AIRBORNE WATER VAPOUR AND WIND LIDAR MEASUREMENTS OF LATENT HEAT FLUXES DURING COPS 2007

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ABSTRACT

During the Convective and Orographically-induced Precipitation Study (COPS) in July 2007 over the Black Forest Mountains in south-western Germany, tropospheric profiles of water vapour and wind were measured with a differential absorption lidar (DIAL) and a heterodyne detection 2-µm Doppler wind lidar collocated on board the DLR Falcon research aircraft. The DIAL "WALES" is a newly developed four-wavelength system operating on three water vapour absorption lines of different strengths, one offline wavelength at 935 nm (each 50 Hz, 40 mJ), and 532 and 1064 nm for aerosol profiling. It is designed as an airborne demonstrator for a possible future spaceborne water vapour lidar mission.

For the study of summertime convection initiation over complex terrain, latent heat flux missions were flown where both lidars were pointed nadir-viewing. Using eddy-correlation of the wind and water vapor fluctuations beneath the aircraft, an area-representative water vapor or latent heat flux profile can be obtained by a single over-flight of the convective boundary layer in complex terrain. The lidars' horizontal and vertical resolution is about 200 m which resolves the dominant circulation patterns and flux contributions. This novel instrumentation allows obtaining profiles of the latent heat flux beneath the aircraft from one single over-flight of the area of interest.

1. THE AIRBORNE LIDAR INSTRUMENTS

Figure 1 shows the instrumentation onboard the Falcon research aircraft. The newly developed "DLR-WALES" water vapour DIAL system [1] was flown for the first time during COPS and operated well. Its two transmitters are based each on an injection-seeded optical parametric oscillator (OPO) pumped by the second harmonic of a Q-switched, diode-pumped single-mode Nd:YAG laser at a repetition rate of 100 Hz. The OPO is optimized to operate in the spectral region between 920 - 950 nm at average output pulse energy of 40 mJ. Each of the two transmitters outputs two spectrally narrow pulses, yielding in total four pulses (each 50 Hz, 40 mJ) at different wavelengths for different water vapour absorption cross sections.

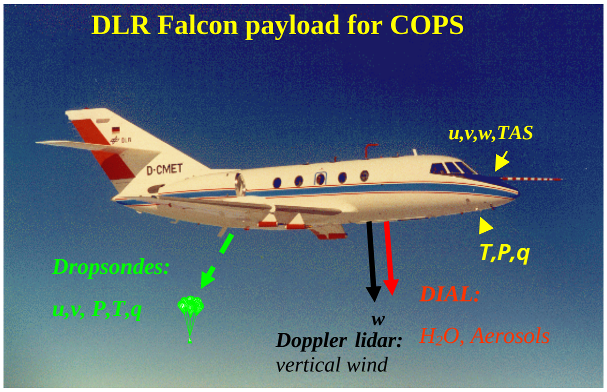

Figure 1. DLR Falcon research aircraft carrying nadir-pointing wind and water vapor lidars for latent heat flux profiling during COPS 2007, plus dropsondes and in-situ instruments.

Table 1. Airborne water vapour DIAL and wind lidar system characteristics. The average DLR-Falcon speed was 170 m/s, which gives a horizontal resolution of 170 m for the 1-s averaged water vapour and wind profiles. Averaging was needed to obtain the indicated precision.

	DIAL	Wind Lidar
Transmitter type	OPO	Tm:LuAG
Wavelength (nm)	935	2022
Pulse energy (mJ)	40	1.5
PRF (Hz)	200	500
Average power (W)	8	0.75
Detection principle	direct	heterodyne
Detector type	APD	PIN diode
Telescope diam. (cm)	48	10
Horizontal res. (m)	170	170
Vertical res. (m)	200	100
Precision	0.4 g/kg	0.1 m/s

The 2-micron wind lidar with heterodyne detection [2] operated in nadir-viewing mode for high-resolution vertical wind measurements during the flux missions. The wind lidar's spatial resolution is 100 m in the vertical (pulse length limited) and 170 m in the horizontal (1-s averaging time). At this resolution the accuracy is better than 0.1 m/s when the ground return signal can be used as "zero speed" reference, which was almost always the case during this experiment. The main water vapour and wind lidar system characteristics are listed in Table 1. For the measurement of the three-dimensional wind field beneath the aircraft the wind lidar possesses two rotating refractive wedges that deflect the lidar beam at 20° off-nadir for conical scans. This was used for the other non-flux COPS missions listed in Table 2.

2. THE CONVECTIVE AND OROGRAPHICALLY INDUCED PRECIPITATION STUDY

One main DLR Falcon objective during the Convective and Orographically-induced Precipitation Study (COPS) in July 2007 was to measure latent heat fluxes over the Rhine valley and the Black Forest Mountains under conditions where convection initiation was predicted to be mainly influenced by the orography and the surface humidity. A climatological study had revealed that heavy precipitation in the Black Forest mainly (70 %) occurs in the approach of a trough when warm and humid air is advected from the Atlantic Ocean, the Iberian Peninsula or the Mediterranean Sea to southwest Germany. The increased air mass instability ahead of the trough, in combination with local orographic forcing leads to a high potential for heavy convective precipitation with the risk of flooding in the Black Forest Mountains.

On the other hand, there is a 30 % chance for heavy precipitation due to deep convection under high pressure conditions. Here, surface fluxes of humidity in relation with the complex orography are expected to play a significant role. Three main objectives for the deployment of this unique airborne lidar configuration were defined and led to the following mission scenarios:

1. Map the pre-convective mesoscale wind and water vapour heterogeneity in a situation when deep convection and heavy precipitation is forecasted, by flying a grid or box pattern across the COPS region.
2. Measure latent heat fluxes over the Rhine valley and the Black Forest Mountains when convection initiation is predicted to be mainly influenced by the orography and the surface humidity.
3. Perform targeted measurements across upstream sensitive regions over SW-Europe for the quantification of humidity advection into the COPS area.

Mission 2 is the focus of this work. The Falcon flights were coordinated with other research aircraft and surface-based measurement stations participating in the experiment, allowing for comprehensive inter-comparisons. Each mission scenario could be flown several times, and all systems were running properly throughout most of the time. Table 2 shows, that a total of 14 mission flights were performed, summing up to 46 flight hours. Of these, four flights were dedicated to the flux measurement mission objective.

Table 2. Overview of all 14 DLR-Falcon flights during COPS.

COPS IOP	Date in 2007	Measurement time (UT)	Mission objective
7a	8 July	07:40-10:40	Upstream
7a	8 July	12:40-14:50	Upstream
8b	15 July	06:10-08:10	Flux
9a	18 July	13:10-16:40	Map
9b	19 July	06:50-09:30	Upstream
9b	19 July	11:20-14:30	Upstream
9c	20 July	06:50-09:20	Map
9c	20 July	11:00-12:50	Map
11a	25 July	12:40-15:50	Flux
11b	26 July	08:50-12:10	Flux
12	30 July	09:50-12:20	Flux
13a	1 August	04:10-07:50	Upstream
13a	1 August	09:10-11:00	Upstream
13a	1 August	14:40-17:20	Map

The flux missions performed in pre-convective conditions had the goal to understand the initiation of convection by studying the spatial variability of humidity, wind and latent heat fluxes in complex terrain. As Figure 2 illustrates, several ~130 km long flight legs above the Rhine valley and the Black Forest Mountains were flown, oriented parallel to the Rhine valley. The high-resolution vertical wind and water vapour lidar profiles shed light on the boundary layer processes and associated fluxes that are expected to be responsible for the development of deep convection under high pressure conditions. For the flux missions the following strategy was applied:

1. Meteorological situations were selected where forcing of convection was expected to be dominated by the surface fluxes.
2. Mid-level (~5 km) flight altitudes helped to get strong boundary layer lidar return signals at high spatial resolution.
3. Three ~130 km long N-S oriented flight legs centred above the Black Forest highly-instrumented COPS “super-sites” were over-passed several times per flight.
4. An additional flight leg in the middle of the Rhine valley was flown for comparison with flat terrain conditions.
5. The flights were coordinated with other aircraft, in particular one low-flying aircraft with in-situ flux measurement instrumentation in order to obtain additional data and flux intercomparison opportunities, detailed in [3].

Optimal for uninterrupted lidar profiles: no clouds. This condition could not always be fulfilled. Methods for dealing with interruptions by fair-weather cumulus clouds or laser readjustment phases were investigated in [3] and applied.

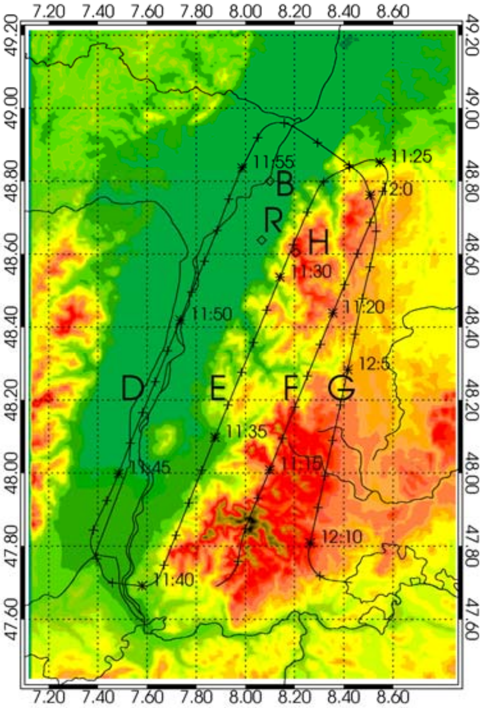

Figure 2. DLR Falcon flight track on 30 July 2007, a COPS flux mission with four flight legs over the Rhine valley (leg D; green; 150 m asl.) and the Black Forest (legs E, F, G; red; up to 1500 m asl.).

3. AIRBORNE LIDAR RESULTS

On 30 July 2007, where convection initiation was expected to be triggered by surface fluxes and orographic features, the most successful COPS flux mission was performed. A little risk of thunderstorms had been predicted, but it turned out that in the end, the fluxes were too weak to generate deep convection.

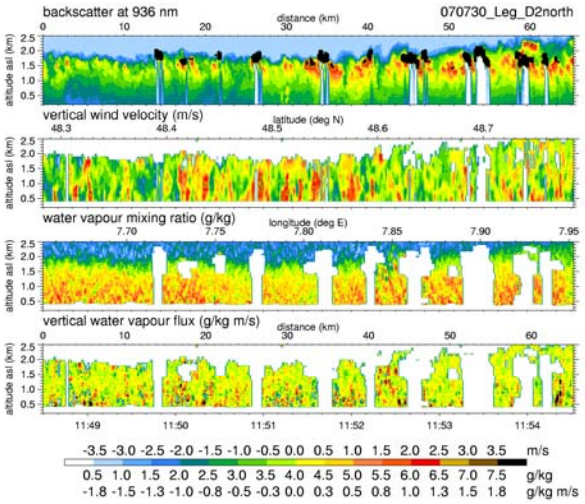

Figure 3. Airborne lidar cross sections over the northern part of the Rhine valley flight leg D in Fig. 2. The convective boundary layer is impressively seen in the wind lidar data.

Figure 3 shows airborne lidar measurements of

1. Aerosol and cloud top backscatter intensity from the DIAL offline signals: scattered fair-weather cumulus clouds are visible as black spots, as well as the top of the convective boundary layer situated at ~2 km altitude.
2. Vertical wind velocity from the Doppler lidar: the convective eddies are accurately detected through the small-scale updrafts (red) and downdrafts (green/blue). Mesoscale (10-20 km) variability also shows up.
3. Water vapour mixing ratio from the DIAL: the variability is less pronounced than for wind; the free atmosphere is dry. Clouds and their shadows have been masked out and whitened.
4. Instantaneous vertical water vapor flux: obtained by the multiplication of the instantaneous DIAL humidity fluctuations (q’) with the vertical wind fluctuations (w’), not the covariance. The result is fairly noisy; yet, intense positive local fluxes show up as black dots, negative w’q’ as blue dots.

Challenges arise due to the fact that the lidar profiles are occasionally interrupted by clouds (see Figure 3) and laser readjustment phases, and due to the complex orography which generates heterogeneous boundary layers over the mountains. Nevertheless, the experience gained from previous studies [4] and the comparisons with in-situ flux measurements co-located in space and time [3] helped constrain the related uncertainties.

After a careful laser beam co-location check, area-averaged fluxes of latent heat are estimated using eddy-correlation from the w and q time series across an entire flight leg. This reduces the sampling uncertainty to roughly 30 %. The instrument noise, mainly originating from the DIAL, has a similar value. The applied methods and the error estimations are detailed in [4]. Figure 4 shows an example latent heat profile, obtained from the over-flight of the Rhine valley of Figure 3.

The negative flux divergence in the well-mixed boundary layer below the entrainment and cloud zone was observed also on another flight leg. Since horizontal moisture advection was estimated to be negligible on that day, the simplified water vapour budget equation, valid in this flat-terrain, homogeneous and quasi-stationary situation indicates a humidification of the boundary layer air. The likely reason is that rain was observed on the previous days, and the present lidar measurements were performed on the rear side of a trough in relatively cold, clean and dry air, so that surface evaporation from the humid soils into the dry air could be expected. This is indeed what the flux profile of Figure 4 tells, even if it stops at ~300 m above the surface due to lidar technical constraints. As expected the flux is zero in the free atmosphere.

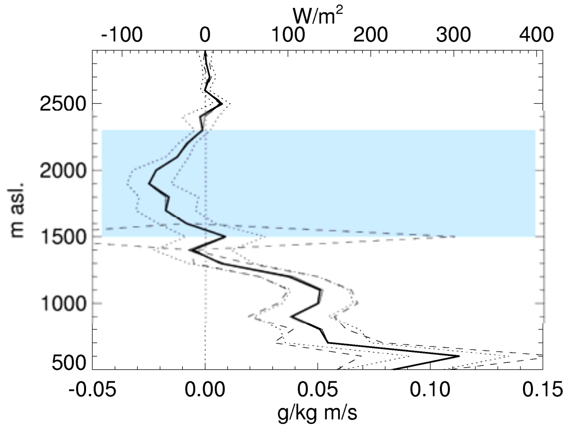

Figure 4. Latent heat flux profile obtained from eddy-correlation of w and q across the Rhine valley flight leg of Figure 3. Instrument noise (dotted) and sampling uncertainties (dashed) are from assessments given in [4]. The blue box shows the entrainment and cloud zone. Top scale gives the latent heat flux, bottom scale the kinematic turbulent flux.

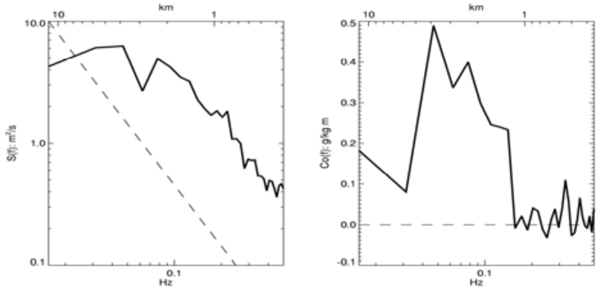

Figure 5. Fourier spectra of w’ (left) with -5/3 slope (dashed), and co-spectra of w’ and q’ (right) for the measurements of Figure 3, averaged vertically between 0.5 and 1.5 km, in order to increase the statistical significance. Top scale is wavelength (km), bottom scale frequency (Hz).

To conclude, the Fourier spectra of w’ in Figure 5 show the expected cascade of turbulent kinetic energy within the inertial subrange as -5/3 slope. The co-spectra of w’ and q’ reveal that the turbulent structures responsible for most of the mid-boundary layer flux have sizes between 1 - 4 km. As already observed in a previous study [4] with vigorous convection over flat terrain, turbulence on spatial scales smaller than 1 km is irrelevant to the net flux. Similar results are obtained over the Black Forest Mountains. We find that the lidar measurements spatial resolution of ~200 m is sufficient to resolve the flux dominant eddies and hence to achieve accurate measurements of the latent heat flux.

REFERENCES

[1] Wirth M., A. Fix, P. Mahnke, H. Schwarzer, F. Schrandt, G. Ehret, 2009: The airborne multi-wavelength water vapor differential absorption lidar WALES: system design and performance. *Appl. Phys. B*, **96**, 201-213, DOI 10.1007/s00340-009-3365-7.

[2] Weissmann M., F.J. Braun, L. Gantner, G.J. Mayr, S. Rahm, O. Reitebuch, 2005: The Alpine Mountain Plain Circulation: Airborne Doppler Lidar Measurements and Numerical Simulations. *Mon. Wea. Rev*. **133**, 3095–3109.

[3] Kiemle C., M. Wirth, A. Fix, S. Rahm, U. Corsmeier and P. Di Girolamo, 2010: Latent Heat Flux Measurements over Complex Terrain by Airborne Water Vapour and Wind Lidars. *Submitted to the Q. J. R. Meteorol. Soc.*

[4] Kiemle C., W.A. Brewer, G. Ehret, R.M. Hardesty, A. Fix, C. Senff, M. Wirth, G. Poberaj, M.A. LeMone, 2007: Latent Heat Flux Profiles from Collocated Airborne Water Vapor and Wind Lidars during IHOP_2002. *J. Atmos. Ocean. Tech.*, **24**, pp. 627-639, DOI: 10.1175/JTECH1997.1.