Determination of the mixing layer height by a ceilometer

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ABSTRACT

The mixing layer height (MLH) is a key parameter in many studies of atmospheric boundary layer processes, including air quality. The MLH determines the volume in which heat, momentum and aerosols are transported from and to the surface due to turbulent mixing. Generally, there is a strong decrease in aerosol concentration at the transition from the polluted mixing layer to the relatively clean free atmosphere. The presence of aerosol can be detected in the backscatter profiles of LIDAR systems. A wavelet algorithm for the routine determination of MLH from the commercial Vaisala-Impulsphysik LD-40 cloud ceilometer was recently developed at KNMI [1] and is currently evaluated within a project of the Dutch BSIK program “Climate changes Spatial Planning”.

MLH estimates obtained from this algorithm applied to data from the RIVM backscatter lidar and a Leosphere ALS-450 lidar are shown and evaluated with MLH estimates from a wind profiler and radiosondes. All these systems were operated at the Cabauw Experimental Site for Atmospheric Research (CESAR).

1. INTRODUCTION

During the past few decades various methods have been developed to detect the mixing layer height from ground-based remote sensing observations. A comprehensive overview of the most commonly used measurement platforms and their advantages and disadvantages is presented in [2] and [3]. Lidar systems have been recognized as suitable instruments to detect the boundaries of aerosol layers. Other commonly used instruments for the MLH detection are SODARs, wind profilers and radiosondes.

A ceilometer is a commercial lidar system that is primarily used for the detection of cloud base heights for aviation and meteorology. It transmits laser pulses and measures the backscattered signal. The time interval between transmission and reception of the signal determines the altitude of the scattering particles. Since aerosols are mainly emitted at the surface, the aerosol concentration in the boundary layer is in general higher than in the free atmosphere. Therefore, a (strong) negative gradient in the measured backscatter profile generally marks the top of the mixing layer. It is however not trivial to distinguish unambiguously between the top of the mixing layer and other features in the backscatter profile that show a strong negative gradient signature, like elevated aerosol layers.

Several methods exist to determine the mixing layer height from lidar backscatter profiles, based on e.g. the vertical gradient and/or temporal variance [4], fitting an idealized profile [5], or image processing/pattern recognition techniques. Wavelet transforms are also commonly used in recent studies on MLH estimation from lidar systems [6].

At KNMI we developed and evaluated a wavelet-based algorithm for the routine determination of the MLH from the Vaisala LD-40 ceilometer. The LD-40 is operated at about 35 locations in the meteorological observation network in The Netherlands. A data set containing six years of backscatter profiles (2000-2005) from the LD-40 at the KNMI test field in De Bilt was analyzed in [1] for an evaluation of the performance of the MLH algorithm. It was found that the overall detection rate of the mixing layer height is between 43% in January and 68% in June. The most important reason for the lower detection rates during the winter months is the larger amount of meteorological conditions, like precipitation, fog and clouds, which inhibit a successful MLH detection. The monthly mean diurnal cycle shows the expected shape of the growth of a convective mixing layer, with a marked annual cycle of the amplitude of the diurnal variation. However, the monthly mean MLH during daytime observed for spring and summer months is lower than expected. This is related to the inability of the algorithm to detect most of the deep mixing layers heights because the signal-to-noise ratio of the backscatter profile rapidly decreases with height.

In this study, it is explored whether application of the ceilometer MLH algorithm to other lidar data available from collocated instruments at CESAR is feasible, in order to obtain more reliable MLH estimates.

2. INSTRUMENTS

2.1 Vaisala LD-40 ceilometer

The Vaisala LD-40 operates at a wavelength of 855 nm [7]. The backscatter profile is the average of the returns from approximately 65,000 pulses emitted every 15 s. The LD-40 has a measurement range of 25 to 43,000 ft and a resolution of 25 ft. The sensor also reports up to three cloud bases (C1, C2 and C3), vertical visibility (VV), maximum range of detection (CX) and a precipitation index (PI). These additional parameters are derived from the backscatter profile by the internal LD-40 software. The backscatter signal is corrected for incomplete overlap up to a height of 1125 m.

2.2 RIVM Backscatter Lidar

The 1064 nm HTRL backscatter lidar of the Centre for Environmental Monitoring of the National Institute for

Public Health and the Environment (RIVM) has operated automatically at Cabauw since 2001. The measurement range is from 150 m up to 15 km, with a vertical resolution of 3.75 m. A measurement is taken every 5 minutes, consisting of ten averaged profiles that are obtained from averaging 25 laser shots each. This takes about 30 s after which the instrument waits for the next 5 min. interval. A cloud screening routine generates a cloud base estimate for each interval.

2.3 Leosphere ALS-450 lidar

A Leosphere ALS-450 UV lidar (353 nm) is operated by KNMI at CESAR since mid 2007. However, due to technical problems with the lidar, the availability since the introduction is limited. Backscatter profiles are reported every 30 s in the range from 100 m to 20 km, with a resolution of 15 m. A depolarization channel is also available.

2.4 Vaisala LAP-3000 wind profiler

KNMI operates a 1290 MHz Vaisala LAP-3000 wind profiler/RASS (Radio Acoustic Sounding System) at Cabauw since July 1994. The profiler takes measurements in 5 different beam directions. Most important measurements of the wind profiler are wind speed, wind direction, vertical wind velocity and virtual temperature fields (RASS). An estimate for the boundary layer height and a quality score for the two operational modes are made automatically every 30 minutes by the algorithm described in [8], which uses both the profiler backscatter profiles and the width of the Doppler velocity spectrum.

3. METHODOLOGY

The ceilometer MLH algorithm described in [1] uses a Haar wavelet function to locate the strong negative gradient in the aerosol backscatter at the top of the mixing layer. The algorithm is applied to the 10 minute averaged range and overlap corrected backscatter profile from the LD-40 on a vertical domain of 90-3000 m. For each profile two candidate aerosol layer top heights can be detected, hereafter called MLH1 and MLH2. This gives the opportunity to detect the mixing layer height and the top of a secondary aerosol layer, e.g. an advected aerosol layer or the residual layer.

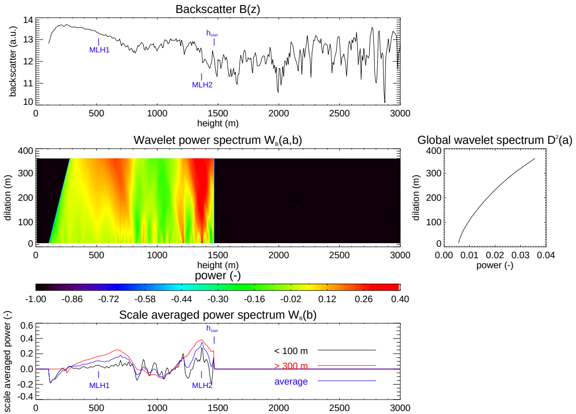

Figure 1. *Results of the wavelet analysis for the 10 min. averaged backscatter profile B(z) measured in De Bilt at 10 UTC on August 29, 2005. The profile of the scale averaged power spectrum (lower panel) is used to derive MLH1 and MLH2 estimates.*

The height where the signal-to-noise ratio (SNR) drops below 1, is used as the stop level h_{SNR}. The upper range of the MLH algorithm is restricted by the lowest value of h_{SNR} and the ceilometer parameters C1, VV and CX.

The Wavelet MLH method uses the scale averaged power spectrum profile of the Haar wavelet transform with 24 dilations between 15 and 360 m and step size 15 m, as illustrated in Figure 1. The top of the first layer (MLH1) is triggered at the first range gate for which this parameter shows a local maximum, exceeding a threshold value of 0.1. MLH2 is optionally determined in the height range between MLH1 and the upper boundary of detection. In case more valid maxima are found the largest is reported as MLH2.

A quality index has been introduced to give an estimate of the reliability of the derived MLH. The quality ranges from good (●) to weak (●) and poor (●) and is derived from the difference in averaged backscatter just below and above the MLH.

4. RESULTS

4.1 LD-40 case studies

The backscatter contour plot and resulting MLH estimates for Cabauw on July 27, 2002 are shown in Figure 2a.

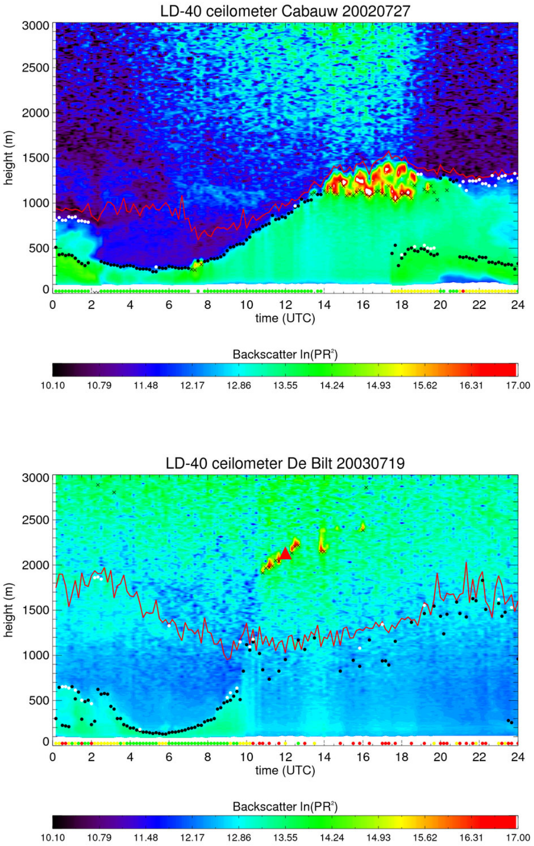

Figure 2. *LD-40 backscatter data and derived MLH and h_{SNR} for Cabauw on July 27, 2002 (top) and De Bilt on July 19, 2003 (bottom) The quality indices are represented by the dots above the time axis.*

The development of a convective mixing layer can clearly be observed, with a sharp and strong decrease in aerosol backscatter between the mixing layer and the free atmosphere, resulting in a MLH1 (●) time series with low variability between successive points. Note that the developing cumulus clouds around 14 UTC cause a termination of the algorithm at the height of the first cloud base C1 (x). During the first two and last three hours of this day, the secondary MLH2 (○) coincides with the top of the residual layer.

In Figure 2b a deep convective boundary layer case is presented that occurred in De Bilt on July 19, 2003. Whereas a well defined aerosol layer is observed until approximately 10 UTC, the MLH estimates in the period thereafter are strongly variable both for MLH1 and MLH2 and have a poor quality. These estimates coincide with a lowered height of the SNR stop level (–), which is only about 1200 m during the afternoon. The radiosonde estimate of the MLH at 12 UTC (▲) is approximately 2100 m, located near the cloud bases which are detected by the LD-40. Hence the vertical range for MLH detection is clearly limited here by the low SNR of the backscatter profile in the mixing layer.

4.2 Comparison with other CESAR instruments

Time series of the mixing layer height (MLH1) derived for the LD-40 (○) and the RIVM backscatter lidar (●) at Cabauw on April 1, 2009, are presented in Figure 3 together with the 5 min. range corrected RIVM backscatter contours and corresponding SNR height (–). Generally, the MLH estimates show good agreement on the detection of the shallow MLH during the night and the convective MLH in the afternoon, located around 1000-1200 m. The MLH detection is sometimes impossible for both systems because of shallow cumulus clouds that arise on top of the boundary layer in the period 11-15 UTC. The correspondence with the wind profiler estimates (●) is promising. Note that the backscatter signal of the RIVM lidar shows a significant wave pattern in the morning, due to an electronic artifact, which was found to deteriorate the MLH estimation on some days.

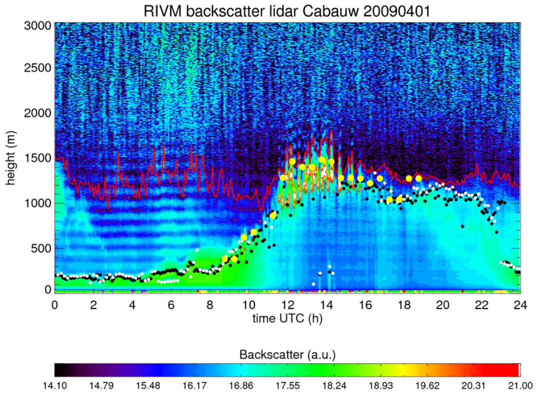

Figure 3. *RIVM backscatter data and derived RIVM and LD-40 MLH for Cabauw on April 1, 2009.*

All simultaneous 30 min. MLH estimates by the LD-40, RIVM lidar and wind profiler at Cabauw in April 2009 (N=1044) are presented in Figure 4. Because simultaneous availability of the lidar estimates is required here, ambiguous detections in e.g. cloud layers or precipitation are omitted. It can be seen that the LD-40 and RIVM lidar agree well on the expected shape related to the convective growth of the MLH for the period 08-17 UTC. However, the retrieval on RIVM lidar data seems to overestimate the MLH at night, with values that are on average 100-200 m higher than for the LD-40 data. Furthermore, the boundary layer height inferred from the LAP-3000 wind profiler shows a plausible shape for the daytime evolution. Nighttime estimates of the profiler algorithm showed large scatter and were considered not to be useful.

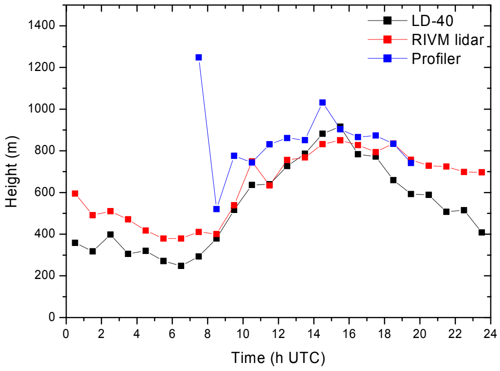

Figure 4. *Monthly mean diurnal cycle for LD-40 and RIVM MLH1 and daytime wind profiler MLH estimates at Cabauw in April 2009.*

Two cases with deep convective mixing layers during the EUCAARI-IMPACT campaign, held in Cabauw in May 2008, are shown in Figure 5. During this campaign, the RIVM backscatter and Leosphere lidar and the LAP-3000 wind profiler were operated continuously and RS92 radiosondes were launched two or three times a day. Unfortunately, the LD-40 in Cabauw can not be used for MLH estimation in this month. Hence the LD-40 MLH1 estimate (○) for De Bilt is included, located approximately 30 km northeast of Cabauw.

The graphs show the RIVM lidar backscatter profiles and MLH1 (●), together with the SNR height (–) and corresponding quality indices above the time axis. It is evident that the SNR for the RIVM lidar also decreases too strongly with height to detect the deep convective mixing layer heights for these days. Most MLH1 values in the afternoon are of poor quality and do not exceed 1000-1200 m, whereas the wind profiler (●) and radiosonde (▲) estimates indicate depths of 1000-1500 on the 5th and 1500-2000 m on the 8th.

The MLH algorithm is applied as well to the 30 min. backscatter profile of the Leosphere lidar (●). No cloud screening or SNR analysis is applied yet, but still the Leosphere already shows promising results for these days. It nicely follows the convective growth of the boundary layer and correlates well with the wind profiler and radiosonde estimates during daytime. The Leosphere detects the residual layer, but misses the low MLH in the morning. Note that the Richardson bulk method described in [9], with a critical value R_{ibc}=0.21, is used here to make a thermodynamic estimate of the boundary layer height from the radiosonde profile.

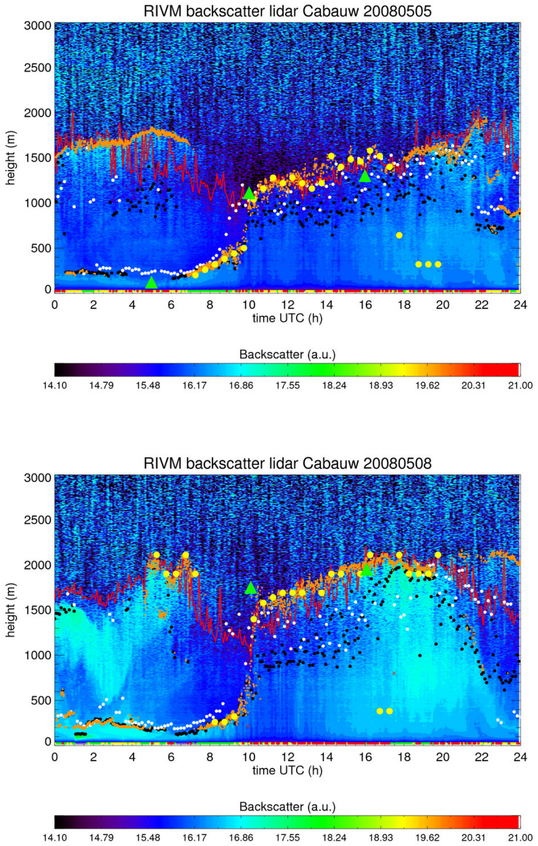

Figure 5. *RIVM backscatter data and derived MLH for Cabauw on May 5 (top) and May 8 (bottom), 2008. Also depicted are the wind profiler (●), radiosonde (▲) and Leosphere (●) estimates.*

5. CONCLUSIONS

A wavelet method was developed by KNMI to derive the mixing layer height from backscatter profiles measured with a Vaisala LD-40 ceilometer. A feasibility study showed that the method gives satisfactory results in case the mixing layer grows not too deep and contains enough aerosol [1]. Currently this algorithm is evaluated for six locations in KNMI's meteorological observation network where backscatter profiles are stored. The ceilometer wavelet MLH algorithm has also been successfully applied to measurements of the backscatter lidar of RIVM and the Leosphere ALS-450 lidar of KNMI, both operated at Cabauw. The algorithm can be used for both systems, although some limitations exist.

The accuracy and reliability of the MLH detection by the lidar systems is strongly related to the variability of the aerosol backscatter signal in height in the mixing layer. Especially in strong convective conditions in spring and summer, the vertical range of MLH detection with the current method applied to the LD-40 and RIVM backscatter lidar is limited due to noise levels that are too high. Furthermore, the results of the MLH algorithm applied to the RIVM lidar shows similar problems as recognized for the LD-40, i.e a correct MLH detection is problematic during the afternoon decay of the convective mixing layer with large amounts residual aerosol and in very shallow (nocturnal) boundary layers. The mean diurnal cycle analyzed for April 2009 for both systems shows good correspondence for the daytime evolution of the convective mixing layer.

The quality of the RIVM backscatter lidar data and the cloud screening requires improvement before automatic use of the MLH algorithm is useful. Applying the wavelet MLH algorithm to 30 s data of the Leosphere UV lidar shows promising first results, especially where the other systems fail to determine the growth of deeper convective mixing layers. The agreement with wind profiler and radiosonde MLH during daytime is good. Further research into an overlap correction for the lowest 100 m and derivation of the extinction profiles should give insight in the added value for obtaining a robust and continuous MLH estimate at Cabauw.

6. ACKNOWLEDGEMENTS

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