Latent Heat Fluxes over Complex Terrain from Airborne Water Vapour and Wind Lidars

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ABSTRACT

Tropospheric profiles of water vapour and wind were measured with a differential absorption lidar (DIAL) and a heterodyne detection Doppler wind lidar collocated onboard the DLR Falcon research aircraft in the past two years. The DIAL 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 space-borne water vapour lidar mission. It operated successfully during the Convective and Orographically-induced Precipitation Study (COPS) in July 2007 over the Black Forest Mountains in southern Germany, and during the Norwegian THORPEX-IPY field experiment in March 2008 over the European North Sea.

For the study of summertime convection initiation over complex terrain and the development of Polar Lows in the North Sea both campaigns included latent heat flux missions where both airborne lidars were pointed nadir-viewing. Using eddy-correlation of the remotely-sensed wind and water vapour fluctuations, a representative flux profile can be obtained from a single over-flight of the area under investigation. The lidars' spatial resolution is ~200 m which resolves the dominant circulation and flux patterns in a convective boundary layer. This novel instrumentation allows obtaining profiles of the latent heat flux beneath the aircraft from one single over-flight of any area of interest.

1. THE AIRBORNE LIDAR INSTRUMENTATION

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 performed 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 absorption cross sections.

Typically three online and one offline wavelengths can be selected to cover the whole range of water vapour mixing ratios varying over four orders of magnitude between the lower stratosphere and the lower troposphere. Due to a system component failure only three of the four wavelengths were available during the COPS experiment. Furthermore, high temperatures and cooling unit limitations during the flux missions flown at lower levels (5 km altitude) prevented the use of both transmitters at a time, so that only two DIAL wavelengths (one online, one offline) were available in this case. This is sufficient for accurate water vapour profiles in the lower troposphere. Here the DIAL horizontal and vertical resolution is approximately 150 m, and its accuracy is around 0.6 g/kg or roughly 10%.

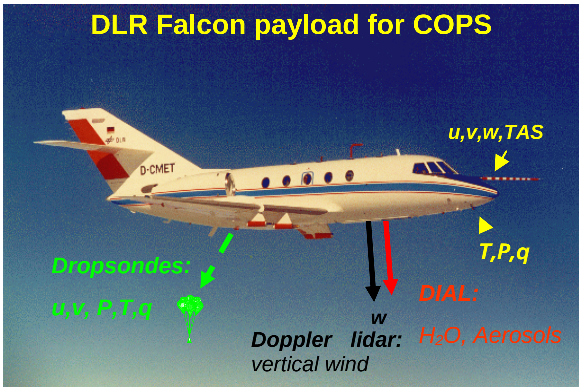

Figure 1. DLR Falcon carrying wind and water vapour lidars during COPS 2007, plus dropsondes and in-situ instruments.

Table 1. Airborne water vapour DIAL and wind lidar system characteristics.

	DIAL	**Wind Lidar**
Transmitter type	OPO	Diode laser
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)	40	10
Horizontal res. (m)	150	150
Vertical res. (m)	150	100
Absolute accuracy	0.6 g/kg	0.1 m/s

The 2-micron wind lidar was 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 150 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.

2. THE COPS 2007 EXPERIMENT

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 when 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 region.

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 intercomparisons. The DLR Falcon participation in COPS 2007 was very successful: each mission scenario could be flown several times, and all systems were running properly throughout most of the time. 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, whereby different synoptic and boundary layer conditions could be sampled, allowing for latent heat flux intercomparison studies. As Figure 2 illustrates, several 150 km long flight legs above the Rhine valley and the Black Forest were flown, oriented parallel to the Rhine valley.

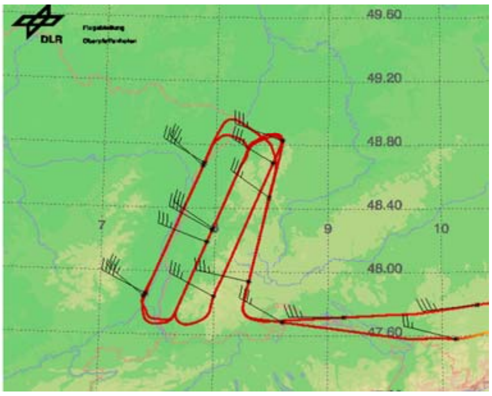

Figure 2. DLR Falcon flight track on July 30, 2007 during a COPS latent heat flux mission. Numbers are latitude and longitude. Wind barbs indicate wind velocity in flight altitude.

These flux flights performed above the Rhine valley and the Black Forest in pre-convective conditions have the goal to understand the initiation of convection by studying the spatial variability of humidity, wind and latent heat fluxes in complex terrain. 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 surface fluxes.
2. Mid-level (~5 km) flight altitudes helped to get strong boundary layer lidar return signals at high spatial resolution.
3. Three 150 km long N-S oriented flight legs centred above the Black Forest highly-instrumented COPS "supersites" 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.
6. 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 and applied.

3. RESULTS FROM COPS 2007

Figure 3 gives a flat-terrain airborne lidar measurement example of

1. Aerosol and cloud top backscatter intensity from the DIAL offline signals: scattered fair-weather cumulus clouds are well visible, as well as the top of the convective boundary layer situated at approx. 2 km altitude asl. The bottom black line is the surface.
2. Vertical wind speed from the Doppler lidar: the convective eddies are accurately detected through the small-scale updrafts (red) and downdrafts (green). Mesoscale (10-20 km) variability also shows up.
3. Water vapour mixing ratio from the DIAL: the variability in the CBL is less pronounced than for wind; the free atmosphere is much drier than the CBL. Clouds and their shadows have been whitened.
4. Instantaneous vertical water vapour fluxes: are obtained by the multiplication of the DIAL humidity fluctuations (q') with the vertical wind fluctuations (w') for each lidar profiles pair. The result is somewhat noisy; nevertheless, intense positive local fluxes show up as black dots, negative w'q' as blue dots.

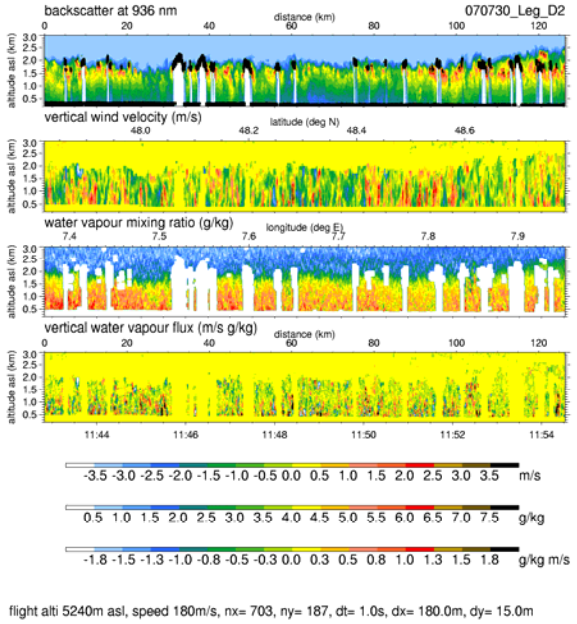

Figure 3. Lidar backscatter intensity (arb. units), vertical wind velocity, water vapour mixing ratio and local water vapour flux (from top to bottom) above the Rhine valley at 14 LT on July 30, 2007.

Challenges arise due to the fact that the lidar profiles are occasionally interrupted by clouds (see Fig. 3), bad signals and laser readjustment phases, and due to the complex orography which generates very heterogeneous boundary layer structures over the mountains. Nevertheless, the experience gained from previous studies [2] is expected to foster the development of adapted methods to solve these issues. Particularly helpful are also the comparisons with in-situ flux measurements co-located in space and time from another participating aircraft during COPS 2007.

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 [2]. Figure 4 shows an example latent heat profile, obtained from the over-flight of the Rhine valley of Fig. 3.

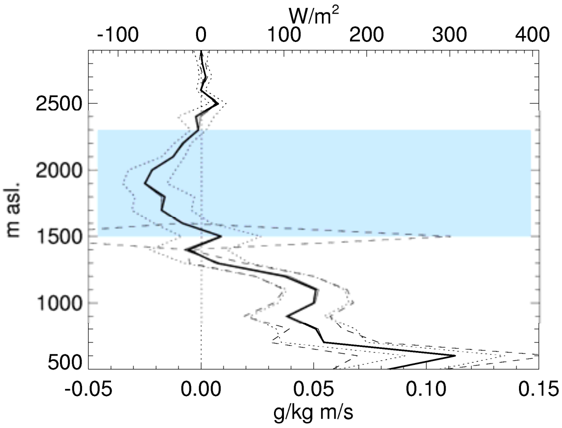

Figure 4. Latent heat flux profile obtained from eddy-correlation of w and q across the Rhine valley flight leg of Fig. 3. Instrument noise (dotted) and sampling uncertainties (dashed) are from equations given in [2]. The blue box shows the entrainment and cloud zone. Top scale gives the latent heat flux, bottom scale the kinematic turbulent flux.

The pronounced negative flux divergence of roughly 0.3 g/kg/h in the well-mixed boundary layer below the entrainment and cloud zone was observed also on other flight legs. 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 yields a humidification of the boundary layer air of roughly 0.3 g/kg/h.

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 strong surface evaporation from the humid soils into the dry air could be expected. This is indeed exactly what the flux profile of Fig. 4 shows, even if it stops at 200 m above the surface due to lidar technical constraints.

Finally, 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, i.e. roughly 0.6-2.4 zi. We conclude that the lidar measurements' spatial resolution of about 200 m is sufficient to resolve the flux dominant eddies.

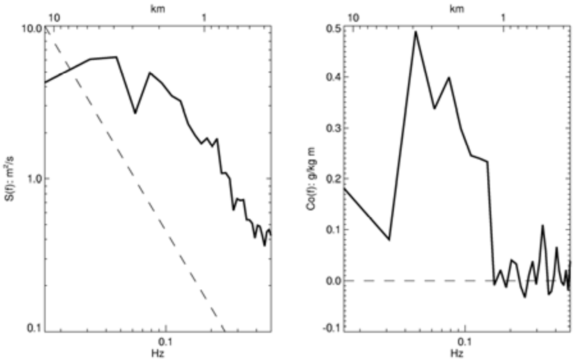

Figure 5. Fourier spectra of w' (left) with -5/3 slope (dashed), and co-spectra of w' and q' (right) for the measurements of Fig. 3 between 0.5 and 1.5 km asl. Top scale wavelength (km), bottom scale frequency (Hz).

4. FLUXES DURING IPY-THORPEX

In the framework of the International Polar Year (IPY), the DLR Institute of Atmospheric Physics performed airborne lidar observations between Greenland and Svalbard over the European North Sea. The focus of the 3 weeks field phase in February/March 2008 was to investigate the generation, structure and development of Arctic storms. This work is part of the IPY-THORPEX cluster. The observations were performed with the DLR research aircraft Falcon equipped with the same payload as for COPS (see Fig. 1). Stronger water vapour DIAL absorption lines were chosen to cope with the low mixing ratios of under 2 g/kg.

During several short episodes of the 67 total flight hours, focus was set on measuring latent heat flux profiles in the same manner as during COPS. Outbreaks of cold air of Polar origin over the North Sea can generate strong heat fluxes at the sea surface and intense mechanical forcing of the ocean. The main oceanic response to such forcing is cooling and deepening of a mixed surface layer. It is of very much interest to quantify this oceanic response since it can represent a major contribution to the large-scale transformation of water masses and to the formation of the North Atlantic Deep Water.

On March 1, 2008, an area with intense convection due to a cold air outbreak over the ice-free North Sea was over-flown by the Falcon. Sea surface temperatures from satellite observations were slightly above the freezing point. Most of the area was overcast, unfortunately, with convective clouds reaching up to 2 km asl. A Lidar derived latent heat flux profile could be obtained from a cloud-free area of about 40 km length. Here the convective boundary layer was about 1 km deep. Its structural aspect in the lidar backscatter, wind and water vapour cross sections is surprisingly similar to typical summer CBLs over land. The measured latent heat fluxes range from about 50 W/m^2 in 200 m asl. to 100 W/m^2 in 700 m asl.

Unfortunately, no additional measurements of temperature or horizontal wind are available in this 40-km area, except low-resolution satellite observations. However, we plan to simulate this particular situation with a mesoscale model. The idea is to constrain the model with the available observations, in particular sea surface temperatures, and see whether it reproduces the measured flux profile.

5. OUTLOOK

The participation of the DLR Falcon in the COPS and IPY-THORPEX experiments was successful. Data evaluation is ongoing, including intercomparisons with in-situ sensors and the elaboration of adapted algorithms for estimating latent heat fluxes in partly cloudy conditions and over complex orography. This novel instrumentation bears considerable potential for future missions over complex terrain or oceans.

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