9.3 HELIPOD MEASUREMENTS IN THE LITFASS-2003 FIELD EXPERIMENT: COMPARISON WITH DIAL, LAS, TOWER, GROUND-STATION, AND LES

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1. INTRODUCTION

The measurements in the EVA-GRIPS project (Regional Evaporation at Grid/Pixel Scale over Heterogeneous Land Surfaces) were a contribution to the German climate research program DEKLIM. The main joint field campaign was carried out in the framework of the LITFASS study (Lindenberg Inhomogeneous Terrain - Fluxes between Atmosphere and Surface: a Long-Term Study, e.g., Beyrich *et al.*, 2002). The measurement area (20 km x 20 km) near the Meteorological Observatory Lindenberg MOL (about 60 km south-east of Berlin) was a heterogeneous landscape. It consisted of a mixture of forest, grassland, agriculture, and lakes as it is typical for large parts of northern Central Europe (Fig. 1). The turbulent structure of the atmospheric boundary layer (ABL) was examined on several flight patterns (horizontal and vertical grids, vertical profiles) in the well-mixed convective ABL using the turbulence measurement system Helipod. The Helipod measurements completed observations performed by ground-based micrometeorological stations, large aperture scintillometers (LAS), RADAR/RASS, differential absorption LIDAR (DIAL), a 99 m meteorological measurement tower, satellites, and other aircraft (Tornado). For a general description of the LITFASS-2003 experiment, see Beyrich *et al.*, 2004a. Furthermore numerical models (e.g. large eddy simulations, LES) simulated the atmospheric flow during the experiment. The comparison of all systems and methods with the Helipod yield in general good or even very good agreement. In the following some case studies are described.

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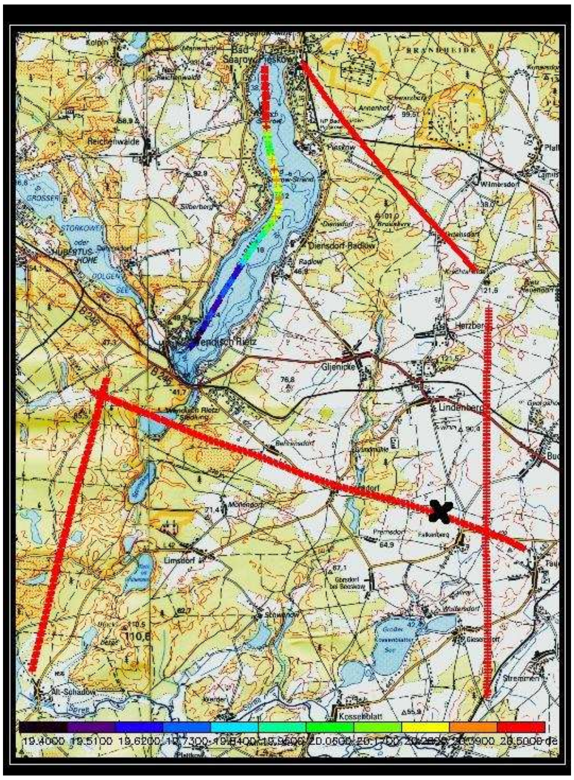

Fig. 1: *The Helipod flight pattern 'Catalog'. The color of the flight path indicates the measured surface temperature. The surface temperature of the lake varied in dependence on its depth. The Falkenberg site where the DIAL, the RADAR/RASS, and the 99 m tower were located within the LITFASS area is marked with a cross.*

2. MEASUREMENT SYSTEMS AND LES

The Helipod (Fig. 2) is an autonomously operated sensor system, attached to a helicopter by a 15 m rope and operates at 40 ms^{-1} air speed (e.g., Bange *et al.*, 2002; Bange and Roth, 1999). During the LITFASS-2003 field campaign (19 May to 17 June, 2003) the turbulence probe performed 27 measurement flights on 16 days. During 65 flight hours the surface and air temperature, the air humidity, and the wind vector as well as the turbulent fluxes were measured at 100 Hz sampling rate. The flights were performed close to the ground (80 m) and within the entire ABL.

Fig. 2: *The helicopter-borne turbulence probe Helipod.*

The Helipod measurements of humidity and vertical wind were compared with data from two remote sensing systems (Senff *et al.*, 1994):

- The DIAL (Differential Absorption LIDAR) measured humidity at a rate of 0.1 Hz between 300 m - 3000 m height with a vertical resolution of 90 m.
- The RADAR/RASS system sampled the vertical wind at a rate of 0.1 Hz between 60 m - 700 m height with a vertical resolution of 60 m.

The remote sensing was performed by the Max-Planck-Institute for Meteorology from Hamburg.

The Wageningen University (WUR, The Netherlands) contributed two LAS systems (Meijninger *et al.*, 2002). One LAS was installed above a forest in the western part of the investigation area (Fig. 3). The optical path length was 2.85 km. The second LAS measured mainly above farmland with a path length of 4.7 km. Theses LAS measurements and analysis were carried out in cooperation with the MOL.

The MOL furthermore performed profile and turbulence measurements on a 99 m meteorological tower located at the boundary layer field site (GM) Falkenberg (Neisser *et al.*, 2002) in the central eastern part of the study region (Fig. 3).

Within the experimental area in total 13 micro-meteorological ground stations were installed (Fig. 3). All stations were equipped with fast responding sensors for the measurement of the wind vector, the air humidity and temperature. The stations were installed over different surface types like grass, maize, rape, cereals, water, and pine forest. Area-averaged fluxes were calculated by weighting the measurements of the individual ground-based stations according to the share of the surface type they were installed on. The land use in the area is divided into 45 % of farmland, 43 % of forest, and 7 % of open water (lakes). The surface flux composites were calculated for different averaging times adapted to the operational characteristics of the Helipod, DIAL and wind profiler systems.

The LES was performed by the University of Hannover (Uhlenbrock *et al.*, 2004; Raasch and Schröter, 2001). The numerical simulations used realistic surface parameters and were initialized with data from the micro-meteorological stations.

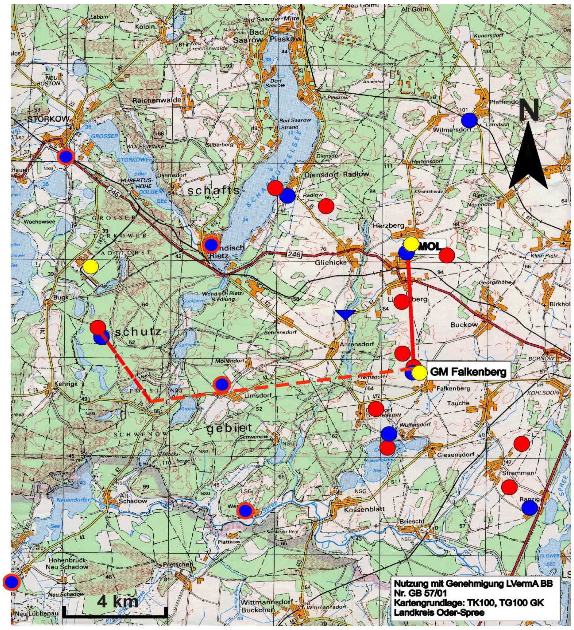

Fig. 3: *Location of the micro-meteorological ground stations during LITFASS-2003 (circles: ground stations, thick lines: LAS paths).*

3. FLIGHT PATTERNS

For the comparison with the various ground-based measurement systems and numerical simulations several different flight patterns were flown. Explicitly for the comparison with the remote sensing the 'Vertical Grid' was performed (Fig. 4). It consisted of several straight legs of 12 km length, oriented along the mean wind direction, at different altitudes. In general these flights were performed between noon and the early afternoon.

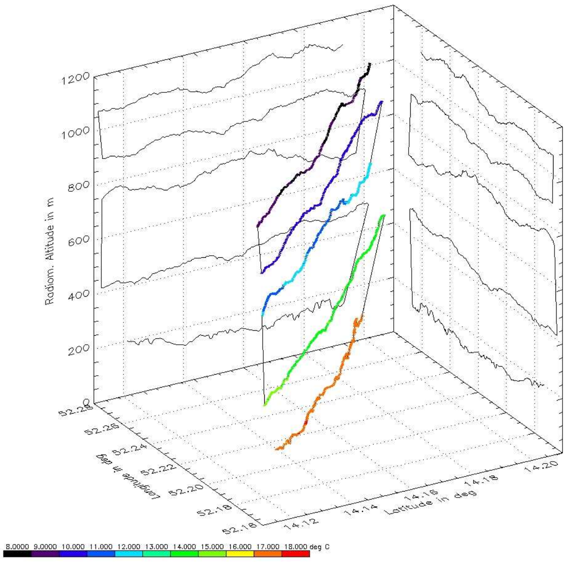

Fig. 4: *The Helipod flight pattern 'Vertical Grid'. The color of the line indicates the measured static air temperature. This Helipod flight was carried out at noon on 12 September, 2002.*

The 'Catalog' (Fig. 1) pattern was used to determine turbulent fluxes above homogeneous subareas within the heterogeneous area. It was mostly performed at noon and in the early afternoon at several altitudes within the ABL. The length of the straight flight paths (legs) was between 8 and 14 km (see also Spieß *et al.*, 2004).

Furthermore the Helipod performed several square-shaped horizontal flight patterns. These low-level grid flights were mainly used to determine the area-averaged turbulent fluxes near the surface with high accuracy (Zittel *et al.*, 2004b).

4. SPECTRAL COMPARISON

A comparison of spectral properties of atmospheric variables in the middle of the ABL was only possible between the Helipod and the remote sensing data, since all other turbulence measurements (surface stations, tower, LAS) were carried out below 80 m altitude, the lowest Helipod flight level. Power-, co-spectra, and statistical distributions derived from the time series of Helipod, DIAL, and RADAR/RASS measurements were analyzed. As an example Fig. 5 shows the power spectra of the vertical wind from Helipod and RADAR/RASS measurements. The flight pattern used to gain the data was the Vertical Grid. Both data sets were measured at around 680 m above the ground and exhibit a Kolmogorov $k^{-5/3}$-law of the turbulent inertial subrange. The wavenumber k was calculated from the original frequency spectra using the mean ground speed of the Helipod of 40 ms^{-1} and the mean horizontal wind speed of 6 ms^{-1} for the RADAR/RASS measurements. So the two spectra became comparable. To assure that the ordinates were correctly calibrated, Parseval's theorem was successfully checked. The spectral power per wavenumber in both diagrams was about identical for the wavenumber range between 10^{-4} and 10^{-2} m^{-1}. The analysis of the spectra of the water vapour measurements exhibited some difficulties. The results from DIAL and Helipod humidity measurements did not agree so good possibly due to the difference in measurement location and volumes. Further analysis is necessary and on its way.

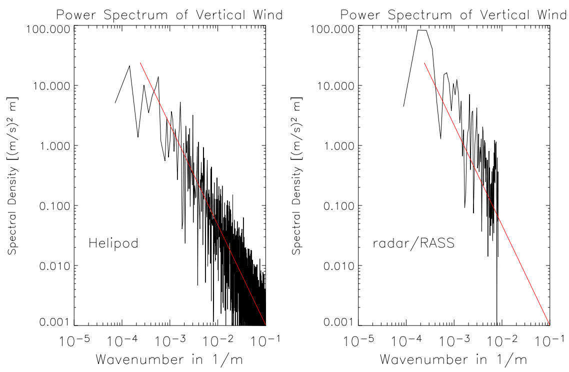

Fig. 5: *Power spectra of the vertical wind. Left: Helipod measurements at about 700 m altitude above the ground. Right: RADAR/RASS measurements at 660 m. The straight line shows the Kolmogorov $k^{-5/3}$-law.*

5. AREA-AVERAGED TURBULENT FLUXES

The area-averaged turbulent flux (e.g., the latent heat flux LE) was calculated at each Helipod flight level z_f within the convective boundary layer according to

$$LE(z_f) = \frac{1}{n}\sum_{i=1}^{n} \rho l_v \langle w'm' \rangle \ , \qquad (1)$$

with air density ρ, latent heat of vaporization of water l_v, number of legs n, vertical-wind fluctuations w', humidity fluctuations m'. Here $\langle \ldots \rangle$ denotes the average over an entire straight flight leg.

The eddy covariance method is a common procedure to calculate turbulent fluxes from airborne and many ground-based in-situ and remote measurements.

5.1 Statistical Error

To calculate the statistical errors of these fluxes a method was used that is based on the determination of the integral scale λ (Lenschow and Stankov, 1986). Within the field experiment LITFASS-2003, the integral scale λ_{ws} (with transported quantity s - air temperature or humidity, respectively) could directly be calculated from both the Helipod and DIAL/Radar measurements. So no approximation of λ_{ws} by λ_w and λ_s was necessary. Also no assumption of Gaussian distribution of the measured data was made. Using the basic equations (Lenschow and Stankov, 1986; Zittel *et al.*, 2004a) led to clearly smaller statistical uncertainties compared with the method that uses the approximations above mentioned (Lenschow *et al.*, 1994).

5.2 Surface Fluxes

During the LITFASS-2003 experiment the area-averaged turbulent heat fluxes measured at flight level z_f were extrapolated to the ground. To do so a combination (LLF+IM) of low-level flights (LLF) (Grunwald *et al.*, 1998) and inverse models (IM) (Tarantola, 1987; Wolff and Bange, 2000) was applied. Using LLF+IM enabled to determine the surface fluxes from flights at only one low flight level (see also Bange *et al.*, 2004) by solving

$$\frac{1}{\rho c_p} \cdot \frac{\partial H}{\partial z} = -\frac{\partial \bar{\theta}}{\partial t} - \left(\bar{u}\,\frac{\partial \bar{\theta}}{\partial x} + \bar{v}\,\frac{\partial \bar{\theta}}{\partial y} \right) . \qquad (2)$$

In (2) H is the turbulent sensible heat, $\bar{u}$ and $\bar{v}$ the mean horizontal wind velocities, and $\bar{\theta}$ the mean potential temperature. The surface turbulent fluxes H_0 were obtained using a linear extrapolation to the ground only for the lowest 80 m.

$$H_0 = H(z_f) - z_f \cdot \frac{\partial H}{\partial z} . \qquad (3)$$

The calculation of the latent heat flux at surface level was very similar.

6. FLUX COMPARISON

6.1 Surface Heat Fluxes

Fig. 6 shows a comparison of surface sensible heat fluxes H_0 derived from Helipod flights with the weighted area-average of the surface flux stations and with the net radiation measured at GM Falkenberg. The area-averaged fluxes obtained during the two-hour flights of the Helipod agreed well with the continuous ground-based measurements, see, e.g., the sharp decrease of the net radiation shortly after noon on June 10, which is followed by reduced sensible heat fluxes derived from both the surface and Helipod measurements. Similar good agreement was also found for a number of other days demonstrating the reliability of the LLF+IM method.

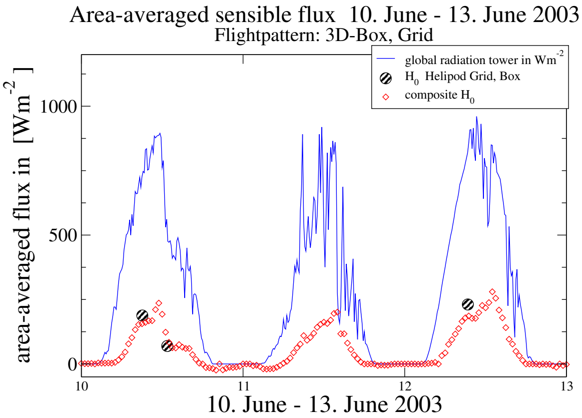

Fig. 6: *Comparison of surface area-averaged turbulent heat fluxes of the LLF+IM Helipod (striped circles) with the composite from the surface stations (red diamonds) during 3 days of the LITFASS-2003 experiment. The blue solid line shows the net radiation measured at GM Falkenberg.*

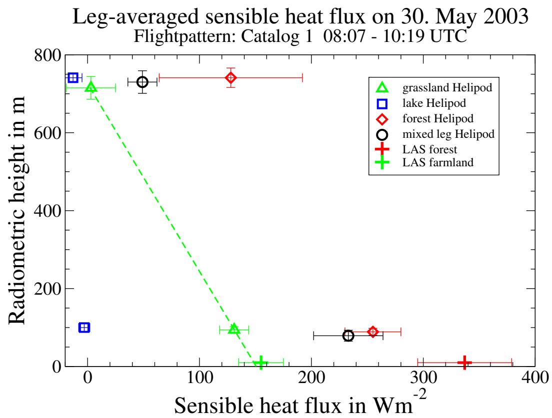

Fig. 7: *Profiles of the sensible heat flux over different land use types in the LITFASS area as derived by combining Helipod and LAS measurements.*

The two LAS measured the atmospheric flow above homogeneous sub-areas (forest and farmland) within the heterogeneous LITFASS site.

Therefore their results could not be compared with Helipod flights above the entire site but only with flight legs over homogeneous surfaces. These were performed in the Catalog patterns. Since the LLF+IM method can not be applied to a single leg (the information about the horizontal variations is missing) no accurate extrapolation of airborne-measured fluxes to the surface was possible. The Helipod and the LAS measurements of 30 May are plotted in Fig. 7. A linear extrapolation of Helipod's grassland measurements to the ground led to good agreement with the LAS. The same method applied to the Helipod measurements over forest led to smaller values compared to the LAS observations. Similar situations were observed on all other days (Beyrich *et al.*, 2004b). A further analysis will follow.

6.2 Mid-ABL Fluxes

The vertical profiles of the latent heat flux from Helipod Vertical Grid flights and DIAL/Radar observations are shown in Fig. 8. The composite of the ground-based micro-meteorological stations is added for comparison. The remote sensing systems give fluxes which deviate from the Helipod fluxes, but the error ranges of both systems match. Below 400 m the measurements behaved in the opposite way. It should be mentioned that the measurements were performed in the morning during the development phase of the convective ABL.

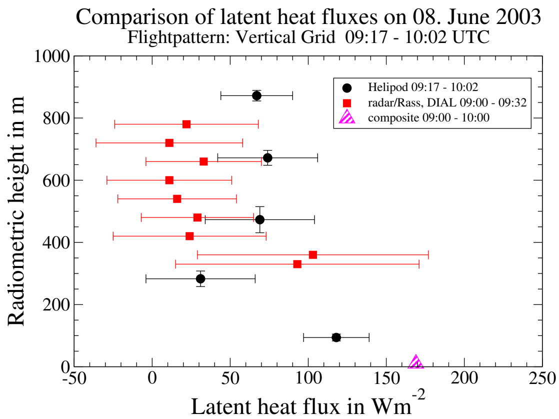

Fig. 8: *Vertical profile of the area-averaged turbulent latent heat flux with error bars.*

Afternoon measurements are depicted in Fig. 9. The flux measurements of the Helipod during a Catalog flight (averaged over all legs) agreed quite well with the remote sensing data and were close to the ground observations.

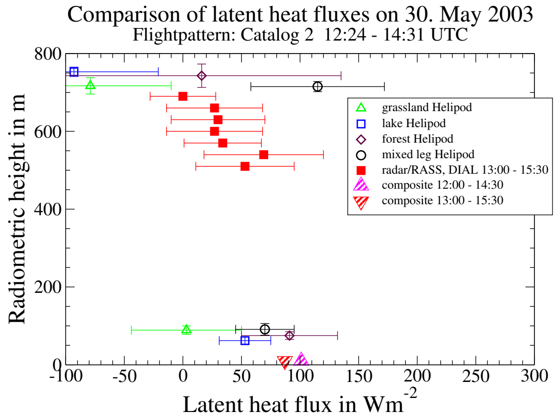

Fig. 9: *Comparison of the area-averaged turbulent latent heat flux using 'Catalog' flights at noon when the convective boundary layer was already established.*

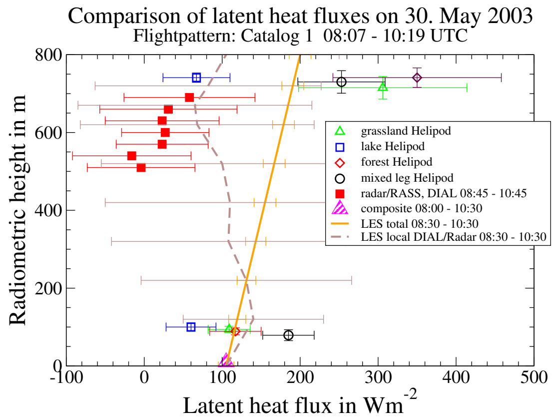

Fig. 10: *Comparison of the area-averaged turbulent latent heat flux using 'Catalog' flights in the late morning. The dashed line shows local LES. The total simulated LITFASS area flux is shown by the solid line.*

Another Catalog flight in the morning is depicted in Fig. 10. Here again the differences between Helipod and remote sensing data were large. The LES results obtained for this situation were analysed in order to identify the cause of the discrepancy. At first the area-averaged fluxes from the LES were plotted (yellow line with small error bars) which agreed well with the Helipod results (the averaged data at two heights from the Catalog flight). Then only the flux calculated within the column above the DIAL site was extracted from the LES and plotted (dashed line with large error bars). The large error bars at the local LES is caused by the large temporal variances. The error of the LES is purely conditionally by turbulence. Here the agreement with LES and DIAL was quite good. Apparently the differences between DIAL and Helipod measurements were due to the heterogeneity of the developing ABL above the heterogeneous LITFASS area.

Discrepancies in turbulent flux measurements at several heights were due to the heterogeneity of the surface. The Helipod measurements were averaged along a 10 km flight path, while the DIAL/Radar time series were averaged over the fetch due to the mean wind direction and speed. Since the wind speed was usually low, the DIAL/Radar measurements were mainly influenced by the vicinity of the DIAL/Radar position, as is shown by LES single profiles.

CONCLUSION

Turbulent flux data both in the middle of the ABL and at the surface as derived from Helipod flights over the heterogeneous LITFASS area were compared with aggregated eddy-covariance surface fluxes (from a network of micrometeorological flux stations operated over different types of land use), with fluxes from LAS and DIAL/Radar measurements, and with LES results. In general, the different methods gave quite consistent values of area-averaged surface fluxes and of vertical flux profiles. The LES helped to explain differences in the flux profiles obtained from Helipod and DIAL/Radar measurements as a consequence of the different sampling strategies. Further analysis of the data set from the whole experiment will be performed in order substantiate the results obtained for first case studies, and to explain systematic deviations where observed (e.g. between the Helipod and forest LAS fluxes).

ACKNOWLEDGMENT

We like to thank Wouter Meijninger (Wageningen University) for the LAS data. The Helipod flights were performed by the FJS Helicopter Service in Damme (Germany). The German government funded the field experiment and the Helipod flights (DEKLIM research program, grant no. 01-LD-0301).

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