7.6 AIRBORNE MEASUREMENTS OF TURBULENT FLUXES OVER HETEROGENEOUS TERRAIN WITH HELIPOD AND DO 128 - ERROR ANALYSIS AND COMPARISON WITH GROUND-BASED SYSTEMS

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1. INTRODUCTION

Airborne measurements of meteorological parameters within the planetary boundary layer (PBL) are of great interest for investigating the water and energy balance between the surface and atmosphere as well as for parameterization and modeling exchange processing. A present-day research topic is the development of turbulent flux estimation methods for heterogeneous terrain. In this context, area-representative data from aircraft measurements are a valuable standard of comparison for the results of averaging strategies for ground-based observations. With this intention a one-day flight experiment was performed on 18 June, 1998, with two different systems. The flights complemented the ground-based measurements carried out during the LITFASS-98 experiment (**L**indenberg **I**nhomogeneous **T**errain - **F**luxes between **A**tmosphere and **S**urface: a Long-Term **S**tudy, Beyrich *et al.* 2002) near the Meteorological Observatory Lindenberg (MOL), Germany.

To determine turbulent surface fluxes from airborne measurements, usually a three-dimensional flight pattern (3D-box pattern) is used (e.g., Scherf and Roth, 1997; Grunwald *et al.*, 1998; Schröter *et al.*, 2000). This pattern consists of horizontal, square-shaped flight tracks at different altitudes within the boundary layer. The mean turbulent fluxes determined at each height are extrapolated to the ground in order to evaluate the surface flux. This method is generally useful in stationary situations if a linear flux profile can be assumed. Unfortunately, systematic differences between ground-based and airborne measurements have often been reported and lessen the reliability of airborne flux measurements (e.g., Desjardins *et al.*, 1989; Betts *et al.*, 1990; Kelly *et al.*, 1992; Mahrt and Ek, 1993; Mann and Lenschow, 1994; Emeis, 1995). In most cases the discrepancies were explained with filter effects, spectral bandwidth of the airborne sensors, and too short flight tracks. To quantify the latter, a complex statistical error analysis was introduced in several publications (e.g., Lenschow *et al.*, 1994).

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2. METHOD

To identify a dependence of the measured fluxes on sensor equipment or flight distance, measurements of two different airborne turbulence measurement systems, the Do 128 'IBUF' and the Helipod, were analyzed.

The Do 128 with the call sign D-IBUF is a proven and very reliable research aircraft that participated in many meteorological campaigns. During LITFASS-98 the twin-engined aircraft operated at an airspeed of 60 ms^{-1} with a data sampling rate of 25 Hz. Humidity and temperature sensors were mounted at the nose of the aircraft (Hankers 1989). The wind vector was measured with a 5-hole probe on a 2.6 m nose-boom in combination with GPS and INS on board. Taking the spatial arrangement of the sensors, the measurement-point distance, and disturbing effects of fuselage and wings into account, the Do 128 could resolve turbulent structures down to 5 m.

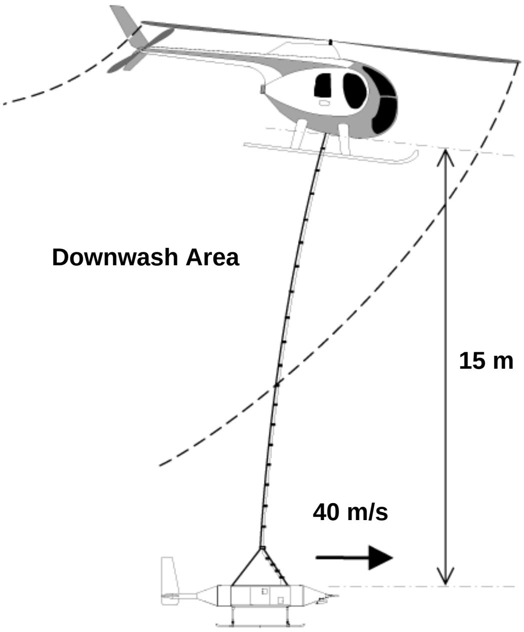

Fig. 1: *The turbulence measurement system Helipod*

The Helipod (Fig. 1) is an autonomously operating sensor package attached to a 15 m rope below a helicopter. At a mission speed of 40 ms^{-1} the Helipod is outside the down-wash area of the rotor blades. The Helipod is equipped with its own power supply, board computer, data storage, navigation systems, radar altimeter, and fast responding sensors for wind, temperature, humidity, and surface temperature measurements. The inertial navigation and all meteorological sensors are concentrated in the nose of the pod. Due to the small fuselage, and absent wings and impulse the influence of the Helipod on the atmospheric flow is small compared to an airplane. Together with a sampling rate of 100 Hz, the system resolves turbulent structures down to 1 m (Bange and Roth 1999).

For the direct comparison of the two systems a special strategy for simultaneous flights was worked out that took the individual mission speeds of the two systems into account (Wolff and Bange, 2000). The area-averaged turbulent vertical fluxes were determined on a 15 km x 15 km (Do 128) and a 10 km x 10 km (Helipod) horizontal, square-shaped flight pattern, respectively, in a way that Do 128 and Helipod reached the corners of their patterns at the same time. The flights were carried out over heterogeneous terrain at three different altitudes within a moderately convective boundary layer with Cumulus clouds.

The ground-based equipment consisted of five micro-meteorological stations installed on different surface types. To calculate area-representative values, the measurements from the ground stations were averaged corresponding to the ratio of their related surface type in the entire area (i.e., 45 % forest, 7 % water, and 16 % triticale, barley, and gras, each). Furthermore, a windprofiler/RASS system (Engelbart *et al.*, 1996), a 99 m meteorological tower equipped at four levels for turbulence measurements, and a large aperture scintillometer measuring over 4.7 km distance were installed.

3. RESULTS

Figure 2 displays the periods of the horizontal flights versus height, together with the PBL height as observed during vertical aircraft soundings and derived from windprofiler/RASS data. The aircraft observations of the PBL top were linearly interpolated. Until 8 UTC the result (dashed line) was in good agreement with the windprofiler/RASS data, although the latter show strong fluctuations of the PBL height. All flights were carried out within the turbulent, convective, and moist boundary layer. The highest flights were close to the PBL top.

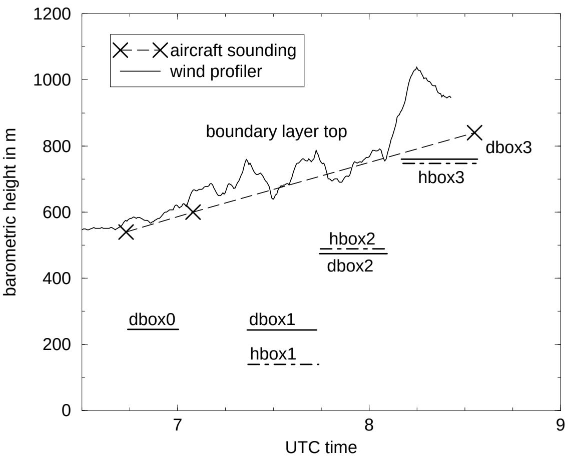

Fig. 2: *Course of the flight experiment and development of the boundary layer (dbox: Do 128 flights; hbox: Helipod). The solid curve represents the PBL height measured by the windprofiler/RASS system. The dashed line represents the PBL height interpolated from observations during vertical aircraft soundings (crosses).*

Cospectra-analysis (Fig. 3) of vertical wind speed w with potential temperature θ and mixing ratio m, respectively, demonstrated that the small scale turbulent transport was completely sampled, while the comparatively small flight patterns were possibly of critical size regarding the large-scale turbulence. The phygoide of the airplane was identified as a significant peak at about 0.045 Hz in some co-spectra (see lowest chart in Fig. 3). The phygoide is a damped, slow harmonic oscillation of air speed and altitude caused by the flight-mechanical transfer of kinetic to potential energy and vice versa. Its occurrence depends on the reaction of the pilot on convection or after turning and can normally be avoided. The phygoide frequency can roughly be estimated by (Brockhaus, 1994)

$$f_p = \frac{1}{\sqrt{2} \cdot \pi} \cdot \frac{g}{v_0} \qquad (1)$$

with the air speed v_0 and the acceleration g due to gravity. Since the vertical wind, the mixing ratio, and the temperature depend on the height, the phygoide causes a systematic error. Its contribution to the flux cannot easily be corrected but is localized on a narrow frequency band and therefore entails only a small flux error. No further systematic errors were identified in the airborne measurements.

The vertical fluxes of sensible heat flux H, latent heat V, and horizontal momentum τ were calcu-

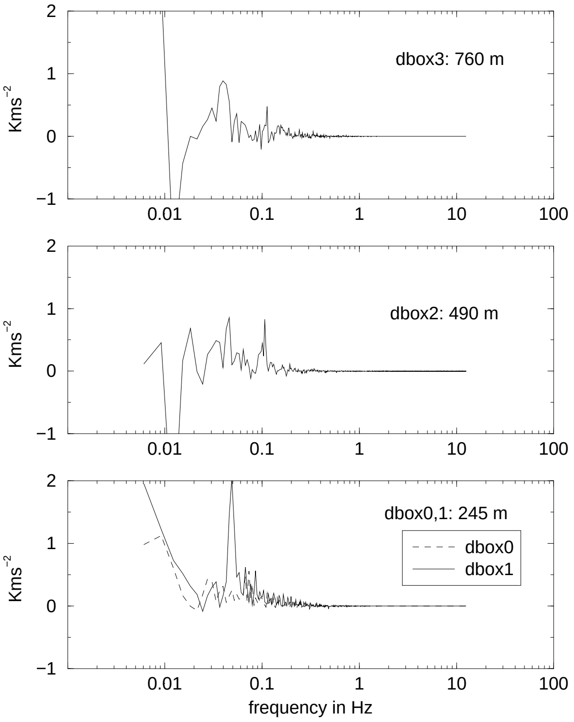

Fig. 3: *Cospectra of w and θ measured by Do 128 at three different heights. In order to smooth the curves, the data was averaged over four legs. The large peak at 0.045 Hz in the lowest spectrum indicates the phygoide of the aircraft.*

lated using the eddy-correlation method, and then averaged over all four legs of each horizontal flight pattern. Statistical error analysis of the fluxes (Lenschow *et al.* 1994) showed that the systematic statistical error

$$\Delta F \;\le\; \frac{2}{r_{ws}} \cdot \frac{\sqrt{I_w I_s}}{L} \cdot F \qquad (2)$$

(s: temperature, humidity, or horizontal wind, respectively; r: correlation coefficient; I integral time scale; L: flight duration; F: flux H, V, or τ, respectively) was one order of magnitude smaller than the standard deviation σ_F, with

$$\sigma_F^2 \;\le\; \frac{2}{r_{ws}} \left(1 + \frac{1}{r_{ws}^2}\right) \cdot \frac{\sqrt{I_w I_s}}{L} \cdot F^2 \,. \qquad (3)$$

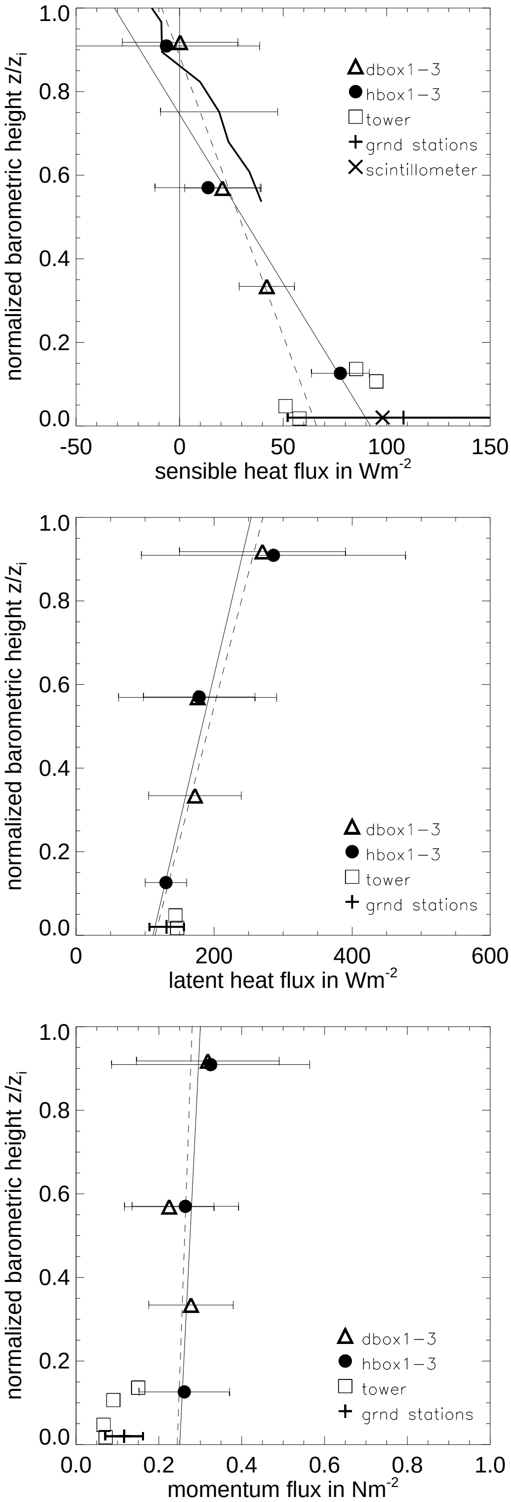

Fig. 4: *Vertical profiles of area-averaged fluxes Linear regression of Helipod data: solid line; Do 128: dashed line. The curve in the upper half of the H-profile represents the windprofiler/RASS system measurements, with one exemplary error bar.*

The area-averaged fluxes derived from simultaneous Helipod and Do 128 measurements were in remarkable agreement. Their differences were much smaller than their standard deviations (error bars in Fig. 4), indicating that the systematic statistical error was possibly over-estimated by the usual method. The vertical flux profiles were normalized using the estimated PBL heights derived from Fig. 2 (Deardorff-scaling). Due to variable PBL height and a patchy pattern of Cumulus clouds, the statistical error was largest at the top of the PBL.

In the upper half of the boundary layer the airborne-measured sensible heat flux agreed well with wind-profiler/RASS data. A linear fit was the best approximation for the height dependence of all three fluxes. The linear extrapolations of the latent and sensible heat fluxes to the ground were in good agreement with tower, scintillometer, and averaged ground-station measurements on various surface types. Systematic discrepancies between airborne and ground-based measurements - as reported from other field experiments - were not found. The results show that the Helipod - designed as a small-scale turbulence probe - and the presented flight strategy with a comparatively small flight pattern are well suited for the moderately convective PBL.

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