flux measurements are discussed in the companion papers by

Meijninger et al. (2006), Bange et al. (2006b), and Hennemuth et al. (2006). In the following, Section 2 provides details of the measurements and data analysis, while Section 3 is devoted to the discussion of the observed variability of surface fluxes across the study region. In Section 4 the methodology used to aggregate the local surface flux data into area-averaged fluxes (which are called “flux composites”) will be described. Aggregated surface fluxes are compared with area-averaged flux estimates from the scintillometer and Helipod measurements in Section 5. Finally, a summary of the results is given in Section 6.

2. Measurements and Data Analysis

The LITFASS-2003 experiment was performed in a heterogeneous landscape around the MOL during a one-month period between 19 May 2003 and 17 June 2003 (see Beyrich and Mengelkamp, 2006). Local flux measurements over single patches of land use in the heterogeneous study area formed a central part of the measurement programme. Fourteen micrometeorological stations were set up at 13 sites to cover all major relevant land use types with representative measurements and to be able to study differences of the local energy and water budget components due to different meteorological forcing conditions over the same type of underlying surface. The distribution of the thirteen measurement sites across the study region is shown in Figure 1.

Most of the sites were arranged in the eastern part of the area where agriculture is the dominant type of land use while the western part is mainly covered by forest. Four of the micrometeorological stations (N2, N4, HV and FS) were in long-term operation during the year 2003 as part of the operational measurement programme of the MOL. The other ten stations were set up temporarily for the period of the experiment. They mainly covered the different types of agricultural farmland that prevail in the region (cereals, particularly rye and triticale, rape and maize). In addition to the lake station of the MOL at the *Großer Kossenblatter See* (FS), which represented a rather small and shallow lake, a second lake site was established close to the eastern beach of the *Scharmützelsee* (SS), the largest water body in the study area. A site characterisation of the different micrometeorological field sites is given in Table I.

All low-vegetation land-use classes (cereals, grass, rape, and maize) were represented by at least two measurement stations. If possible the stations were set up in such a way that those installed over the same type of surface allowed for representative measurements under different wind directions in order to cover each land-use class by at least one station, independent of the actual wind direction. As can be seen from Table I this was nearly

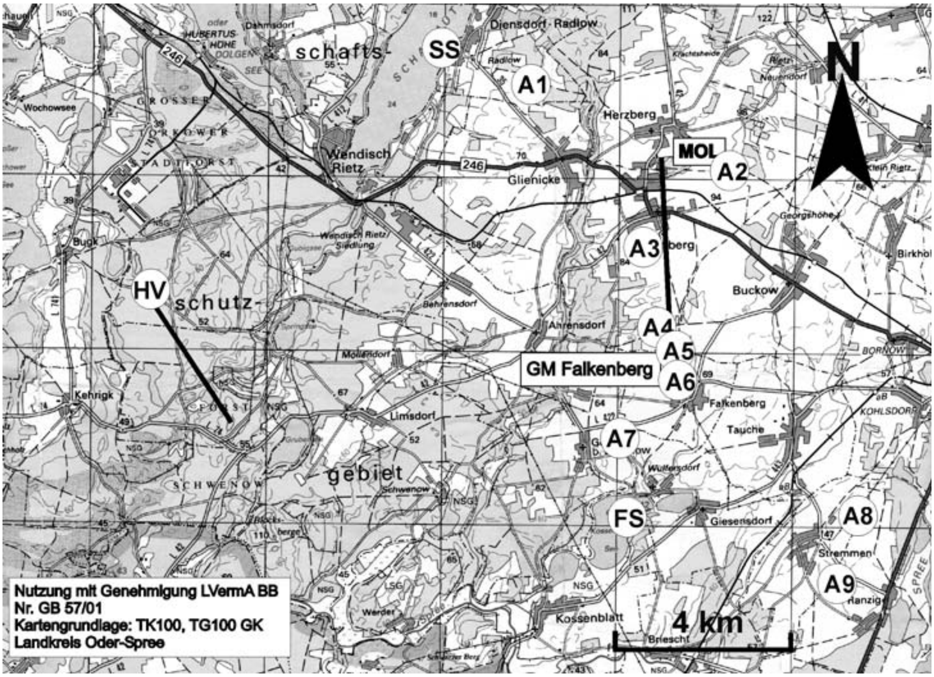


Figure 1. Positions of the micrometeorological measurement sites during LITFASS-2003 in the heterogeneous landscape around the MOL (the N2/N4 stations were both operated at the GM Falkenberg, the dashed lines mark the LAS paths over forest and farmland). *Remark*: This figure is based on a topographic map TK100 issued by the Landesvermessungs-amt Brandenburg, reproduction has been kindly permitted under Ref.-No. GB 57/01.

achieved for cereals and rape. For logistical reasons, no undisturbed measurements could be performed for easterly winds at the lake sites and for northerly winds over grass and maize.

Vegetation height and leaf area index (LAI) were measured at weekly time intervals at the nine farmland sites, the LAI being measured using a LAI-2000 sensor (LiCor Inc.). The various types of cereals differed quite substantially with respect to their vegetation height, and large deviations in the LAI occurred between the three rape fields. The two maize fields were mainly bare soil at the beginning of the experiment, but after five weeks the maize had grown to more than 0.5 m. The grass at the boundary-layer field site (in German: Grenzschichtmessfeld – GM) Falkenberg of the MOL was cut a few days before the start of the measurements and grew continuously until the end of the measurement period.

Measurements at all micrometeorological stations included the determination of basic atmospheric parameters (air temperature, air humidity, wind speed and direction) and of the major components of the surface energy budget (net radiation, sensible and latent heat fluxes, soil heat flux).

TABLE I

Site and instrumentation characteristics of the micrometeorological measurement sites during LITFASS-2003.

Site	Surface	Operator[a]	Distance from GM Falkenberg (km)	Height above sea level (m)	Undisturbed fetch sector (clockwise) (deg)	Vegetation height (m)	Leaf area index	Turbulence sensors	Measurement height (turbulence) (m)
HV	Pine forest	DWD	12	49	030–330	14	No meas.	USA-1 / LI-7500	30.5
N2	Grass	DWD	–	73	060–180	0.05…0.25	No meas.	USA-1 / LI-7500	2.40
N4	Grass	DWD	–	73	150–330	0.05…0.25	No meas.	USA-1 / LI-7500	2.40
A1	Rye	TUDD	7.5	69	090–300	0.70…1.55	1.5…3.2	USA-1 / KH20	3.55/3.45
A3	Barley	GKSS	3	86	090–270	0.50…0.65	1.6…2.5	CSAT3 / KH20	3.25
A5	Rye	UBT	0.5	73	060–030	0.75…1.50	1.9…3.6	USA-1 / KH20	2.80/2.75
A8	Triticale	WUR	5	52	030–210	0.60…1.10	1.5…3.7	CSAT3 / LI-7500	3.55/3.25
A2	Rape	TUDD	5	93	090–330	1.05…1.25	1.2…2.0	CSAT3 / KH20	3.60
A7	Rape	GKSS	2	67	030–240	0.70…0.90	2.2…5.0	CSAT3 / KH20	3.40
A9	Rape	WUR	6	48	060–210	1.00…1.20	1.7…4.2	CSAT3 / LI-7500	3.50/3.25
A4	Maize	GKSS	1	75	090–270	0.05…0.95	No meas	CSAT3 / KH20	3.25
A6	Maize	UBT	0.2	73	090–270	0.05…0.70	No meas.	CSAT3 / LI-7500	2.70/2.65
FS	Water	DWD	3	43	180–030	No veg	No veg	USA-1 / LI-7500	3.85
SS	Water	MPI	9	38	180–030	No veg	No veg	USA-1 / LI-7500	2.85/2.50

[a] Operator of the sites: DWD – German Meteorological Service; TUDD – University of Technology Dresden; GKSS – GKSS Research Centre Geesthacht; WUR – Wageningen University and Research Centre; UBT – University of Bayreuth; MPI – Max-Planck–Institute for Meteorology Hamburg.

Soil temperature and soil moisture were measured at most of the sites. The turbulent fluxes of sensible heat (H) and latent heat (λE, where λ is the latent heat of vaporisation) were determined by the eddy-covariance method based on the wind, temperature and humidity fluctuation measurements. These were performed using sonic anemometer–thermometers and optical hygrometers at 10–20 Hz sampling rates. In order to reduce possible flux differences due to different sensor configurations and geometry, just two types of sonics (CSAT3 manufactured by Campbell Scientific Ltd. and USA-1 manufactured by METEK GmbH) and hygrometers (the Krypton hygrometer KH20 manufactured by Campbell Scientific Ltd. and the infrared gas analyser LI-7500 manufactured by LiCor Inc.) were used in LITFASS-2003 (see Table I for details on the flux instrumentation of the sites). Deviations between these instruments had been assessed during a pre-experiment in May and June 2002, when up to seven eddy-covariance systems were operated parallel to each other at GM Falkenberg. During this intercomparison study differences of less than 10% between the different sensor configurations were found for the sensible heat flux, and mean deviations for the latent heat flux were less than 15%. For the same type of instruments these values reduced even more by about 5% (for details, see Mauder et al., 2006).

Data processing and analysis of the eddy-covariance measurements were performed with the help of one unique software package in order to exclude possible differences between the final flux datasets resulting from differences in the data treatment. The data processing included the detection of spikes, the performance of a planar-fit coordinate rotation, and the application of corrections for high-frequency spectral losses due to sensor geometries (line averaging, spatial separation), for oxygen cross-sensitivity (in the case of the Krypton hygrometer), for buoyancy and cross-wind effects on the sonic temperature, and for volume–mass conversion and density effects on the trace gas (water vapour) fluxes (for details, see Mauder et al., 2006). The quality of the resulting flux values was characterised by the performance of a steady-state test and a test on integral turbulence characteristics, according to a scheme proposed in Foken et al. (2004). The final data products were time series of 30-min averaged surface flux values for each of the 14 micrometeorological stations.

Three large-aperture optical scintillometers (LAS) were operated during LITFASS-2003 over distances between 3 and 10 km in order to determine area-averaged values of the sensible heat flux. A microwave scintillometer (MWS) was installed parallel to one of the LAS (measuring over 4.7 km between the GM Falkenberg and MOL sites), which allowed additional determination of the latent heat flux at the meso-γ scale. Details of the scintillometer measurements are discussed in Meijninger et al. (2006). From the three LAS paths, one extended over the forested part of the LITFASS area, and a second mainly represented the farmland region. The position of these two paths is also shown in Figure 1. The third LAS path extended over a mixed area. The results from these measurements are not used in the present study.

Independently, area- and path-averaged values of the (near-) surface energy fluxes were obtained from airborne measurements with the Helipod, a turbulence probe carried by a helicopter (e.g. Bange and Roth, 1999). Twenty-seven flights were performed on 16 days of the LITFASS-2003 experiment. Most of these flights included flight legs at low altitudes (typically at about 80 m above ground). This was well below $0.1\,z_i$ (where z_i is the boundary-layer height) in most cases so that the fluxes measured along these legs can be considered to closely represent the surface fluxes. Extrapolation and inverse modelling methods were used to determine the averaged surface fluxes over the whole LITFASS area from the Helipod data (Bange et al., 2006a).

3. The Variability of Surface Fluxes

The variability of the local energy fluxes at the surface between different sites in a heterogeneous landscape depends both on the vegetation and soil characteristics and on the meteorological forcing conditions (inhomogeneous distribution of incoming radiation and precipitation). Different radiative and thermal properties of the surface may cause substantial differences in the amount of energy available for the turbulent exchange between different sites even under conditions of comparable incoming shortwave and longwave radiation. Mean values of the albedo around noontime and of the net radiation when compared to the values measured at GM Falkenberg on two days with clear-sky conditions for the major surface types in the LITFASS area are given in Table II.

The lowest albedo was measured over the water and over the forest, values over farmland roughly varied between 0.16 and 0.22 during the course of the experiment. Daytime net radiation was highest over the lake due to the low albedo and the relatively low water temperature. Lowest values of net radiation were measured over the short grass at GM Falkenberg and over the maize (bare soil) fields. Rye usually had the highest net radiation when compared to the other low vegetation surfaces at the beginning of the experiment, while towards the end the net radiation over the rape was higher.

Much more pronounced differences than for the net radiation resulted for the turbulent fluxes between the different surface types. An example is presented in Figure 2, showing the diurnal cycle of the sensible and latent heat fluxes for a day during the first phase of the experiment.

TABLE II

Mean values of the surface albedo during LITFASS-2003 and of the net radiation (R_n) normalised by the net radiation at GM Falkenberg on two clear-sky days (29–30 May 2003) for different land-use types.

Surface/Site	Mean albedo (0800–1400 UTC)	R_n/R_n(grass) (0800–1400 UTC)
GM Falkenberg (grass)	0.19	1.00
HV (pine forest)	0.10	1.36
FS (water)	0.07	1.42
A2 (rape)	0.19	1.11
A5 (rye)	0.18	1.22
A6 (maize)	0.20	1.06

Over the forest, the sensible heat flux was up to four times higher than over the farmland, while the latent heat flux was smaller than over most of the other vegetated surfaces (except for the maize/bare soil). Obviously the surplus in available energy (from the higher net radiation) was basically used for heat transport while evaporation was reduced due to a low soil moisture content (on 25 May, soil moisture in the upper 0.3-m layer was 7–10% of volume at GM Falkenberg, and 5–7% of volume at the forest site) and reduced plant activity of the pine trees when compared to growing crops during the main vegetation period. Comparing the farmland sites it could be noticed that differences between the same types of crops (maize versus maize, rape versus rape, rye versus rye, only shown for two rape fields in Figure 2 for simplicity reasons) were relatively small, but significant deviations were found between the different types of cereals (sites A5 versus A8 in Figure 2). This appeared somewhat surprising, particularly with respect to triticale and rye, which visually did not differ much from each other. Also, significant differences (up to a factor of two, and exceeding by far the instrumental and measurement uncertainties) were found between the latent heat fluxes over the different types of farmland. Evaporation was high over the rape and rye fields, which, in contrast, showed smaller sensible heat flux values than the grass, maize and barley. Over the water, the sensible heat flux showed a weak diurnal cycle with negative values during daytime and an upward transport of heat at night, due to the thermal inertia of the water. Stable stratification over the cold water during the day and its effect on suppressing turbulence is also seen as the main cause for the relatively small latent heat fluxes over the open water surface.

Conditions changed during the four weeks period of the LITFASS-2003 experiment, which is illustrated in Figure 3 showing the mean ratio

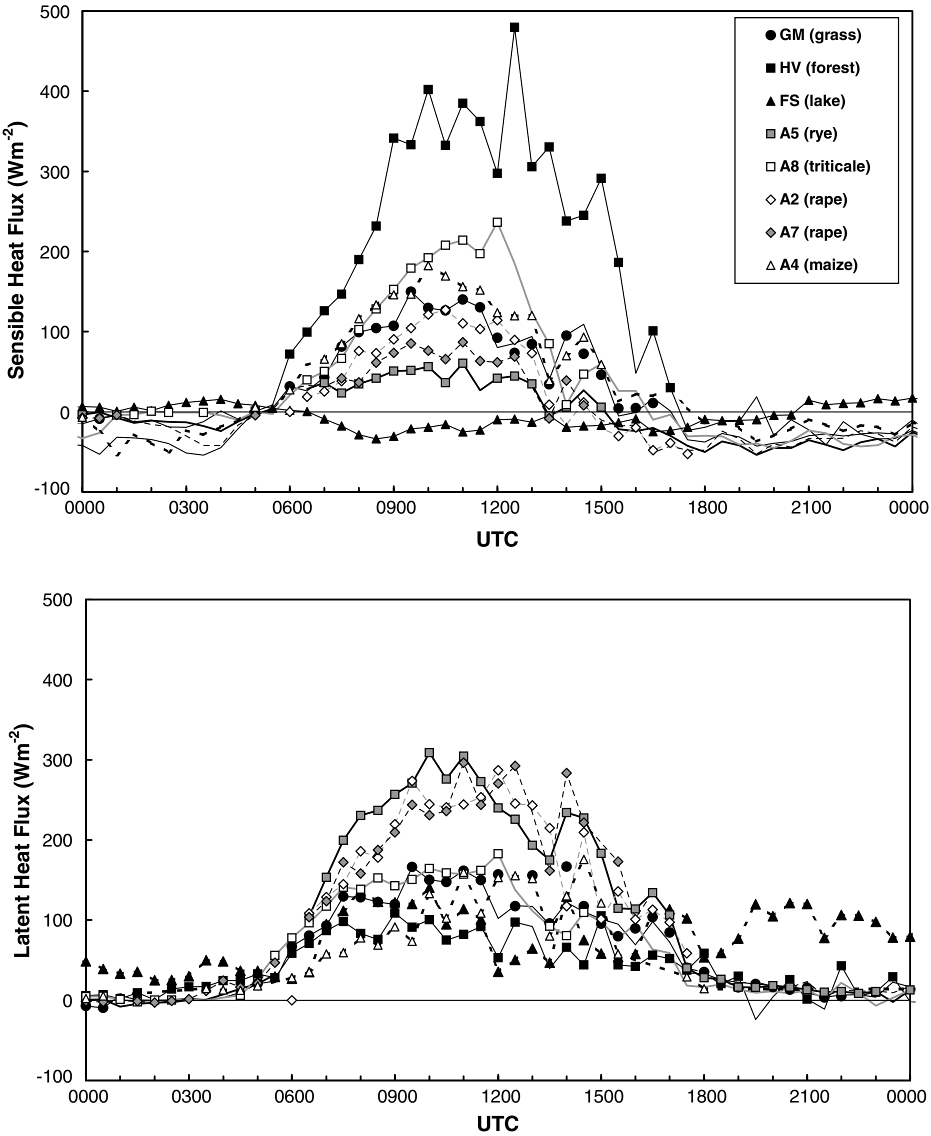


Figure 2. Diurnal cycle of the sensible (upper panel) and latent (lower panel) heat fluxes over different surfaces for 25 May 2003: all measured values are shown by the lines, values of high quality are additionally marked by the symbols.

of the fluxes at several of the sites compared to those measured at GM Falkenberg (over grass) during the period of the experiment.

The data presented in Figure 3 are daily mean values, and for a clearer presentation the single data series are allocated to a different time. Flux ratios were computed only for those time intervals when the single values from the

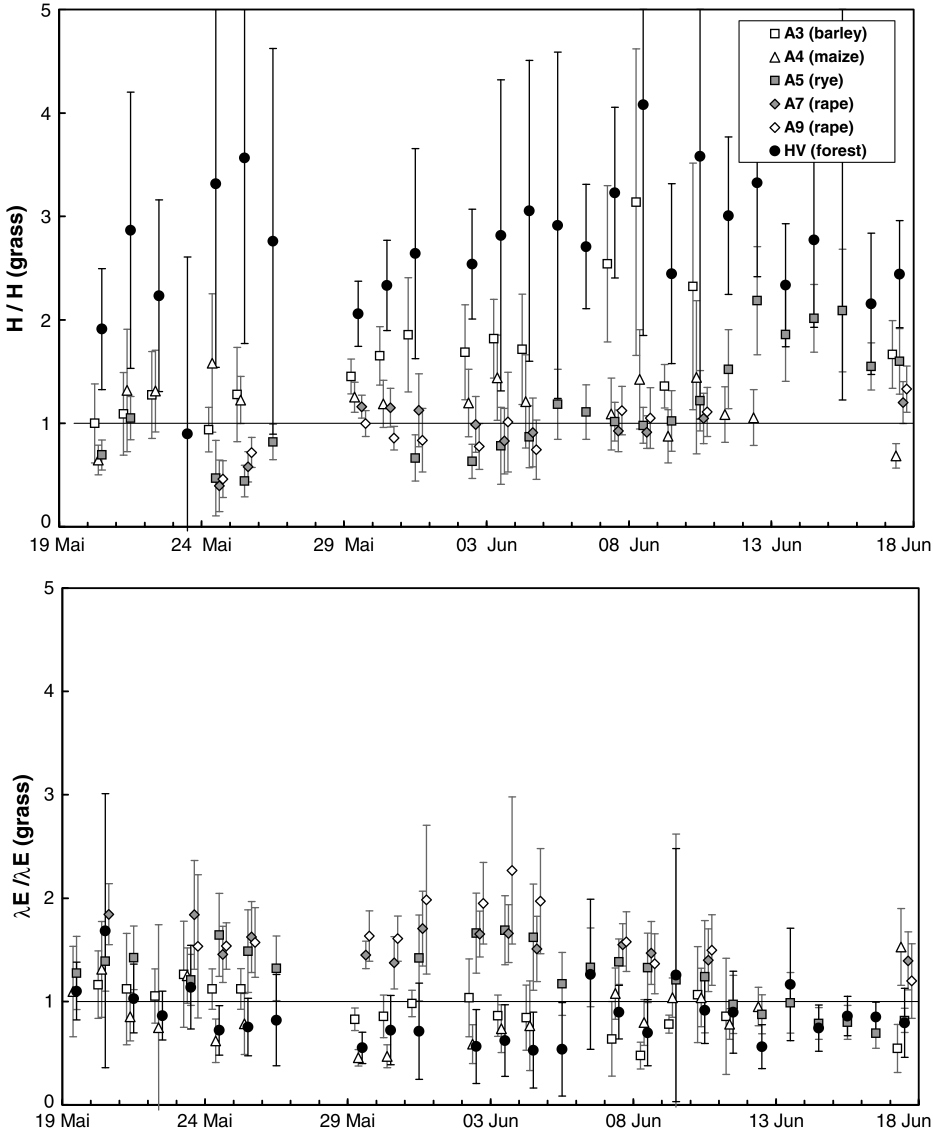


Figure 3. Mean ratio between the sensible (upper panel) and latent (lower panel) heat fluxes over different surfaces and over the grassland at GM Falkenberg during the course of the LITFASS-2003 experiment (error bars represent the root mean square differences).

two stations both had passed the quality check procedure and had an absolute value above $10\,\mathrm{W\,m^{-2}}$. The flux ratios thus basically represent daytime conditions. Moreover, the resulting daily mean flux ratios were displayed only if at least six single half-hour values were available for a given day. This selection procedure explains the gaps in Figure 3. H(maize)/H(grass) was >1 at the beginning of the experiment and increased towards the end, being the only ratio <1 on the last day. Accordingly, the ratio of the latent heat fluxes over maize versus grass increased. It is obvious that the evolution of these flux ratios was only small except for the last week of the experiment when the maize started to grow rapidly. The cereals showed an increasing trend for H and a decreasing tendency for λE related to the vegetation development of the grain crops during the experiment towards maturity. An obvious time delay existed between the barley and rye sites with respect to this tendency. For the rape, evaporation was higher than over grass during the whole LITFASS-2003 period.

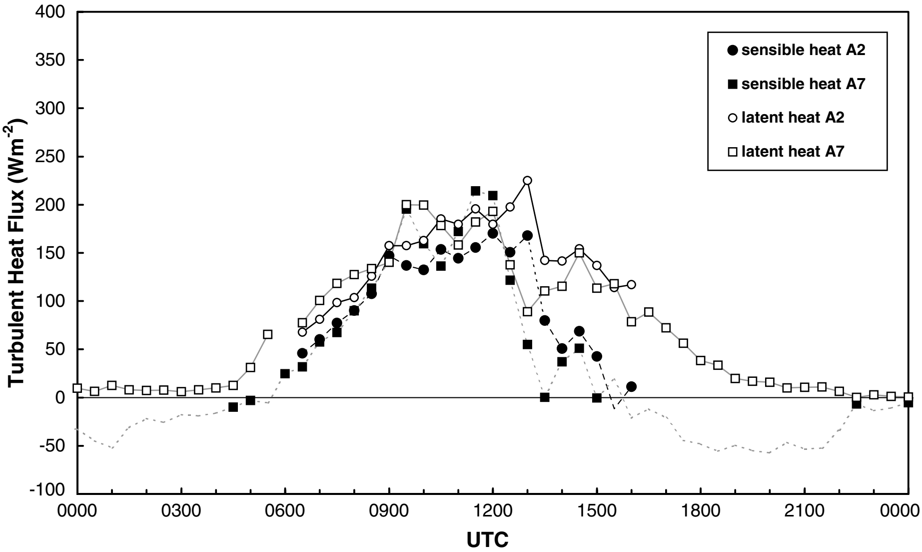
Root-mean-square differences (rmsd) between the flux values at the different stations in the southern part of the study area (sites GM and A4 to A9) are listed in Table III. It can be seen that, except for the cereals, the smallest rmsd values always occur between the two sites of the same surface type, while the differences for other surface types are usually significantly larger. This is particularly pronounced for the grass for which the two stations (N2 and N4) both represent the same site (GM). The rmsd values between the two rape and between the two maize stations are already larger by a factor around two due to the different characteristics of the two maize and rape surfaces, respectively. The differences between the two grain crop sites (rye versus triticale) are of the same order as those between the cereals and the other types of farmland surfaces. It should be noticed that these mean differences are mostly well above the estimated uncertainty of the turbulent flux values and can thus be attributed to different meteorological and site conditions.

A pronounced regional differentiation between the fluxes measured at the different sites is noticed after 5 June, after a frontal system with thunderstorms had passed the study area. This brought a rather heterogeneous distribution of precipitation (see also Beyrich and Mengelkamp, 2006) with just 1–4 mm of rain in the northern part of the area (sites Al, A2, A3), but up to 40 mm of rain in the southern half (sites A8, A9). Consequently,

TABLE III

Root-mean-square differences (in W m^{-2}) between the turbulent energy flux measurements over the different surfaces.

H	Grass	Maize	Rape	Cereals	λE	Grass	Maize	Rape	Cereals
Grass	11	24	31	50	Grass	16	32	60	45
Maize		23	43	49	Maize		26	74	57
Rape			26	52	Rape			32	43
Cereals				72	Cereals				52



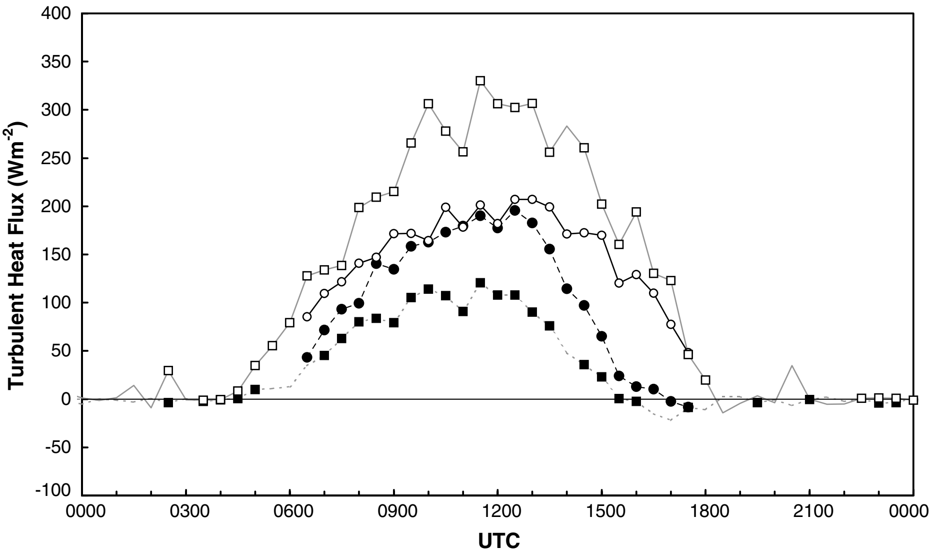


Figure 4. Diurnal cycle of the sensible and latent heat fluxes over two rape fields on 4 June 2003 (upper panel) and on 7 June 2003 (lower panel) showing a strong differentiation in the energy partitioning following rain on the evening of 5 June 2003.

evaporation was high over the following two days at those sites that were well supplied with rain, while the sensible heat flux remained dominant in the drier parts of the area. This is illustrated in Figure 4 by comparing the turbulent fluxes at the two rape sites A2 and A7 before and after the precipitation event of 5 June.

On 4 June 2003, the sensible and latent heat fluxes were of comparable magnitude at the two sites all peaking around 200 W m^{-2} during noontime. On 7 June 2003, the conditions were roughly the same over the rape field in the northern part of the area (A2) with a Bowen ratio around 1.0 and absolute flux values close to 200 W m^{-2} again. In contrast, at the southern rape site the latent heat flux exceeded the sensible one by a factor of about three. The strong differentiation between the northern and southern parts of the area disappeared (see Figure 3) after passage of a second front on the evening of 8 June yielded between 8 and 19 mm of rain all over the region.

4. The Formation of Flux Composites

In order to determine an area-average of the surface fluxes for the LITFASS-2003 study region from the local surface-layer measurements, a suitable aggregation strategy had to be applied. Previous studies reported in the literature achieved good results with a land-use weighted averaging of the available surface-layer measurements (e.g., Halldin et al., 1999; Mahrt et al., 2001) both for the sensible and latent heat fluxes. However, as discussed in Mahrt et al. (2001) a number of limitations has to be overcome before performing the averaging. This includes the correction and quality assessment of the eddy-covariance measurements, the treatment of gaps in the times series of measured fluxes, and the application of reasonable assumptions on the fluxes over those land-use types that were not covered by measurements. In this study we applied a three-step procedure in order to aggregate the single surface-flux measurements to flux composites, and to obtain area-averaged values of the sensible and latent heat fluxes. This algorithm is illustrated schematically in Figure 5.

First, an average or representative flux for each of the land-use classes covered by measurements was determined, giving six time series of surface fluxes, namely for forest, water, grassland, cereals, rape, and maize. In a second step the data from the four different types of low vegetation were composed into one time series of fluxes over farmland, and finally a land-use weighted averaging was performed between the values for forest, farmland and water to arrive at the area-averaged fluxes.

The forest-flux time series had to be based on the measurements at only one station representing the pine forest in the western part of the LITFASS area (HV site). A low-pass filter was applied to the forest dataset using a running mean over the time series with a triangular (1-2-1) weight filter function. Moreover, results of the automatic quality control were checked manually and flagged data that appeared plausible were further considered for the averaging procedure.

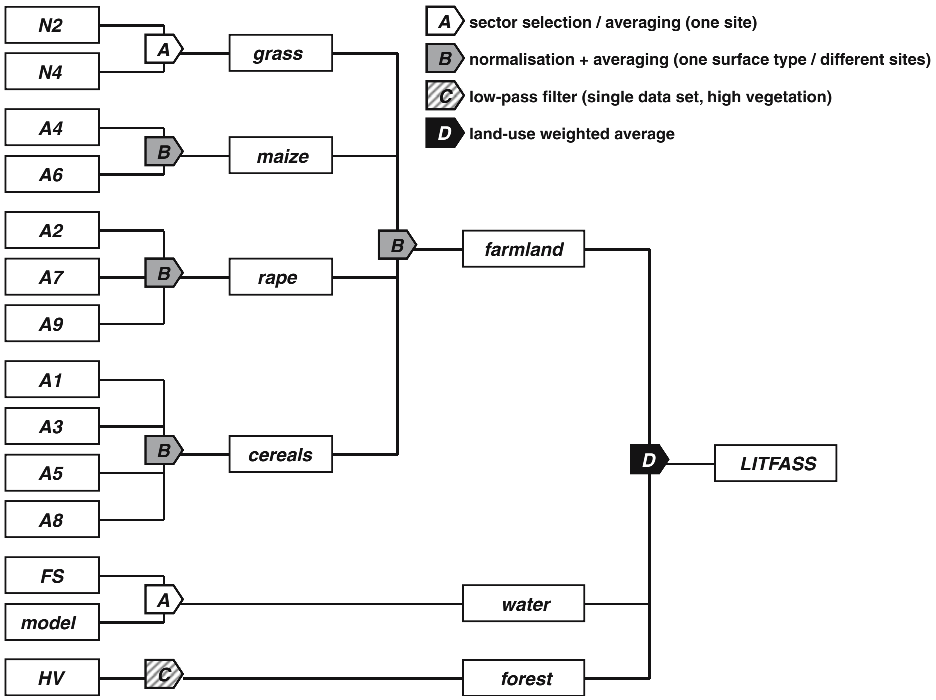


Figure 5. Schematic illustration of the algorithm used to determine the surface-flux composite from the measurements at the 14 micrometeorological stations.

The data available for grassland were from two flux stations representing the same surface, since the N2 and N4 stations both were operated at the GM Falkenberg: N4 close to the eastern edge and N2 at the western edge. Consequently, measurements from the two stations are representative of different wind direction sectors (see Table I) with a small overlap for winds from 150 to 180 degrees and with a gap for winds from 330 to 060 degrees when both stations experienced some flow distortion. The grassland composite was thus formed by simply selecting the representative data dependent on wind direction, thereby performing an arithmetic average when the wind was from the south-south-east sector.

For the three types of agricultural farmland, the creation of a representative flux dataset was not straightforward. Measurements were made with different types of instruments and the data represented different fields in different parts of the experimental area (see Figure 1). Time series of flux data from all sites contained a number of gaps that were due either to instrumental problems (e.g., dew or rain on the windows of the optical hygrometers) or to a non-favourable wind direction resulting in flow distortion or limited fetch conditions. Moreover, a certain number of data failed to pass the quality tests and hence were classified as “poor”. This means that at any given moment both the number and grouping of station data available for forming the flux composite may be different. For the selection or averaging of flux data from a number of sites over a certain surface type this could easily introduce artificial jumps in the resulting time series if the measurements at the single stations typically differ from each other, as was found in particular for the cereals. Therefore, each flux time series measured at a particular site was first normalised with respect to the corresponding surface-type mean before performing the averaging. Details of this procedure are outlined in Appendix A.

Instrumental, fetch and flow distortion limitations were most serious at the lake sites. After two weeks of operation the sonic of the station SS had to be sent to the manufacturer for repair causing an 11-day gap in the data. At both the lake sites (see Table I) flux values measured for wind directions from the sector between north-east and south were heavily distorted and non-representative due to the close vicinity of the shore and of high trees forming the shoreline. Therefore a simple exchange parameterisation model was used to simulate the turbulent fluxes over water for the whole experiment and to replace the measured values by the modelled ones when the wind direction was between 030 and 180 degrees. More details of the flux modelling over the lake are given in Appendix B.

In the second step, the fluxes determined for the different types of low vegetation were aggregated to a mean flux representative of farmland. The procedure followed was the same as in the first step described above and in Appendix A. In addition an attempt was made to give an uncertainty range of the derived fluxes. Mauder et al. (2006) have estimated the uncertainty of the single flux data in the individual time series to be of the order of 10% (or $10\,\mathrm{W\,m^{-2}}$, whichever is larger) for the sensible heat flux, and of 15% (or $15\,\mathrm{W\,m^{-2}}$) for the latent heat flux. For the composite, the uncertainty is assumed to be at least of the same order of magnitude. Moreover, in order to account for limitations in the area representativeness, the maximum difference of the single flux data (H_i, λE_i) when compared to the normalised mean land-use specific flux (H_{norm}, $\lambda E_{\mathrm{norm}}$) was added as a third criterion. The uncertainty estimate (Δ) for the composite constructed from a number of n single time series is therefore given by

$$\Delta H = \max(0.10\,H, 10\,\mathrm{W\,m^{-2}}, \max_{i=1,n}(\mathrm{abs}(H_i - H_{\mathrm{norm}}))), \tag{1}$$

and

$$\Delta\,\lambda E = \max(0.15\,\lambda E, 15\,\mathrm{W\,m^{-2}}, \max_{i=1,n}(\mathrm{abs}(\lambda E_i - \lambda E_{\mathrm{norm}}))), \tag{2}$$

respectively.

As an example of the results, the diurnal cycle of the sensible and latent heat fluxes over the different types of farmland is shown in Figure 6 for the

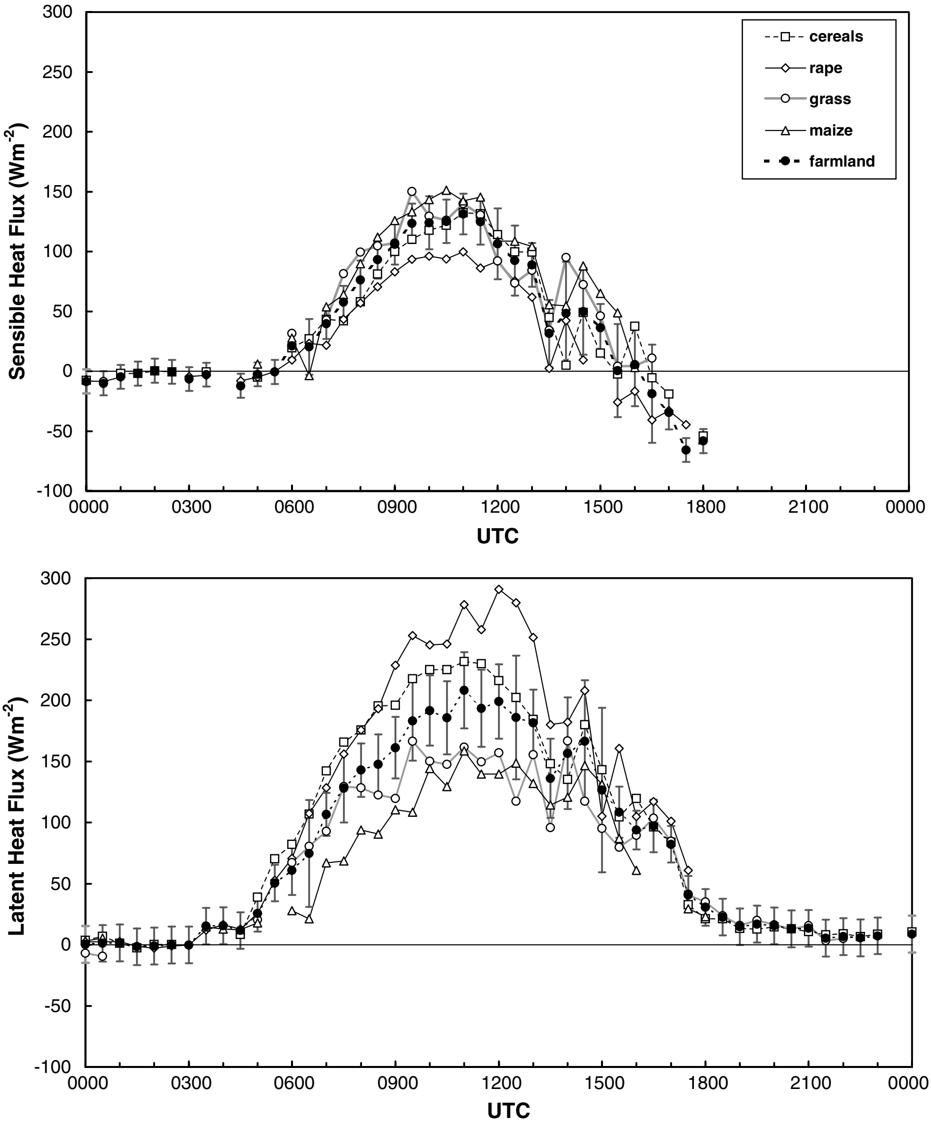


Figure 6. Diurnal cycle of the composite sensible (upper panel) and latent (lower panel) heat fluxes for the different types of agricultural farmland and the farmland composite on 25 May 2003.

same day as discussed above (Figure 2). The uncertainty range indicated for the composite *H* is mostly within the 10% or 10 W m^{-2} range except for the afternoon (1400–1700 UTC) when the single values show larger scatter and thus their deviations to the normalised mean are more significant. For the latent heat flux, the overall uncertainty is larger due to the larger uncertainty assumed for a single flux value but also due to the higher variability of λE between the different land-use types.

The ratio between the flux values over the single types of agricultural crops and the farmland composite has been determined for both H and λE over the whole period of the experiment; a frequency distribution for the latent heat flux for each of the low-vegetation surface types is shown in Figure 7.

The results confirm and generalise the findings derived from Figure 3 for some of the sites. It can be seen that the evaporation over rape was mainly higher than for the farmland composite, while it was mostly lower over maize. The distribution for cereals covers a rather broad range and exhibits several maxima. Contrary to this, the frequency distribution for grassland is quite narrow and well centred slightly below a value of one. This indicates that the measurements of the latent heat flux over grassland during the period of active vegetation growth (in May and June) can be considered as quite representative for farmland. A similar conclusion holds for the sensible heat flux.

The final step towards an aggregated surface flux representative for the LITFASS area was the calculation of a weighted average from the time series of fluxes for forest, farmland and water. The three main land-use classes were weighted according to their relative frequency of occurrence in the study area. Since no measurements were available from inside one of the settlements, their 5% frequency of occurrence was added to the percentage of forest. This was motivated by the enhanced roughness of both

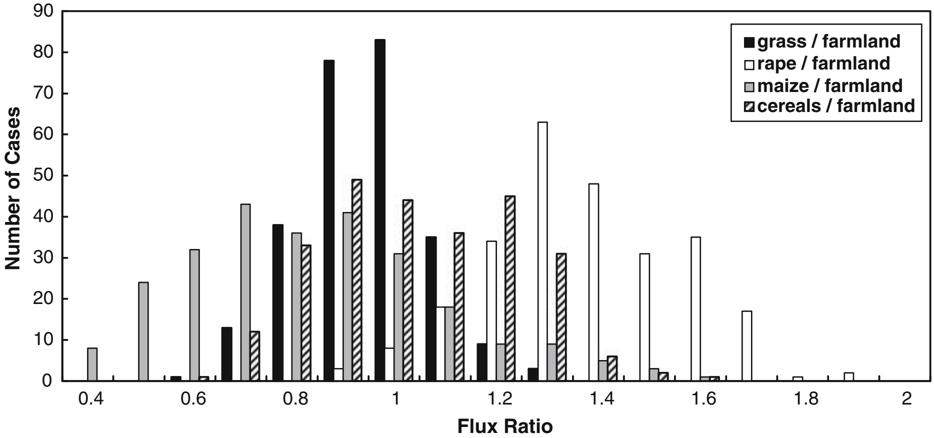


Figure 7. Frequency distribution of the ratio between the latent heat flux over different agricultural crops and the farmland mean latent heat flux over the period of the LITFASS-2003 experiment.

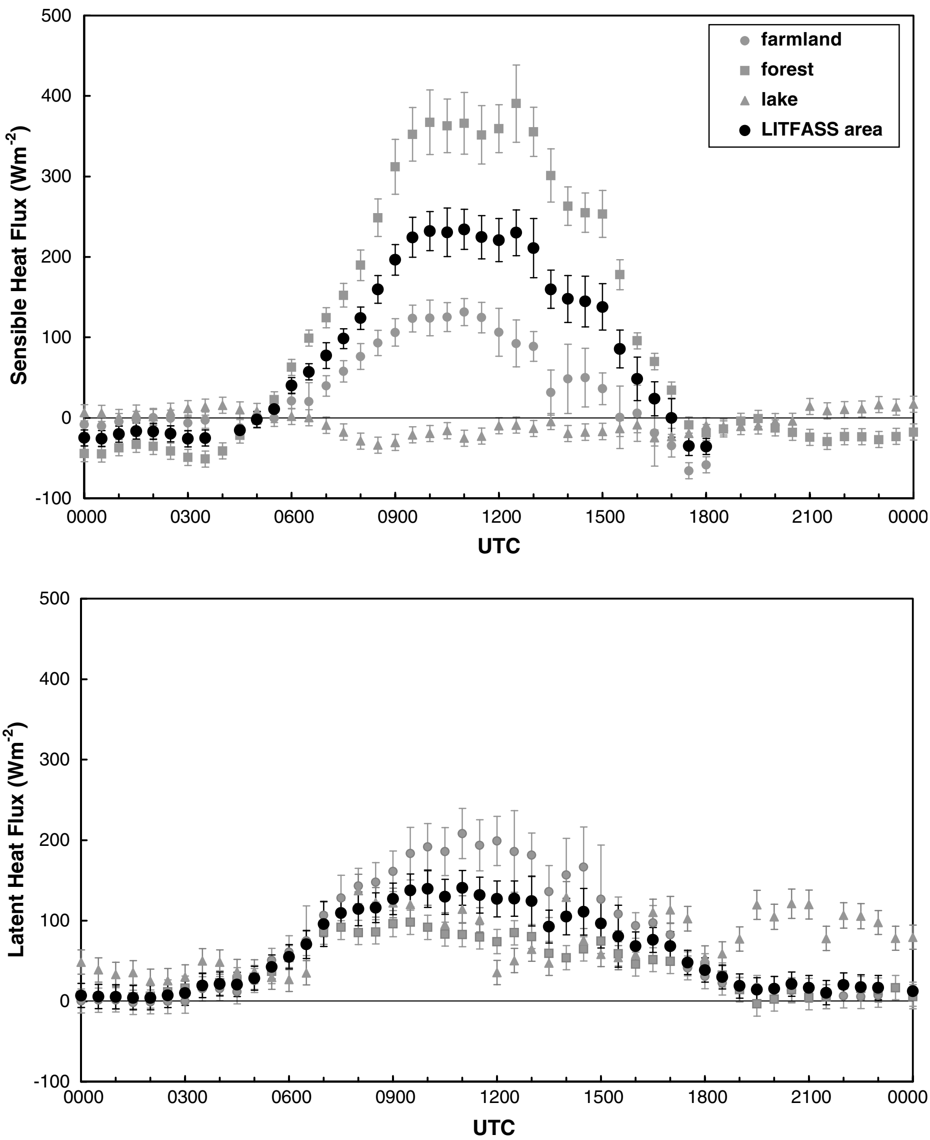


Figure 8. Diurnal cycle of the (composite) sensible (upper panel) and latent (lower panel) heat fluxes for the major land-use classes and for the whole LITFASS area on 25 May 2003.

these land-use types and by the fact that villages also would support higher sensible heat fluxes due to a certain fraction of sealed surfaces. Thus, the final percentages for the averaging were 48%, 45% and 7% for forest, farmland, and water, respectively. The resulting flux composites for the example discussed thoroughly in this section are shown in Figure 8.

Due to the relatively small area contribution of the lakes, the daytime fluxes lie between the forest and farmland values, significant evaporation over the lake at night, however, may increase the area-averaged latent heat fluxes beyond those over the land surfaces.

The aggregation procedure described above not only produced a consistent and representative time series but it also resulted in a more complete dataset of area-averaged fluxes than obtained for most of the single sites. While the availability of high-quality flux values did not exceed 50% for H and 60% for λE at a single low-vegetation measurement site, the farmland composite covers about 80% and 90% of time for H and λE, respectively. The higher availability of the latent heat fluxes when compared with the sensible heat flux (which is usually easier to measure) is due to the fact that the quality test on integral turbulence characteristics is more relaxed for λE due to the absence of a well-defined similarity relationship between the water vapour flux and the turbulent humidity scale (see Mauder et al., 2006). This implies a lower confidence level of the latent heat flux data. The data availability for the farmland composite also determined the overall completeness of the time series of area-averaged fluxes, since the forest times series was more than 90% complete (no limited fetch sector and a very small flow distortion sector only) and the flux dataset for water was complete at 100% due to the matching of measurements and model results (see above and Appendix B).

5. Evaluation of Aggregate Surface Fluxes

In order to evaluate the reliability of the flux composites determined from the eddy-covariance measurements at the fourteen surface flux stations, the area-averaged fluxes derived from the LAS/MWS systems and from the Helipod measurements can be used (see also, Bange et al., 2006b; Meijninger et al., 2006). One of the LAS was operated over a 2.85-km path completely over the forest, and data from this system were compared with the sensible heat flux measurements made on the forest tower (HV). The LAS/MWS system covered a 4.7-km path between the GM Falkenberg and the MOL sites. Meijninger et al. (2006) have performed a footprint analysis for this set-up, which showed that more than 85% of the footprint area represents farmland for all wind directions. This fraction increases to about 95% for winds from the south-east sector. The LAS/MWS data could thus be used for a validation of the farmland composite.

Some of the Helipod flights were especially designed to perform flux measurements over the three major land-use classes. These flights consisted of a series of straight flight legs at low altitude that were performed over rather homogeneous sub-areas of the experimental region, namely over the eastern farmland part, over the forest in the west, and along the eastern or western shoreline (depending on the prevailing wind direction) of the lake Scharmützelsee. The length of these legs was about 12–15 km. Two other flight strategies (the box and grid flight patterns, see Bange et al., 2006b) were especially designed to determine the area-averaged surface fluxes, and consisted of straight legs of 10–15 km length arranged in a geometrically regular way, flown in north-south and east-west orientations. North-south-legs in the west of the area mainly represented the forest again, while those in the eastern part of the study region were basically over farmland. Thus there were additional pure forest and farmland legs available for comparison from these flights, in addition to the total area-averaged fluxes.

As a first example for the intercomparison of methods the diurnal cycle of the forest and farmland fluxes for the case already discussed above is presented again in Figure 9. Here the surface-flux composite is now compared with the path-averaged fluxes derived from the scintillometer and Helipod measurements. For the sensible heat flux, remarkable agreement (within the error bars) can be seen between the flux values of different origin. Particularly, the eddy-covariance measurements from the forest tower are well supported by the LAS measurements, which gives confidence into the representativeness of the single forest flux station. For the latent heat flux, larger deviations occur. Here, scintillometer estimates are available from the LAS/MWS combination for the farmland part only. The overall diurnal evolution of λE is in remarkable agreement with the two estimates, but the LAS/MWS fluxes appear to be systematically higher by about 20–25%. Meijninger et al. (2006) discuss possible reasons for this deviation, and also show that a better closure of the energy budget is achieved with the scintillometer data. Helipod measurements of the latent heat flux scatter around the *in-situ* data. For the forest legs, the deviations are within the uncertainty range while a number of farmland legs tend to give lower latent heat fluxes than the aggregated surface stations. This especially concerns the fluxes between 0930 and 1030 UTC determined from a box flight pattern with a leg length of 10 km only, which is probably too short to achieve a representative sample. Moreover, it should be noticed that the Helipod data displayed in Figure 9 refer to fluxes at the Helipod flight level of around 80 m above ground.

An overall comparison of the surface fluxes from the ground and scintillometer measurements is discussed in Meijninger et al. (2006). For the Helipod flights, Figure 10 shows a statistical comparison of the turbulent energy fluxes over the three major land-use classes. As can be seen, the results of the case study presented in Figure 9 appear to be rather general. The sensible heat fluxes agree quite well (within the range of uncertainty) for the farmland and forest surfaces taking into account that the Helipod data were obtained a few decametres above the surface. Over the

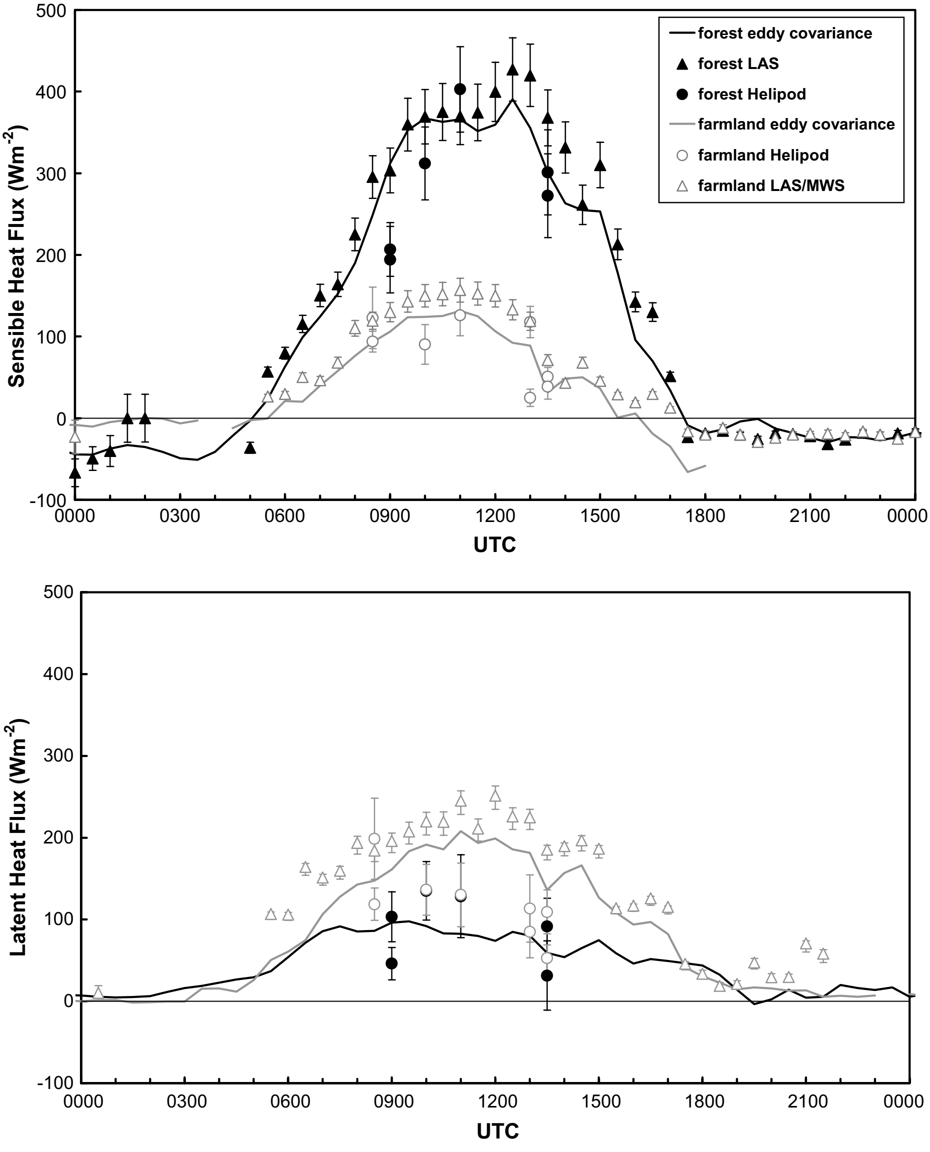


Figure 9. Diurnal cycle of the sensible (upper panel) and latent (lower panel) heat fluxes over farmland and over forest: comparison of the composite from the eddy-covariance measurements with the line-averaged fluxes derived from the LAS and Helipod measurements on 25 May 2003.

lake, the Helipod fluxes are usually higher than the near-surface measurements, this is attributed to the limited size of the lakes, implying a certain contribution from the upwind land surfaces to the fluxes measured at flight level. For the latent heat flux, considerable scatter is noticed and the error

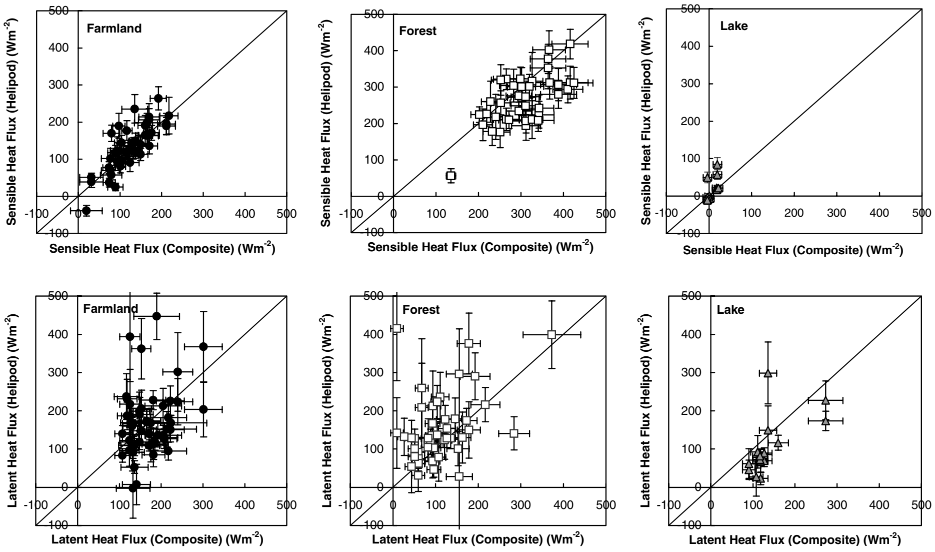


Figure 10. Comparison of the (composite) surface fluxes from eddy-covariance measurements over the three main land-use types with measured fluxes along the low-level Helipod flight legs over farmland, forest and water.

bars are considerably larger, especially for the Helipod measurements (see also, Hennemuth et al., 2006).

In Figure 11, the surface-flux composites for the LITFASS area as derived from the eddy-covariance measurements at the 14 ground stations are finally compared against the area-averaged surface fluxes determined from the Helipod measurements for each of the grid and box flights by the application of the "low-level-flight + inverse model" method (LLF + IM method, Bange et al., 2006a). The latter are all based on data from at least four flight legs (corresponding to 40-km sampling length, box flight pattern), but rely on up to 16 flight legs (corresponding to a sampling distance of more than 200 km, grid flight pattern). Consequently, the statistical errors are substantially smaller than for a single flight leg (compare with Figure 10). For the grid-pattern flights, the Helipod fluxes represent an average over about 2 h of flight time. In order to reduce uncertainties of the derived fluxes due to non-stationarity most of the flights were performed around local noon. Moreover, non-stationarity of the atmospheric variables is taken into account in the LLF+IM method and directly reflected in the error bars of the fluxes. For comparison, the surface-flux composites were averaged over the duration of the flight, and the error bar is given as the maximum of the overall uncertainty estimate according to Equations (1) and (2) and the maximum deviation of a single half-hour flux value during the flight time from the averaged flux. For the

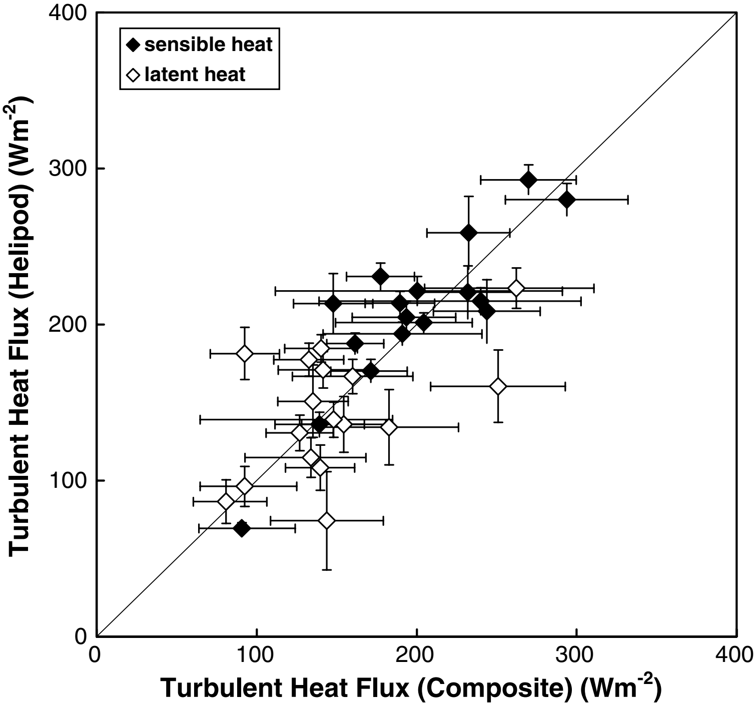


Figure 11. Comparison of the composite surface fluxes from eddy-covariance measurements with the area-averaged fluxes from the Helipod flights for the whole LITFASS area.

sensible heat flux, the mean relative deviation between the ground-based flux composite and the Helipod data (determined as the arithmetic mean of $\mathrm{abs}(H_{\mathrm{composite}} - H_{\mathrm{Helipod}})/0.5(H_{\mathrm{composite}} + H_{\mathrm{Helipod}})$), is about 11%, and it exceeds 30% in 1 out of the 17 cases. For the latent heat flux, the agreement is slightly worse and increased scatter is noticed, and the mean relative deviation is about 23%, exceeding 30% in 4 out of the 17 cases. Overall, this can be considered as good agreement.

6. Summary and Conclusions

Local surface-flux measurements using the eddy-covariance technique were performed during the LITFASS-2003 experiment at 13 sites covering all major relevant land-use classes that occur in the study region. The variety of sensors was reduced to two types each for sonic anemometers and fast-response hygrometers, and the data evaluation was performed with one unique software package, both in order to minimise the potential uncertainty of resulting flux values due to different sensor characteristics and geometries and to different data analysis algorithms. The final uncertainty of the flux measurements at a single site was estimated to be not larger then 10% (or $10\,\mathrm{W\,m^{-2}}$, whichever is larger) for the sensible heat flux and 15% (or $15\,\mathrm{W\,m^{-2}}$) for the latent heat flux, respectively (Mauder et al., 2006). The quality assurance and quality control (QA/QC) procedures applied to the LITFASS-2003 eddy-covariance measurements ensured a high and comparable quality of the estimated surface fluxes. The overall flux measurement programme in LITFASS-2003 overcame some of the limitations of earlier experiments over heterogeneous land surfaces as discussed in Mahrt et al. (2001).

Measurements performed during the relatively dry LITFASS-2003 experimental period revealed substantial flux differences between the three major land-use classes in the area (forest, farmland, open water). In general, the variability of the surface fluxes between the different types of land use was larger for the sensible than for latent heat flux. The sensible heat flux over the forest was larger by a factor of two to four when compared with the farmland, a result that is in agreement with earlier studies (e.g., André et al., 1988; Frech and Jochum, 1999). It is explained by the higher net radiation of the forest surface, and also by a lower soil moisture at the sandy forest site. In addition, agricultural crops are in the phase of active vegetation growth during May and June and available energy is used more on evapotranspiration than on the exchange of sensible heat. However, significant differences in the magnitude of the fluxes were also found between different types of farmland. In most cases, these differences were larger than the estimated uncertainty of the measurements and can therefore be considered as significant. They can be partly explained by the differences in plant physiology and vegetation stage between cereals, rape and maize. But the largest differences occurred between the different types of cereals although they all "looked green". Flux differences appeared to be small between different rape fields despite considerable differences in the LAI; a comparable finding has been reported by Soegaard (1999) for cereals. Flux ratios between the different crops varied over the period of the experiment as a result of the vegetation evolution and also in reaction to different meteorological forcing, namely the heterogeneous distribution of rain following frontal passages.

A methodology has been developed to aggregate the flux measurements performed over different types of low vegetation (agricultural farmland) to farmland flux composites. It considers the quality and availability of measurements from each site and takes into account the limited representativeness of a single-site dataset by normalisation on the mean land-use-type flux based on an analysis of the limited data periods when measurements of good quality from all sites were available. Comparison of the single-surface flux data with the farmland mean flux has shown that the measurements over grass were quite representative for the agricultural sites during the period of the experiment. By performing a land-use weighted average between the farmland composite and the measurements over forest and water, the area-averaged surface fluxes over the study region were determined. The resulting time series covers more than 80% of the LITFASS-2003 experiment.

For validation, the flux composites derived from the eddy-covariance surface measurements were compared with area-integrated fluxes from long-distance scintillometer and from airborne measurements. A mostly consistent picture between the different regional flux estimates was obtained, which is in line with findings from the NOPEX experiment reported, e.g., in Halldin et al. (1999). It can thus be concluded that both the sensible and latent heat fluxes can be aggregated from land-use weighted local eddy-covariance measurements over all relevant surface types. Scintillometry is well-suited as an independent method for the determination of regionally representative fluxes. Both local micrometeorological and scintillometer measurements can be performed operationally and may constitute the experimental base for the construction of a surface-flux climatology over heterogeneous terrain and for the provision of long-term datasets covering a broad spectrum of meteorological situations for climate modelling and satellite data analysis.

Appendix A – Forming the Farmland Type Flux Composite

As shown in Section 3, the flux data measured over the different classes of agricultural farmland differed quite significantly even between the same surface type in several cases, in particular for the cereals. This implies that simply averaging all "cereal fluxes" available at a given moment might easily produce jumps in the resulting time series when the number or the selection of station data considered for the averaging changes. To illustrate this, imagine that for some timestep only the measurements at the A1 and A5 sites, which both showed high evaporation during the first half of the experiment, were available for forming the cereal composite. The resulting mean value would be high too. Imagine now, one time step later A1 and A5 data were not available, but rather data from A3 and A8, where the evaporation was about 40% less than at A1 and A5 at the beginning of the experiment, could be used to determine the "cereal" mean. This would now give a value significantly lower than half an hour before solely caused by the selection of the stations for performing the averaging. To avoid this type of problem all time series of fluxes were normalised with respect to the mean value of the corresponding land-use class. These mean values were determined for those time periods when measurements from all sites

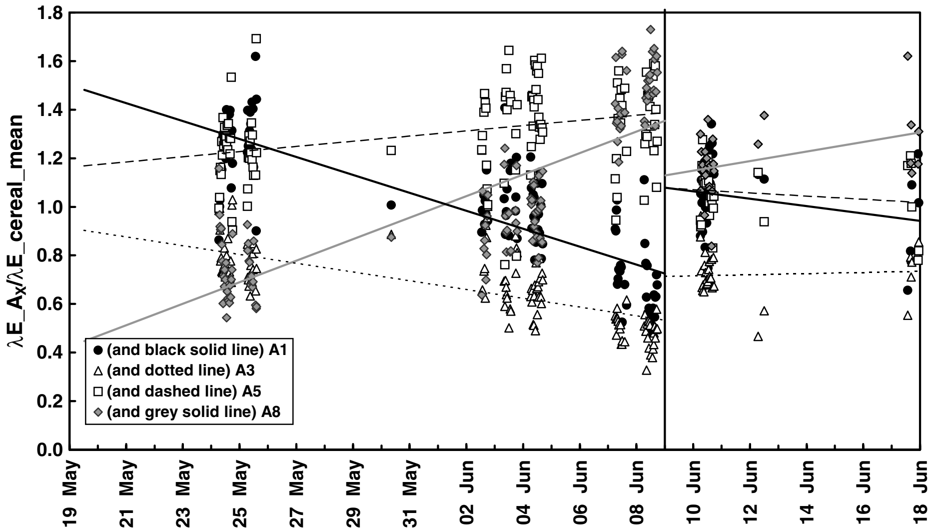


Figure A1. Flux ratios between the latent heat flux measurements at the four cereal sites and the "cereal mean" for the time periods when data from all four stations had passed the quality check procedures, and the trend lines derived for the single sites for the time periods before and after 8 June 2003, respectively.

belonging to a specific land-use class were available of good quality. As shown in Section 3, flux ratios between the sites changed during the course of the experiment, and normalisation therefore had to consider this trend. Moreover, the two rain events on 5 June and 8 June can be seen as a disturbance in the time series of flux ratios. The trends and normalisation factors were therefore determined separately for the time periods before and after 8 June. This is illustrated in Figure A1.

Normalisation factors for the different sites were determined as the reciprocals of the flux ratios prescribed by the regression lines for a specific day. At the beginning of the LITFASS-2003 experiment, the latent heat flux measurements at A3 and A8 usually were below the mean for cereals; when considered for forming the composite flux on, e.g., 29 May they thus had to be multiplied by a factor of 1.33 (1/0.75) and 1.1 (1/0.9), respectively. Normalisation factors for the rye sites (A1, A5) on 29 May were 0.9 (1/1.1) and 0.75 (1/1.3), respectively. An example of the resulting composite for the latent heat flux over cereals is shown in Figure A2. In the late morning (between 0600 and 1200 UTC), the wind direction was favourable for reliable measurements at all four sites, and the resulting composite represents an average of the values measured at the single stations. In the early morning (between 0400 and 0600 UTC), data were available from

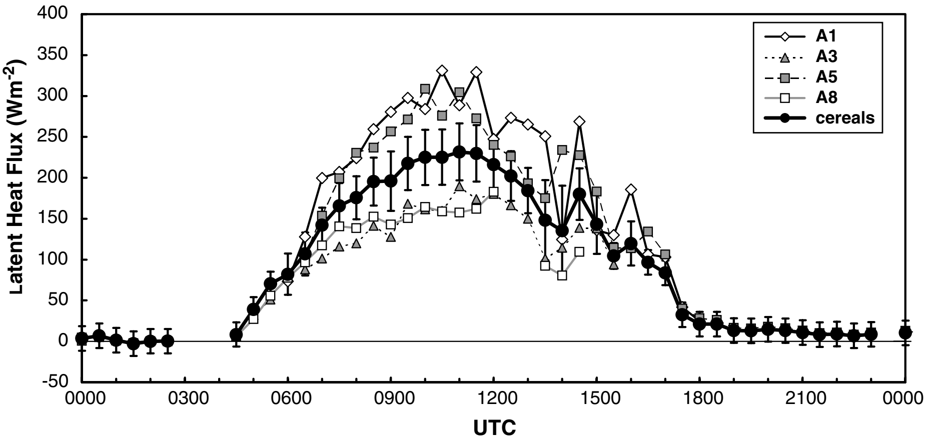


Figure A2. Time series of the latent heat flux at the four grain crop sites and the "cereal composite" on 25 May 2003.

the A3 and A8 sites only, and at both sites the latent heat flux was below the cereal mean during this phase of the experiment. The normalisation increased the values and the flux composite is thus higher than the two measurements actually available. In contrast, in the late afternoon (1600–1700 UTC), reliable measurements were available from the A1 and A5 sites only. Since these were both greater than the mean they had to be normalised with a factor below one, and the resulting composite is smaller than each of them.

Appendix B: Modelling the Fluxes Over the Lake

Flux modelling for the lake site was performed using the parameterised model described by Mironov et al. (2003), which has also been incorporated in the operational NWP model of the DWD. It uses a bulk parameterisation for the energy fluxes at the air–water interface and contains a two-layer parameterisation of the temperature profile in the water body of the lake. Meteorological input parameters for the model calculations are the air and water temperatures, humidity of the air, global radiation and wind speed. The lake is characterised by its size and depth.

As discussed in Section 3, measurements at the *Großer Kossenblatter See* (FS site) were heavily distorted for winds from easterly directions. This did not only concern the flux data but it also held for the wind measurements. The wind measurements at the lake site therefore had to be replaced by some proxy if the wind direction was between 030 and 180 degrees. For

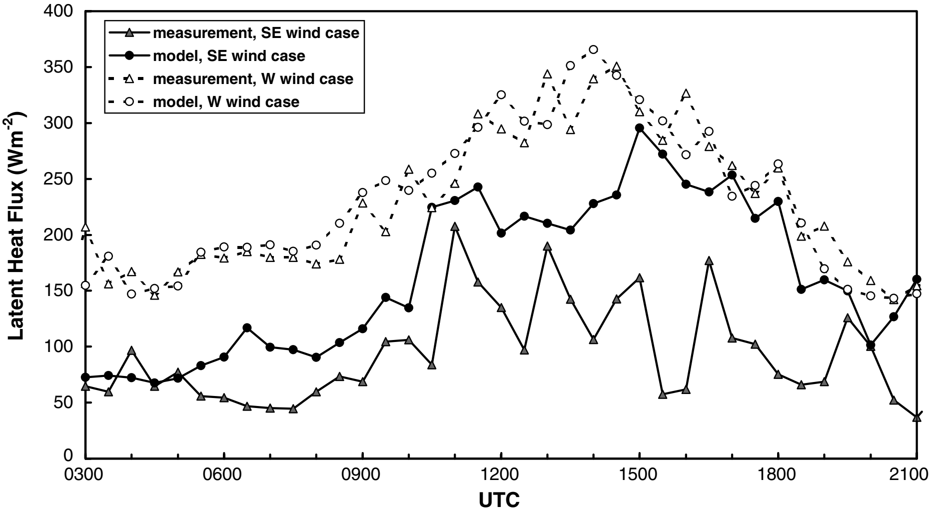


Figure B1. Diurnal cycle of the measured and modelled latent heat flux for the *Großer Kossenblatter See* (FS site) on 4 June 2003 (south-easterly winds) and 11 June 2003 (westerly winds).

this, the wind data from the GM Falkenberg, the standard measurement site closest to the *Großer Kossenblatter See,* were used. The GM Falkenberg is situated on a very open plain while the *Großer Kossenblatter See* lies in a hollow. These topographical differences apparently compensate for the higher roughness of the grassland surface at Falkenberg in such a way that for undisturbed fetch conditions the wind speed measurements at the two sites are quite comparable. A linear regression analysis of the wind speed measurements during the LITFASS-2003 experiment for wind speeds $> 3\,\mathrm{m\,s^{-1}}$ and wind directions from the sector 200 to 330 degrees gave a slope of 0.97 for the best fit line and a correlation coefficient of $r^2 = 0.75$.

Modelling of the fluxes over the lake was performed for the whole period of the LITFASS-2003 experiment. For westerly wind directions, the measurements and model results were in quite good agreement, as can be seen from Figure B1. For easterly winds, the model gave significantly higher fluxes, an example is also shown in Figure B1. The flux composite for the lake was thus formed from the measurements and model results depending on the wind direction, as described in Section 3.

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