VERTICAL PROFILES OF WATER VAPOUR FLUXES IN THE CONVECTIVE BOUNDARY LAYER MEASURED BY GROUND-BASED DIFFERENTIAL ABSORPTION LIDAR AND HETERODYNE DOPPLER LIDAR

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1 INTRODUCTION

The transport of water vapour from the earth's surface into the free atmosphere is an important part in the water and energy cycle. The atmospheric boundary layer which is mostly topped by a temperature inversion is the link between surface and atmosphere. The idealized picture of the water vapour flux profile within the well-mixed convective boundary layer (CBL) is a linearly decreasing profile due to bottom-up transport of water vapour. An entrainment of overlying dry air into the boundary layer produces an increasing flux near the top of the CBL . Realistic turbulent and convective fluxes of water vapour within the atmospheric boundary layer are still hard to measure. Ground-based remote sensing systems which simultaneously measure fluctuations of water vapour density and vertical velocity can close this gap. The progress in development over the last decade results in remote sensing systems which continuously record turbulent fluctuations up to the top of the boundary layer. The link to the surface is accomplished by tower measurements.

2 MEASUREMENTS

In the frame of the project EVA-GRIPS (EVAporation at GRId/Pixel Scale) the field experiment LITFASS-2003 took place in May/June 2003 in a rural, mixed landscape southeast of Berlin. The aim of the experiment was the determination of area-averaged evaporation over a heterogeneous terrain on the scale of a regional model gridbox or a satellite pixel, i.e. 20 km x 20 km (Beyrich et al., 2004). Two approaches to determine area-averaged fluxes are to calculate an appropriate mean from a dense network of eddy-covariance surface-layer stations over the dominant landuse types (Beyrich et al., 2004) and to extrapolate turbulent water vapour fluxes measured in the convective boundary layer down to the surface (Parlange et al., 1995).

During LITFASS-2003, turbulent fluxes of latent heat were measured at 13 micrometeorological stations over various surface types in the LITFASS-area (grass, maize, rape, cereals, water and pine forest). Each station consisted of a Sonic and an optical fast response hygrometer. A weighted area-averaged of the fluxes has been calculated from these measurements taking into account the relative occurrence frequency (percentage) of each type of land use in the area and considering also the data quality of the individual measurements.

A 100 m tower was equipped with turbulence instruments measuring sensible and latent heat fluxes at 50 m and 90 m. At the same location ground-based lidar systems were operated, two Differential Absorption Lidar (DIAL) systems measuring the absolute humidity and one Heterodyne Doppler lidar system measuring the vertical wind (Bösenberg and Linné (2002), Ertel (2004)).

The time resolution of both lidar systems is 10s, the height resolution approximately 90 m. Turbulent fluxes are calculated by the eddy-covariance method. Both instruments have the capability to measure continuously. The joint measurements cover 14 days from early morning to late afternoon and the range from 400 m above ground to the top of the boundary layer. The 100 m tower is the link between lidar measurements within the CBL and the surface.

Fig.1 shows time-height cross-sections of absolute humidity and vertical wind on 30 May 2003 over a range from 400 m to 3000 m agl and of 06 UTC to 18 UTC corresponding to 07:00 to 19:00 local time. The devolpment of a convective boundary layer is clearly visible both in humidity and in vertical wind. The onsetting convection with upwind and downwind structures comprises the whole CBL and mixes the evaporated water vapour within

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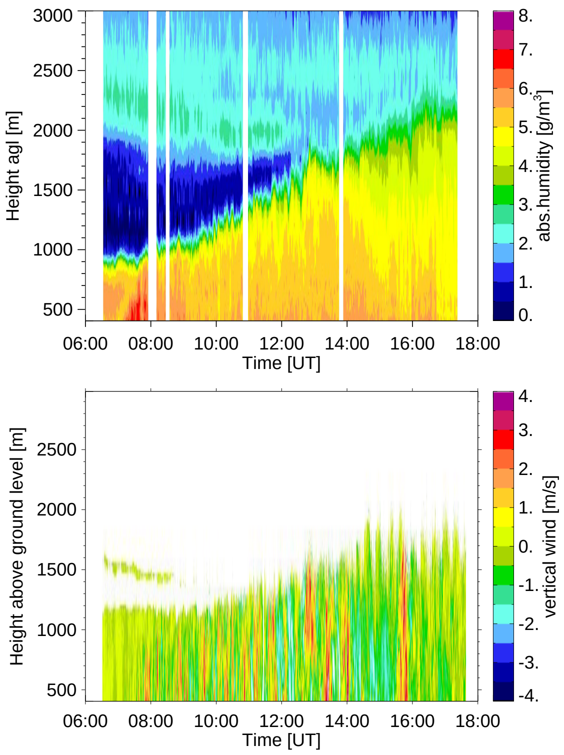

FIG. 1: Time-height section of absolute humidity (upper panel) and of vertical velocity (lower panel) at Lindenberg on 30 May 2003.

the growing CBL.

Spectra of humidity and vertical wind fluctuations (Fig. 2) show that the inertial subrange is well reached by both systems, but the DIAL signal is superimposed by considerable noise. At the high-frequency end of the spectrum the atmospheric signal is smaller than the noise level. As can be seen from the co-spectrum, this spectral range does not contribute to the flux calculation. In this particular case, vertical wind variances are about an order of magnitude larger than humidity variances which indicates the weak evaporation from the dry surface.

3 WATER VAPOUR PROFILES

Water vapour fluxes from remote sensing systems and the tower are calculated with an averaging time of one hour which corresponds to horizontal scales of 10 - 20 km for mean wind speeds of 3 - 6 m/s. Area-averaged surface fluxes and tower fluxes are available as 30 min averages. The variability of the fluxes both in time and - for the lidar data - in height is rather large, and hint at instationarity and spatial inhomogeneity.

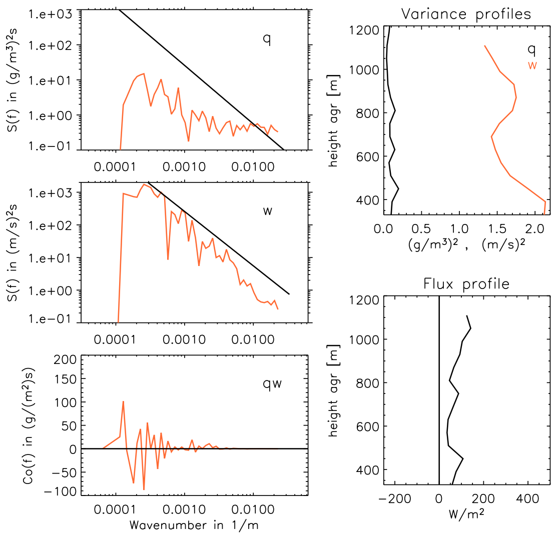

FIG. 2: Variance spectra of absolute humidity and vertical wind fluctuations w' and q' and co-spectrum of $w'q'$ at 1000 m agl (left) and vertical profiles of variances of fluctuations and latent heat flux (right) over Lindenberg on 30 May 2003 for the time interval 11:45-13:45 UTC. The spectra are shown in the wavenumber domain, calculated by mean wind speeds. The solid lines in the variance spectra plots follow a $-5/3$-law.

Systematic errors due to the limited averaging interval are calculated following Lenschow et al. (1994) and are shown in Fig. 3. They can be as large as $60\ W/m^2$. Random errors due to system noise are by an order of magnitude smaller and are not shown here. The time variability of surface fluxes is illustrated by the three 30 min-values at 13:30, 14:00 and 14:30 UTC.

In the following, vertical flux profiles are plotted without error bars. Systematic errors of $\pm 50\ W/m^2$ are normally calculated. Fig. 4 shows the vertical profiles of latent heat fluxes on 30 May

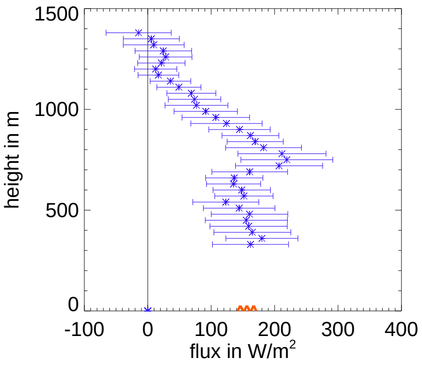

FIG. 3: Vertical profiles of latent heat fluxes on 7 June 2003 12:50-14:20 UTC at Lindenberg and corresponding area-averaged surface values.

2003 (compare Fig. 1). The near-surface fluxes are small (mostly less than $150\_W/m^2$). The link between near-surface and CBL measurements implies a linear decrease of the fluxes which is steeper in the morning than in the afternoon. May 30 was a day with dry air lying above the humid boundary layer and during the growth of the CBL large water vapour fluxes in the upper part of the boundary layer show the entrainment of dry air into the CBL. In the afternoon the fluxes decrease with height and entrainment has stopped. This case shows that the entrainment flux may even exceed the surface flux when evaporation is low. Since decreasing water vapour fluxes cause a moisturing of the layer and increasing fluxes cause a drying this strong entrainment dries out the upper part of the CBL.

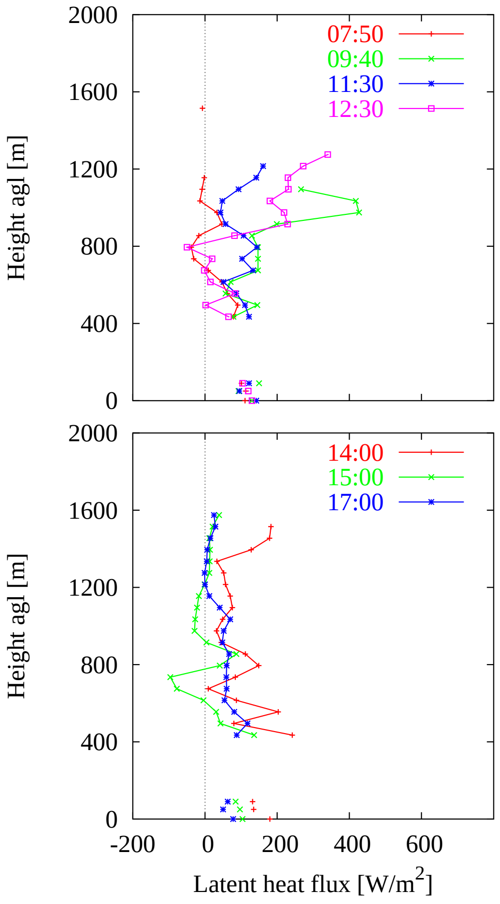

FIG. 4: Vertical profiles of latent heat fluxes on 30 May 2003 at Lindenberg. Upper panel: morning, lower panel: afternoon. The surface values are flux composites over agricultural areas, the values at 50 m and 90 m are tower measurements.

The second example (Fig. 5) shows latent heat flux profiles on a day with larger surface evaporation. The very dry period in the first half of LITFASS-2003 was for a short time interrupted by showers in the area. The surface and tower values can be linked to the atmospheric profiles to show a linear decrease of the fluxes with height. Latent heat fluxes are approximately zero at 1000 m which is about the half of the convective boundary layer. On this day with humid air lying over the boundary layer the entrainment flux is nearly zero and does not contribute to the humidity concentration within the boundary layer. The entrainment of air from above - thus the growth of the boundary layer - does not noticeably transport water vapour. The humidity profiles on this day are nearly uniform up to at least 4000 m depth.

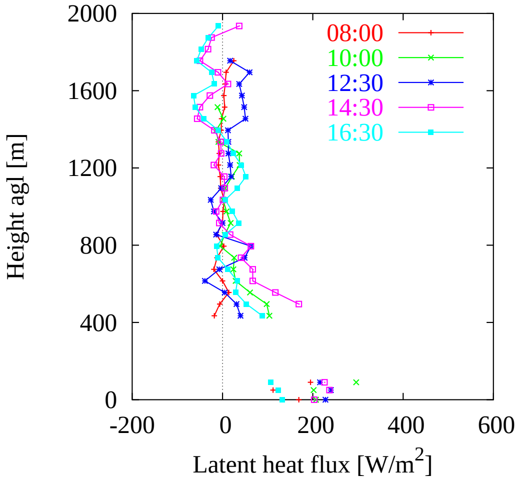

FIG. 5: Vertical profiles of latent heat fluxes on 8 June 2003 at Lindenberg. The surface values are a weighted average over the farmland part of the LITFASS area, the values at 50 m and 90 m are tower measurements.

4 CONCLUSIONS

The combination of ground-based lidar systems to measure turbulent fluxes approves to be a suitable tool for the investigation of transport processes within the boundary layer. In most cases fluxes can be determined up to the top of the CBL. Tower measurements at 50 m and 90 m are the link to the surface, which is in this case represented by the area-averaged flux from the ground stations. So complete profiles of water vapour fluxes can be shown. They underline the influence of entrainment on the humidity CBL. A linear decrease with height of latent heat flux profiles is observed which can be superimposed by entrainment fluxes in cases of dry air being mixed into the boundary layer. Entrainment fluxes can exceed surface fluxes, in particular in dry periods with weak evaporation like the LITFASS-2003 period

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