JP2.16

Water vapor characterisation over Oklahoma using DIAL

A. Lammert and J. Bösenberg

Max-Planck-Institut für Meteorologie, Bundesstraße 55, 20146 Hamburg, Germany

1 Introduction

The knowledge of the distribution and variability of the water vapor with time and height yields important hints to atmospheric processes like the development of an atmospheric boundary layer (ABL). Measurements with high temporal and spatial resolution are necessary to characterise the ABL appropriately. With a time resolution of 10 seconds and a height resolution of 60m within the ABL for the absolute humidity the differential absorption lidar (DIAL) is well suited for the observation and analysis of turbulent processes in the atmosphere which are coupled with the development of the ABL. The determination of mean values of the ABL top height is necessary for the scaling of atmospheric parameters like water vapor distribution functions, which can be used for a more realistic parameterisation in numerical forecast or dispersion models. In addition the DIAL technique yields the instantaneous ABL height with a high temporal resolution, which is important for e.g the examination of entrainment processes.

The use of DIAL offers the advantage of providing 2 different parameters for the retrieval of ABL heights, water vapor and aerosol distributions. While the results of both methods generally show good agreement, there are more complex situations where only the combined information from both parameters yields satisfactory results.

2 Methodology

2.1 Lidar and DIAL

Lidar techniques use the light that is backscattered by aerosol particles or molecules for range resolved determination of atmospheric parameters. Excellent height resolution is achieved because short pulses of light are transmitted into the atmosphere and the travel time from the transmitter to the scattering volume and back to the receiver is used for height determination. In a pure backscatter lidar the signal P as a function of range R is determined by the lidar equation

$$P(R) = CR^{-2}\beta(R)exp(-2\int_0^R \alpha(r)dr) \qquad (1)$$

where C is an instrument constant, β the range dependent total backscatter coefficient, and α the total extinction coefficient. For studies of the aerosol stratification it is convenient to use the logarithmic derivative of the range corrected signal, $d/dr(ln(PR^2)) = d/dr(ln\beta) - 2\alpha$. In weakly absorbing regions the first term on the right hand side is much larger than the second, so that relative changes in backscatter are clearly indicated.

The DIAL technique uses two lidar signals at slightly different wavelengths, one of which is chosen at the center of an absorption line of the gas under study (“online”), and the second one in a weakly absorbing spectral region (“offline”). When the wavelength difference is sufficiently small the backscatter and extinction are the same except for the gaseous absorption. This leads to the DIAL equation

$$\frac{d}{dR} ln\frac{P_{on}}{P_{off}} = -2\Delta\sigma\varrho \qquad (2)$$

where $\Delta\sigma$ is the differential absorption cross section and ϱ is the gas density. When $\Delta\sigma$ is known from spectroscopic studies the gas density can be retrieved as a function of range. For practical applications some complications arise mainly from the details of the spectral distributions of the transmitted and the backscattered beams as well as from the temperature and pressure dependence of $\Delta\sigma$. For the case of water vapor retrieval the reader is referred to the literature, e.g. Bösenberg, 1998. DIAL is a double differential technique, differentiation of the raw signal with respect to range and to wavelength has to be applied. Therefore the accuracy of the retrievals is critically dependent on signal quality. This limits the achievable range in particular for ground-based systems to a few kilometers, and also limits the achievable range resolution to typically 60m in the near range and 1km or more in the far range.

2.2 ABL determination

The determination of the ABL top height depends in the first place on the definition. We use the definition of Stull, 1988, so the ABL is identified as the part of the atmosphere, "... that is directly influenced by the presence of the earth's surface, and response to surface forcings with a time scale of about an hour or less.". Several methods for the height determination of this part of the atmosphere exist which use different properties of the turbulent well mixed ABL. The variance analysis is one of them (see Stull, 1988) and is based on the assumption of an increase of variance of the time series at the top of the ABL and a decrease above. This effect is a result of mixing at the transition of ABL and free troposphere (entrainment). One necessary condition for this analysis is the existence of time series which are long enough to include a sufficient number of turbulent incidents to reduce the statistical error. The disadvantage is the poor time resolution of this kind of ABL determination. Moreover, for the observation and analysis of a turbulent and increasing ABL, this method is comparably inaccurate. A better way is the gradient method, which uses the fact that the surface layer is the most important source of water vapor and aerosol and this produces a strong gradient for water vapor and aerosol at the top of the ABL. In this method height profiles at different times are analysed as provided by a measurement system like DIAL. This analysis allows the detection of turbulent and entrainment processes identifiable in the plot of $d/dR(\ln(PR^2))$. It was used to determine the ABL heights from $d/dR(\ln(PR^2))$, following Flamant et al., 1997, and in a similar way from water vapor distributions.

3 Observations

3.1 Experimental description

In 2000, the DIAL of the Max-Planck-Institut participated in two experiments at the ARM Southern Great Plains (SGP) site in Oklahoma, the WVIOP (Water Vapor Intensive Observation Period) in September/October and AFWEX (ARM-FIRE Water Vapor Experiment) in December. One example from each experiment was selected for this presentation.

With a maximum temperature of 34.5 °C, light wind from South and clear sky, the weather situation on Oct 2, 2000 was favorable for the observation of a turbulent ABL. Similarly good conditions were dominant on Dec 6, 2000, with light wind from W to SW, a temperature decrease from 6 °C to 0°C and clear sky.

3.2 Data

The absolute humidity data was analysed as described in Bösenberg, 1998 and Wulfmeyer and Bösenberg, 1998, from circa 300 to 7000 m above ground using a time resolution of 10 s, and a height resolution as shown in Tab. 1. The measurement on Oct 2, 2000 started at 18:30 UT end ended at 00:10 UT (the time shift between UT and Oklahoma LT is 5 hours). For the Dec 6, 2000 the measurements were taken from 21:05 to 07:40 UT (the time shift to LT is 6 hours).

Height range 10/02/2000	Height range 12/06/2000	Resolution
300- 720m	300-1020m	60m
720-2160m	1020-2100m	180m
2160-3840m	2100-3360m	420m
3840-5040m	3600-5760m	600m
5040-7040m	5760-6760m	1000m

Table 1: Height resolution of absolute humidity data for the measurements of 10/02/2000 and 12/06/2000.

4 Cases studies

4.1 Development of a turbulent ABL

Fig. 1 shows the increase of a turbulent ABL and the end of convection and turbulence on Oct 2, 2000 over a six hour period for a height range from 700 to 6000m. The turbulent ABL height can be identified by the logarithmic derivative of the range corrected offline signal $d/dR(\ln(PR^2))$. The high variability of the ABL top, caused by turbulent processes, is clearly visible in the gradient plot. Similar structures, but with lower resolution, are observed in the corresponding water vapor distribution.

Fig. 2 shows the time series of the ABL height determined from the data shown in Fig. 1 with the method described in 2.2. There is a good agreement between the two time series for the first and second part of measurement (until 22:30 UT) and an overestimation of the ABL heights of the backscatter data compared to the water vapor data in the late afternoon. These differences can only partly be explained by the different height resolutions of the measurements. In the last period the water vapor distribution is more complex, but the aerosol gra-

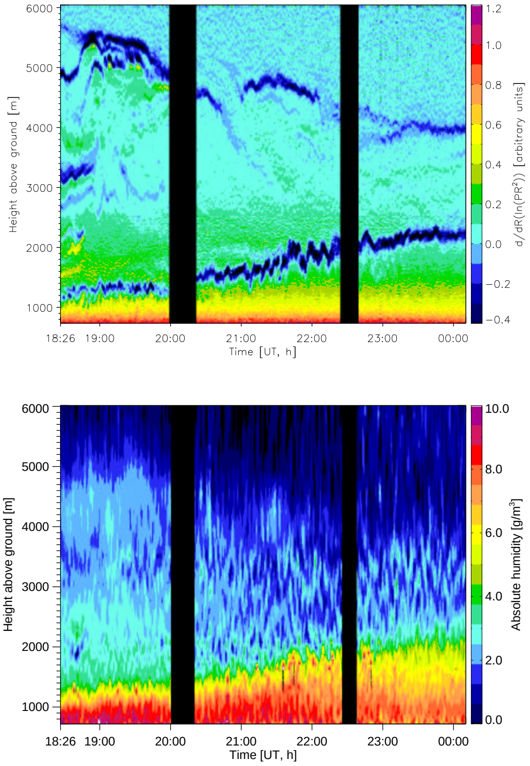

Figure 1: Time-height cross section of d/dR(ln(PR^2)) (top) and the absolute humidity (bottom) measured on Oct 2, 2000. The height resolution of the gradient plot is 30m, the time resolution 10s with a gliding average of 2 min. The humidity was calculated with 10s time resolution, 2min gliding average and the height resolution shown in Tab. 1 with a gliding average of 15m.

dients suggest that a significant layer boundary still exists around 2100m height.

The mean value of the determined ABL height can be used to scale distribution functions of the absolute humidity. Fig. 3 shows the plot of the distribution functions with height at the left side, scaled with the mean ABL height z_i and selected heights at the right side. Plotted are the distribution functions at 0.6, 0.8, 1.0, 1.3 and 1.4 z_i. The similarity of the shape of the functions below and above the ABL top is obvious, while the distribution at the transition between the well mixed ABL and the relatively stable free troposphere (1.0 z_i) is broader.

4.2 Transition of a turbulent ABL to a residual layer

The measurement of Dec 6, 2000 was analysed from 300 to 6800m above ground (the height resolution is

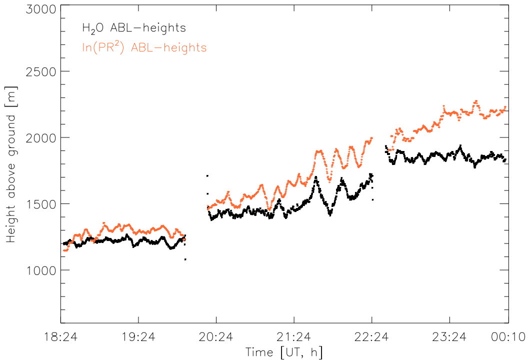

Figure 2: Time series of the ABL heights determined from the gradient of the absolute humidity (H_2O, black) and the logarithm of the range corrected offline signal (ln(PR^2), red) for the measurements shown in Fig. 1. The time resolution is 10s with a gliding average of 5min.

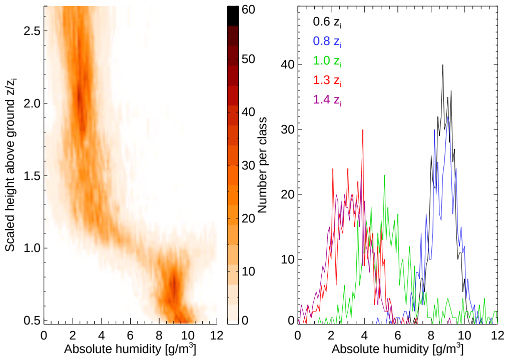

Figure 3: Distribution functions of absolute humidity with height for the measurement part from 18:30 to 20:00 UT (left). The height resolution is the same like in Table 1 and scaled with the mean ABL height z_i = 1202m (the darker the color the higher the number per class, one class correspond to 0.1 g/m^3). At the right side the distribution functions are plotted at selected heights at 0.6, 0.8, 1.0, 1.3 and 1.4 z_i.

shown in Tab. 1). At the beginning there is a turbulent ABL in circa 1000m identifiable both in the gradient of ln(PR^2) and in the humidity in Fig. 4 on the height fluctuation in this range. This boundary subsides slowly in the course of measurement and dissolves at circa 00:00 UT, as cognizable in the plot of d/dR(ln(PR^2)). In addition Fig. 4 shows a second layer above 3000m in the humidity plot. This layer subsides in the course of measurement. It is only seen during the first 3 hours in the gradient of ln(PR^2). The origin of this layer cannot be derived

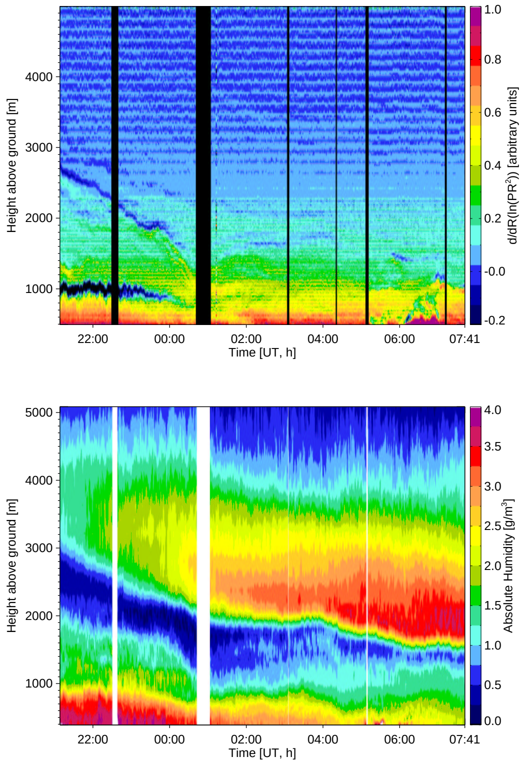

Figure 4: Time-height cross section of d/dR(ln(PR^2)) (top) and the absolute humidity (bottom) measured on 6 Dec 2000. The height resolution of the gradient plot is 30m, the time resolution 10s with a gliding average of 2min. The humidity was calculated with 10s time resolution, 2min gliding average and the height resolution shown in table 1.

from this observations, but it is not dependent on the surface and apparently not on the wind direction either. For this case the wind direction was W to SW, but there were also cases with a double layer with wind from N, NO and SO observed during this campaign. This case shows the advantage of DIAL measurements to analyse that kind of stratification, which is not reliably visible in a normal backscatter profile but is able to play an important role for e.g. cloud development.

5 Conclusions and outlook

The DIAL technique provides the observation of atmospheric water vapor with a high time and height resolution in the lower troposphere. Simultaneously it provides high resolution images of the aerosol distribution, which is an excellent indicator for the atmospheric stratification. These data can be used to determine the height of the turbulent ABL or the stable residual layer with the same time resolution. Consequently the exploration of ABL development is possible. The analyses show a good agreement between the retrieved ABL heights in the case of a turbulent ABL but some deviations for a residual layer. That can be the result of the aerosol effect of swell and dry, with a change of the optical properties and a shift of the gradient minimum. The time series show the high variability of the ABL top height and the advantage of high temporal and spatial resolution measurements for the observation of the ABL.

The second example demonstrates clearly the importance of humidity measurements for the identification of atmospheric stratification, in particular for layers that are not aerosol loaded. The weather efficiency of this kind of layers could be observed during the measurement campaign (AFWEX) based on the development of clouds (not shown).

The high resolution of the time series of the ABL heights allows the exploration of entrainment processes as shown in Flamant et al., 1997 for a backscatter Lidar. This will produce interesting comparisons between humidity and backscatter data. In addition, the determined heights of the ABL top can be used to scale distribution functions of the humidity with height. In the near future these data will be used for the parameterisation of more realistic distribution functions in numerical forecast models.

Acknowledgement. The authors would like to thank the staff of the SGP site for their assistance and support during the measurement campaigns. Financial support through the Department of Energy's Atmospheric Radiation Monitoring Program, contract 354425-A-Q5, is gratefully acknowledged.

We are particularly grateful for the contributions of our colleagues Klaus Ertel, Friedhelm Jansen, Holger Linné, Tom Wilkerson, and Sven Deinert. It is due to their great efforts that the measurements were performed successfully.

References

[1] Bösenberg, J., 1998: Ground-based differential absorption lidar for water vapor and temperature profiling: methodology. *App. Optics*, Vol. 37, No. 18, 3845-3860.

[2] Flamant, C., Pelon, J., Flamant, P.H., Durand, P., 1997: Lidar determination of the entrain-

ment zone thickness at the top of the unstable marine atmospheric boundary layer. *Boundary-Layer Met.*, 83, 247-284.

[3] Stull, R.B., 1988: An Introduction to Boundary Layer Meteorology. Kluwer Academic.

[4] Wulfmeyer, V. and Bösenberg, J., 1998: Ground-based differential absorption lidar for water-vapor profiling: assessment of accuracy, resolution, and meteorological applications. *App. Optics*, Vol. 37, No. 18, 3825-3844.