

# AIRBORNE LIDAR OBSERVATIONS OF WATER VAPOUR VARIABILITY AND TRANSPORT

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## ABSTRACT

Water vapour, a minor constituent of the earth's atmosphere, plays a major role in the radiation budget and the water cycle with important implications for weather and climate. Due to the heterogeneous distribution of its sources, evaporation, and sinks, condensation and precipitation, and due to the complexity of atmospheric motion and mixing, its distribution is highly variable. Despite the relevance of this trace gas, its variability and instrumental shortcomings impede accurate measurements of its concentration. Advanced airborne lidar instruments aid to better observe water vapour and its transport in the atmosphere, in view of an improved understanding of the related key implications. The combination of a water vapour differential absorption lidar and a heterodyne detection Doppler wind lidar on an aircraft allows to measure vertical profiles of the latent heat flux in a convective boundary layer and to portray the small- to meso-scale humidity transport and variability beneath the aircraft with high accuracy and spatial resolution, in the frame of dedicated meteorological process studies.

## 1. INTRODUCTION

Water vapour is routinely measured at the surface, with the global radiosonde network and with satellite sensors. The radiosondes' accuracy is sufficient in the lower and middle troposphere, but the representativeness of the one-dimensional vertical profiles is poor. Furthermore, few data are collected over the oceans, at high latitudes, and in the southern hemisphere. In these regions, and in the upper troposphere, satellite spectrometers partly fill the observational gap, but with coarse spatial resolution. Better accuracy and resolution is obtained by active, optical lidar remote sensing. Since 1987 the DLR atmospheric physics institute's lidar group develops and operates airborne water vapour lidars. Participation in numerous field experiments helped characterize the distribution of water vapour in the frame of case studies dedicated to specific physical and meteorological processes. A recent instrumental highlight is the co-deployment of a newly developed water vapour and a wind lidar on board the DLR Falcon research aircraft (Figure 1; Table 1). The wind lidar is operated either in conical-scanning mode with 20° off-nadir angle for 3-d wind field profiles, or in nadir-viewing mode for vertical wind speed profiles.

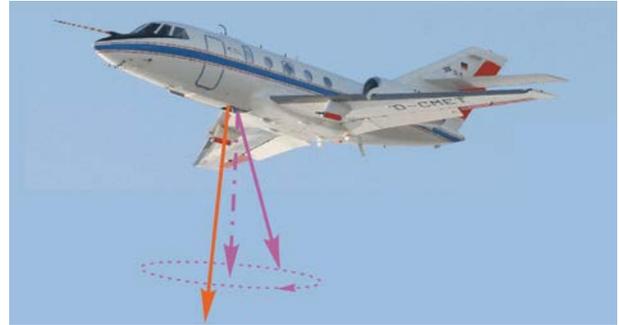


Figure 1: DLR Falcon research aircraft with idealized wind (pink) and water vapour (orange) lidar beams. The wind lidar can be operated either in conical scanning mode for estimates of the three-dimensional wind vector, or in nadir viewing mode for vertical wind velocity measurements.

	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
Precision	0.4g/kg	0.1 m/s

Table 1: Main characteristics of airborne water vapor differential absorption lidar (DIAL) and Doppler wind lidar.

The difference between a laser emission wavelength tuned to the centre of a H<sub>2</sub>O absorption line and a non-absorbed off-line reference is proportional to the H<sub>2</sub>O molecule density in air. The DIAL has two transmitters, each based 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 pulse repetition frequency (PRF) of 100 Hz [1]. The OPO is optimized to operate in the spectral region between 920 - 950 nm at average output pulse energy of 40 mJ. Each transmitter outputs two spectrally narrow pulses, yielding in total four pulses (each 50 Hz, 40 mJ) at different wavelengths for different water vapour absorption lines.

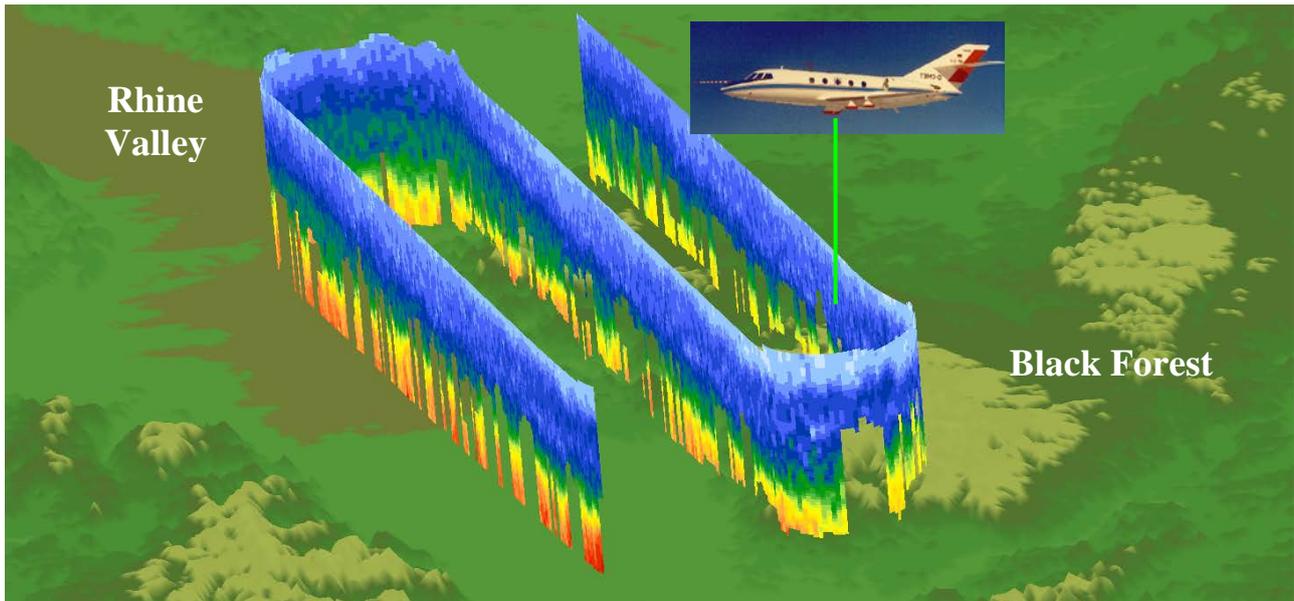


Figure 2: Airborne water vapour lidar measurements over complex terrain in Southwest Germany, on 30 July 2007 at noon. Blue represents dry air above, yellow and red show humid air within the convective boundary layer (CBL). The length  $\times$  height of the data curtains is 150 km  $\times$  4 km. The topographic heights range from 150 m to 1500 m. Interruptions are due to scattered fair-weather clouds at the CBL top.

## 2. TROPOSPHERIC HUMIDITY VARIABILITY

Spectral analyses of long-range water vapour lidar cross-sections obtained during the above experiments at altitudes from 2 km to 10 km show power-law scaling between ranges of about 10 km to 100 km. Structure functions reveal that humidity smoothness typically increases with height, while intermittency decreases. The results suggest a water vapor distribution determined at upper levels by advective mixing, but increasingly influenced at lower levels by local injection of humidity by moist convection. It appears that the structure function exponents provide a compact statistical description of moisture variability on scales just below the resolution of weather and climate models. This can be directly applied, for example, to the design of stochastic parameterizations for clouds and convection by using the spectral information to construct realizations of the small-scale moisture field. The interested reader is referred to [4] for further information.

## 3. VERTICAL WATER VAPOR TRANSPORT, LATENT HEAT FLUX

Evaporation over land and especially over complex, mountainous terrain can be very heterogeneous on small scales that are both under-sampled by observations, and un-resolved by numerical weather prediction (NWP) models. Over a land surface heated by solar irradiation, a convective boundary layer (CBL) develops, typically

reaching heights of 1 – 2 km above ground in the afternoon. The buoyancy of warm air parcels transports the humidity vertically away from its surface sources. Cloud condensation at the boundary layer top, and subsequent cloud growth with occasionally heavy precipitation may occur. Observational and modelling deficits due to the heterogeneity of surface and atmospheric moisture are main reasons why numerical weather prediction (NWP) models fail to accurately forecast the precipitation in the warm season, even if evaporation and subsequent humidity transport are key elements of the hydrological cycle.

Consequently, a field experiment called “Convective and Orographically-induced Precipitation Study” (COPS) was conducted in July 2007 over the Black Forest low-mountains in south-western Germany, with the participation of the DLR Falcon aircraft. Figure 2 exemplarily shows two-dimensional vertical cross-sections of humidity beneath the aircraft along the flight track. This kind of data gives a decisive advantage over conventional one-dimensional “in-situ” measurements, particularly in this heterogeneous situation, where e.g. higher humidity is observed in the Rhine valley. One of the main goals of the DLR Falcon was to measure the vertical humidity transport within the CBL over the Rhine valley and the Black Forest on days when thunderstorms, mainly influenced by the orography and surface humidity, were forecasted [2]. From the remotely-sensed wind and water vapour fluctuations in

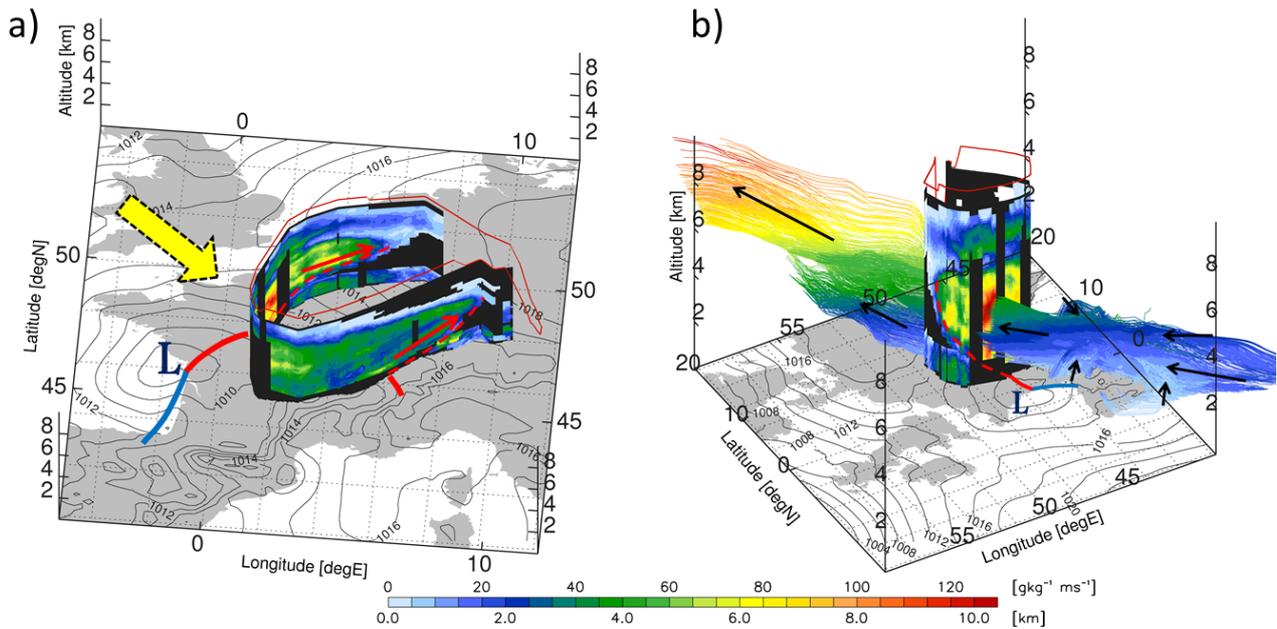


Figure 3: Airborne observations of water vapor transport on 1 August 2007 from combined water vapor and wind lidars. Perspective from the south (a) and from northwest (b), indicated by the yellow arrow in (a). The aircraft flew along the thin red line. The curtain-like 2-dimensional cross-section shows the transport of water vapor beneath the aircraft. Blue represents weak transport; yellow and red mean strong transport. Thin black contour lines on the map show the surface pressure [hPa]. The thick blue and red lines depict the location of the surface cold and warm front, respectively. The dashed red lines show the vertical extension of the warm front along the lidar curtain. In addition, (b) shows selected trajectories of air parcels with the maximum observed water vapor transport. Their colors indicate the altitude of the parcels for 2.5 days in advance and 1.5 days after the flight. Data gaps are black.

the convective boundary layer, a representative area-averaged latent heat flux profile is obtained by the eddy-correlation technique. The lidars' horizontal and vertical resolution is 200 m, sufficient to resolve the dominant contributions to the flux. The lidar-derived latent heat fluxes over the mountains vary between 100 – 500 W/m<sup>2</sup> but are roughly constant with height. The positive fluxes moisten the growing CBL by upward transport of humidity from surface evaporation due to previous days' rain.

#### 4. HORIZONTAL MOISTURE TRANSPORT

In the mid-latitudes between 30 and 60°N, cyclones effectively remove energy differences between polar and subtropical areas as a result of differing solar radiation by transporting moist and warm air pole-ward and cold and dry air equator-ward. Typically, the polar and subtropical air masses are separated by a narrow band in the mid-latitudes possessing a sharp meridional temperature change. Along this frontal zone, low pressure systems evolve that transport air horizontally and vertically, generating cloud development and precipitation. Due to the minor depth of the layer where weather happens, the troposphere (0-12 km), most atmospheric transport processes can be considered

quasi-horizontal. Advanced observation techniques like lidar are required to observe the water vapor transport in low pressure systems. Besides the understanding of the physical processes, the verification of model simulations by independent observations helps pinpointing insufficiencies in current NWP models.

Figure 3 shows an example from the COPS field experiment to highlight the value of high resolution lidar data to observe the highly-complex three-dimensional transport of moisture in the surrounding of a low pressure system. The curtain-like two-dimensional cross section represents a snapshot of the water vapor transport, determined by the product of wind velocity and water vapor concentration, and reveals an up to 6 km deep layer of enhanced water vapor transport in the warm sector of the cyclone [3]. Maximum values occur on the most western part of the flight facing the cold front, where increased wind speeds and water vapor concentrations coincide. Nicely, the strong horizontal gradients of the moisture transport at the warm front show a tilting with height, coming along with the north-eastward ascending air masses (red dashed lines along the lidar cross section). The tilting is observed on both overpasses of the warm front. Red arrows denote the up-gliding of the warm and moist air above the colder air to the north. In contrast, in the

north-eastern part the horizontal transport in the boundary layer is weak.

Figure 3b shows the same scenery from a north-western perspective. The increased transport on the western side that extends upward along the tilted warm front is clearly visible. The figure also displays trajectories that describe the pathways of the observed air parcels in space and time. Shown are the pathways up to 2.5 days in advance and up to 1.5 days after the lidar observation. The trajectories were calculated using NWP wind data. The strong moisture transport clearly originates from the southwest. Air in the lower troposphere is humidified over the Atlantic and the Mediterranean by evaporation and subsequent vertical transport in the boundary layer. These air masses converge over south-eastern Europe. The developing cyclone incorporates and transports the moisture north-eastwards towards the flight path. Many air parcels slightly ascend towards the lidar cross section and further up until they reach the upper troposphere (~8 km) 1.5 days after being observed by the lidar. An in-depth discussion of this case study and a comparison with NWP data is found in [3].

The airborne lidar instruments are able to map the clear-air transport of water vapour into cyclones that is known to play a key role in the structure, intensity, and further evolution of cyclones. The latent heat release is expected to amplify cyclones, and also to affect the upper-level wind fields which control the weather development further downstream. This emphasizes the importance of a correct representation of moisture for the quality of weather forecasts. Further studies show that the lidar observations are useful for diagnosing NWP model errors which result from either incorrect horizontal or vertical transport of moisture or from insufficiently represented evaporation in moisture source regions.

## 5. CONCLUSIONS AND OUTLOOK

Accurate water vapour measurements are sparse and challenging because of the high variability of its sources in space and time, and because of the complexity of atmospheric motion and mixing. Advanced airborne water vapour observations are, as shown, valuable for addressing relevant issues of current research in atmospheric water vapour and transport. The lidars can portray the two-dimensional water vapour and wind variability, as well as the horizontal and vertical moisture transport with high accuracy and spatial resolution along the flight path in cloud-free areas. Eddy correlation of vertical velocity and water vapour provides profiles of the CBL latent heat flux above land or water. On 30 July 2007, during the COPS experiment, the lidar-derived latent heat fluxes over the mountains moistened the growing CBL by upward transport of humidity from surface evaporation due to rain on the previous days.

There is an increasing need for improved measurements, for example of the relative humidity in the upper troposphere in regions with ice super-saturation. This implies having simultaneous information on temperature from NWP data or auxiliary measurements. A combined water vapour and temperature lidar is a future challenging task, as temperature profiling by lidar is basically possible yet still subject to high detection noise, which necessitates long averaging periods and consequently means coarse spatial resolution.

Water vapour in the lower troposphere is particularly relevant for weather, while water vapour in the upper troposphere and the stratosphere is particularly relevant for climate, where, after vertical transport from the surface sources, it strongly influences Earth's radiation budget. Consequently, understanding the transport and distribution of atmospheric humidity and the processes that control it is of primary importance to both climate research and weather prediction. New instrument developments such as multi-wavelength lidar will, on board the new German HALO research aircraft, advance the science, building on the knowledge gained in the above-mentioned experiments. In addition, future satellite missions to measure wind (ESA Atmospheric Dynamics Mission) or water vapour (ESA WALES: Water vapour Lidar Experiment in Space) will be supported and validated.

## 6. REFERENCES

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