

TOWARDS A CLOUD CEILOMETER NETWORK REPORTING MIXING LAYER HEIGHT

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ABSTRACT

The Royal Netherlands Meteorological Institute (KNMI) developed and evaluated an algorithm for the derivation of the mixing layer height (MLH) from the backscatter profiles of a commercial cloud ceilometer. Although a ceilometer is not designed to measure absolute aerosol concentrations, the aerosol signal can be observed in the backscatter profiles if the aerosol concentrations are not too low. Since aerosol is well mixed in the atmospheric boundary layer and concentrations decrease rapidly above this layer, the aerosol gradient can be used to estimate the MLH. The evaluation of the algorithm for the Vaisala LD40 ceilometer showed that the MLH can be derived in about 55% of the cases of which 25% is of a good quality. The MLH determination is poor in case of a very low (<300m) or a high (>1250m) MLH with low aerosol concentrations, in both situations the bi-axial ceilometer has limited sensitivity. In 2007 and 2008 a field test has been conducted during which backscatter profiles at 5 locations throughout the Netherlands were archived. The MLH is derived off-line and made available to users. After acceptance of the MLH product by the users, the MLH could be made operational. KNMI operates more than 30 ceilometers in the national meteorological network. Hence a near real-time geographic overview of the MLH can be made available that is not only of importance for the meteorological community, but also for air quality forecast.

1. INTRODUCTION

Cloud ceilometers can by now be considered as part of the standard meteorological instrumentation. Ceilometers are used for synoptic and/or aeronautic purposes, either as an aid for the observer for the determination of cloud base height or as part of a fully automated weather observation system. Ceilometers are commercially of the shelf instruments that can be operated continuously and require little maintenance. Ceilometers are generally easy to use, but when working with fully automated cloud information one needs to keep in mind that the ceilometer performs basically a point measurement so that the spatial representativity of cloud information derived from time series of ceilometer data can be poor. In addition, the detection of high cirrus clouds is still problematic due to the limited sensitivity of ceilometers and the detection of the cloud base during precipitation also remains a challenge since precipitation masks the signature of the cloud base in the backscatter profile (cf. Wauben et al., 2006). Sometimes, medium and low clouds can also be missed or falsely reported by the ceilometer as compared to a human observer when the cloud or moist layer is near the visual detection threshold. The verification of the performance of a ceilometer against a well defined cloud base, or using either a hard target or a cloud simulator only ensures the correct operation of the instrument. These tests can, however, not be considered a verification of the absolute calibration, although a ceilometer generally monitors and adjusts the power output of the laser and the sensitivity of the receiver. For a detailed verification of the performance of a ceilometer the basic observed quantity, i.e. the backscatter profile - the received atmospheric backscatter as a function of height, should be considered. Unfortunately a ceilometer is not that powerful and sensitive that the constant molecular background can be used for that purpose. The backscatter profile of a ceilometer can, however, still be useful to monitor the technical performance of the sensor.

Users and researchers at KNMI have for some years stated their interest in receiving the backscatter data of ceilometers since other information apart from the cloud base might be useful. The measurement network of KNMI and the sensor interface do not allow transmission of backscatter data because that would require the creation of many variables since array data is currently not supported. The sensor interface, however, does request the backscatter profile data from the LD40 so that it can be forwarded to systems outside the measurement network. Backscatter profiles are archived for 5 locations throughout the Netherlands since 2007 for the evaluation of the mixing layer height. In the near future the backscatter profiles of the 4 ceilometers at Schiphol airport will be made as well on a 10-minute basis in order to evaluate their usefulness for nowcasting of fog and low clouds. For the mixing layer height determination from ceilometer backscatter data an algorithm has been developed (De Haij et al., 2007). Currently the evaluation

and incorporation of this algorithm in the sensor interface is discussed with the users. Today, KNMI and its partners the Dutch Royal Air Force and Royal Navy operate 33 ceilometers, 5 of which are in a pre-operational state, and additional ceilometers will be installed at platforms in the North Sea and around Schiphol Airport for nowcasting of fog and low clouds. Figure 1 gives an overview of the current ceilometer network in the Netherlands and the expected changes in the near future. Once the mixing layer height algorithm is included in the sensor interface the mixing layer height information can be made available in near real-time for all ceilometers of the measurement network.

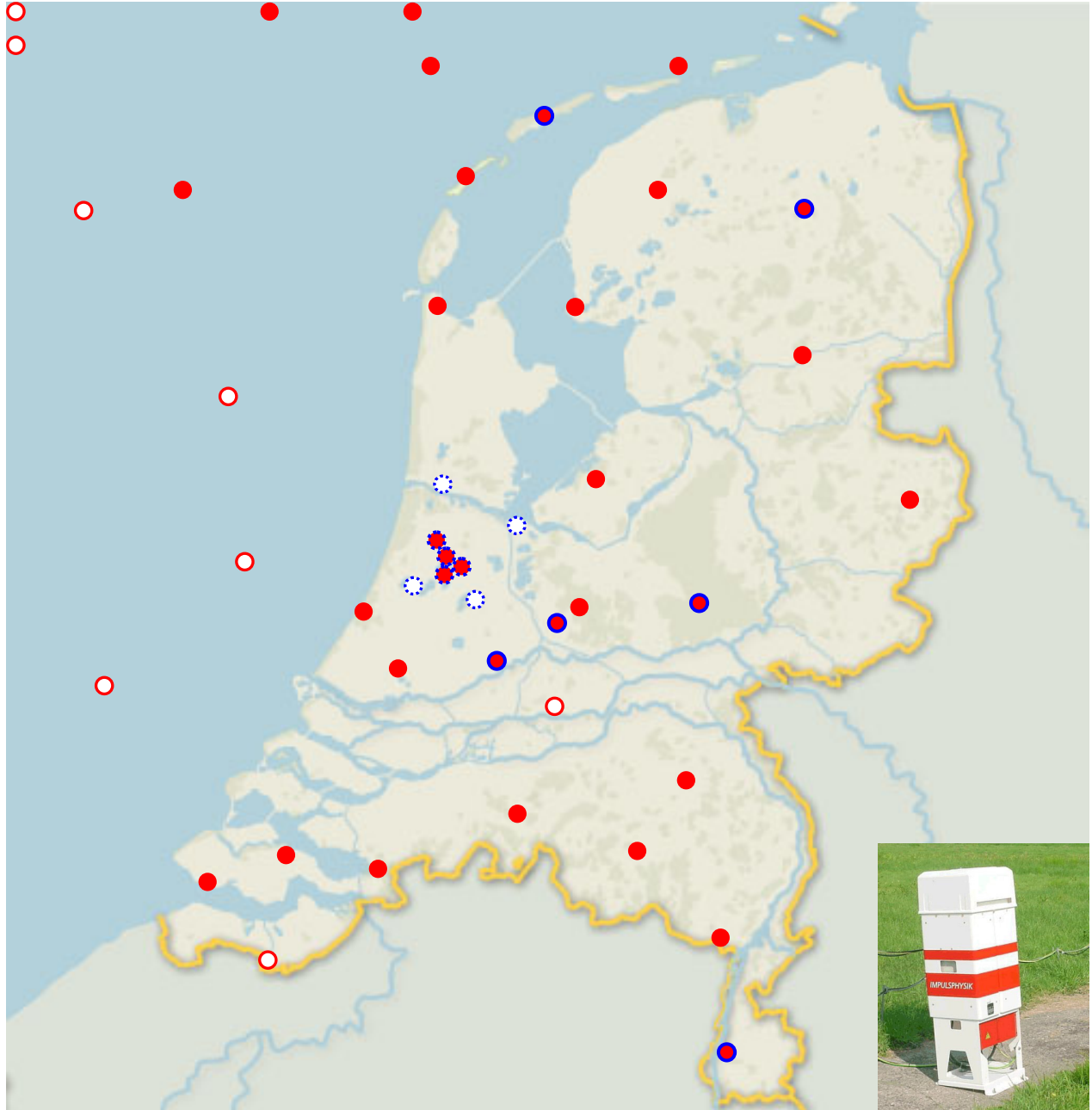


Figure 1: The locations of operational (●) and planned (○) LD40 ceilometers in the Netherlands. Blue borders denote the stations where backscatter data is currently stored (solid) or planned in the near future (dotted).

2. MIXING LAYER HEIGHT ALGORITHM

The mixing layer height (MLH) is a key parameter in studies of many atmospheric boundary layer processes, including air quality. It primarily determines the volume in which turbulence is active and into which constituents emitted near the surface are dispersed. The height of the mixing layer typically varies between 50 and 2500 m for the Netherlands, depending on, for example, the season, time of day, the synoptic situation and local conditions as orography, land use and surface roughness. As aerosols are mainly emitted at the surface, the concentration is generally higher in the mixing layer than in the free troposphere. The presence of aerosols can be detected in the backscatter profile of a ceilometer. Therefore the MLH

estimation by lidar systems is based on the detection of the sharp decrease (gradient) in aerosol backscatter at the top of the mixing layer. This decrease marks the interface between the aerosol containing mixing layer and the relatively clean free troposphere.

The ceilometer MLH algorithm (De Haij et al., 2007) applies a Haar wavelet transform to locate the strong negative gradient in the aerosol backscatter at the top of the mixing layer. The wavelet algorithm is applied to the 10 minute averaged, range- and overlap-corrected, backscatter profile within a vertical domain of 90-3000 m. Furthermore the upper range limit is restricted by the lowest cloud base and the $SNR < 1$ height. The latter is the height where the SNR (signal-to-noise-ratio) drops below 1, indicating the range for which the backscatter signal is assumed to be reliable enough for MLH estimation. The algorithm is able to report up to two mixing layer heights, referred to as MLH1 and MLH2. A quality index has been introduced to make a first estimate of the reliability of the derived mixing layer height. This index is related to the difference in backscatter of 150m layers just below and above the estimated mixing layer height. In addition, time series of the MLH detection give the user information on the consistency of the results. Other commonly used instruments for the estimation of the mixing layer height are SODARs (SOund Detection And Ranging), wind profilers and radiosondes (cf. e.g. Seibert et al., 2000). These instruments use gradients in the acoustic refractive index, radar refractive index and in the temperature and humidity profiles respectively, to determine the MLH. De Haij et al. (2007) gives an evaluation of the MLH algorithm applied to LD40 backscatter data versus some of these alternative methods.

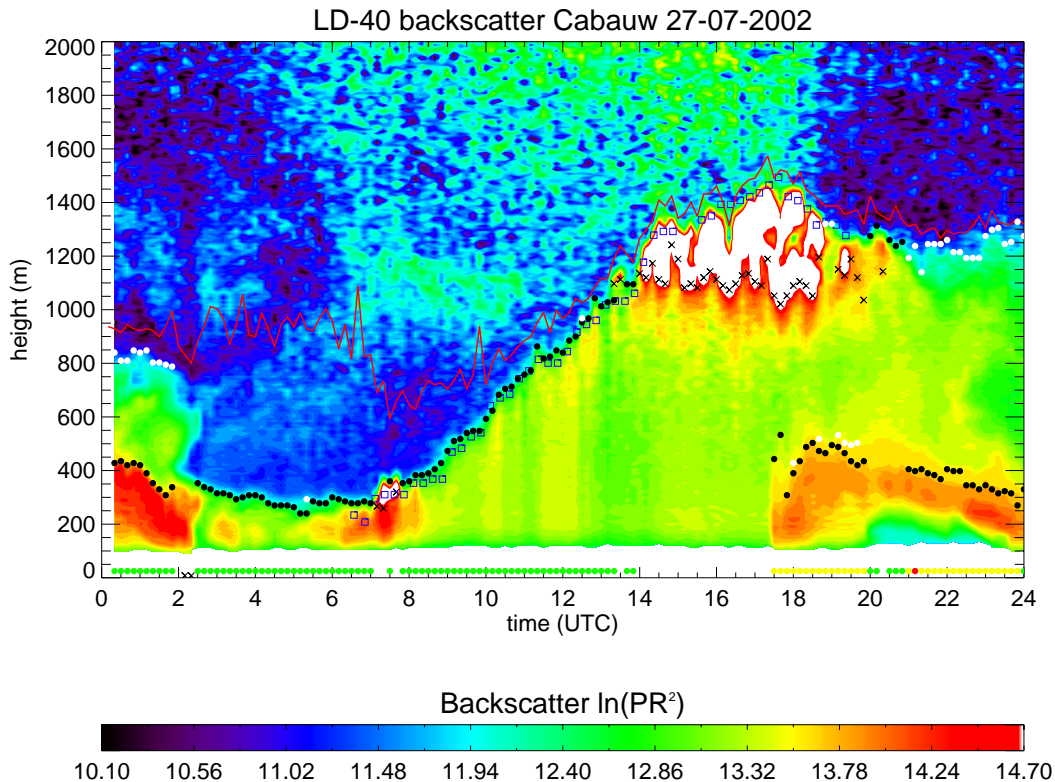


Figure 2: LD40 backscatter contours and derived mixing layer heights for Cabauw on July 27, 2002. Legend: MLH1 (black dot), MLH2 (white dot), wind profiler MLH (blue square), $SNR < 1$ height (red line). The MLH1 quality indices are represented by the dots below the contours (green='good', yellow='weak', red='poor').

The backscatter contour plot and resulting MLH estimates for Cabauw on July 27th, 2002 are shown in Figure 2. The development of a convective mixing layer is clearly observed, with a sharp and strong decrease in aerosol backscatter between the mixing layer and the free atmosphere. The resulting MLH time series shows a low variability between successive points. The build up of the convective layer is disturbed around 1400 UTC by the development of cumulus clouds on top of the mixing layer. These clouds restrain the algorithm from detecting the mixing layer height successfully. Around 1730 UTC a new aerosol layer is observed, which extends between 200 and 500 m above ground level during the evening. The occurrence of this layer coincides with a change in wind direction and marks the advection of an air mass containing aerosol from a different source area. During the first two and last three hours of this day, a secondary MLH is detected above the elevated aerosol layer. This secondary MLH is associated with the top of the so-called residual layer.

Six years of backscatter profiles (2000-2005) from the LD40 ceilometer at the KNMI test field in De Bilt have been used to assess the overall performance of the ceilometer MLH algorithm with respect to the monthly availability and reliability of the MLH estimates. The monthly mean diurnal cycle of the mixing layer heights and the SNR<1 height for January, April, July and October are shown in Figure 3, representative for the winter, spring, summer and autumn season, respectively. The typical shape of the development of a convective mixing layer is observed, as well as an evident annual cycle of the amplitude of the diurnal variation. However, the monthly mean MLH1 during daytime observed for spring and summer months is lower than expected. Further research showed that the ceilometer is unable to detect most of the deep mixing layers heights, especially under strong convective conditions. One must keep in mind that the ceilometer MLH algorithm needs sufficiently high aerosol concentrations in order to be able to derive a MLH. Since the backscatter signal of aerosol is much less than for clouds, the sensitivity and hence the range of a ceilometer for MLH detection is much less than for cloud base detection. The overall detection rate for MLH1 is between 42 % (December) and 60 % (June). However, the relative contribution of 'Weak' and 'Poor' detections increases with increasing detection rate. Hence, the higher daytime values of mixing layer height as observed for April and July in Figure 3 generally coincide with lower quality indices. This is related to the enhanced vertical variability in the backscatter signal and hence the increased chance on a faulty MLH detection on a less pronounced jump in the aerosol backscatter. The most important reason for the lower detection rates during the winter months is the frequent occurrence of weather conditions, like fog, rain and clouds, which inhibit a successful MLH detection. Note that in case of boundary layer clouds the cloud base height can sometimes be used as an approximation for the MLH.

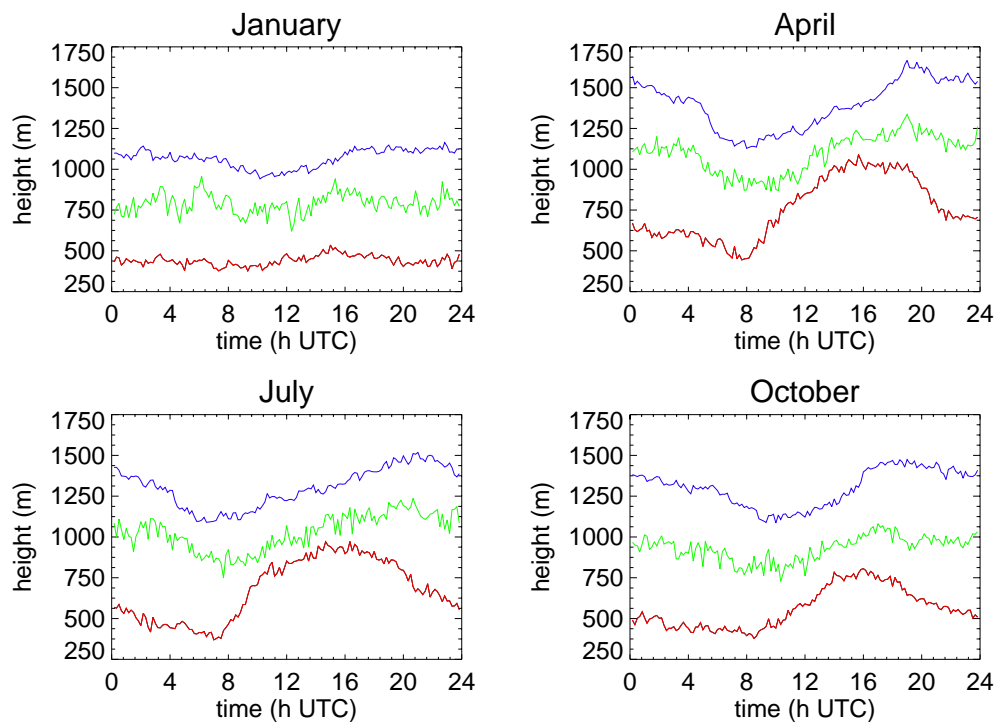


Figure 3: Monthly mean diurnal cycle in January, April, July and October for De Bilt (2000-2005), of MLH1 (red), MLH2 (green) and the SNR<1 height (blue).

An example of the MLH ceilometer network that is operated in the Dutch BSIK-ME2 project is given in Figure 4. Spatial and temporal differences in the evolution of the mixing layer height can be observed that are related to the presence of clouds, and local differences. With northerly winds the MLH observed on the island Terschelling often deviates significantly from that of the other locations. Also the onset and growth rate of the MLH can show local variations that are related to the presence of clouds and moisture. Furthermore differences in the backscatter values can be observed that are related to local aerosol levels, but also instrument sensitivity.

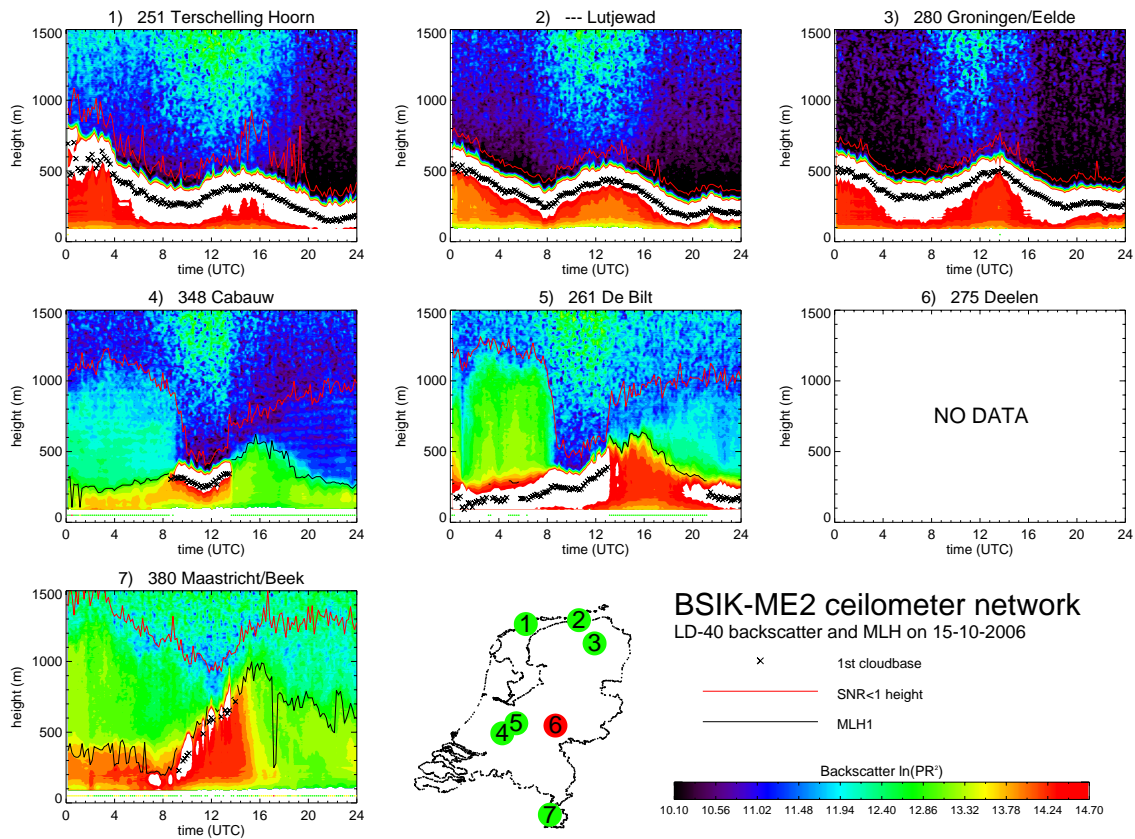


Figure 4: LD40 backscatter contours and the estimated mixing layer height for the BSIK-ME2 ceilometer network on October 15, 2006.

4. CONCLUSIONS AND OUTLOOK

An automated method was developed to derive the MLH from the backscatter profiles measured with a Vaisala LD40 ceilometer. The detection of the MLH is based on the (strong) decrease in aerosol backscatter at the transition from the polluted mixing layer to the relatively clean free atmosphere. Although the detection is feasible by the method presented, limitations exist. The reliability of the MLH detection is strongly connected to the variability of the aerosol backscatter signal in height in the mixing layer. Profiles that show a fairly constant and sufficient amount of aerosol backscatter generally give a reliable detection of MLH. This mainly occurs when the mixing layer grows not too deep, e.g. in a shallow wintertime mixing layer. Furthermore, problems sometimes occur during the afternoon decay of the convective mixing layer or for the nocturnal mixing layer. The problems encountered are partly caused by instrumental limitations. As commercial ceilometers were originally developed for cloud base detection, their sensitivity to aerosols is much lower compared to research LIDARs. Users must keep in mind that the presence of atmospheric constituents may be also caused by other sources than local ones. The quality index gives a good indication of the reliability of the MLH detection. In addition, time series of the MLH detection give the user information on the consistency of the results.

The backscatter profiles have also been used for other purposes. Firstly the backscatter values can be used as a check of the sensitivity of the instrument. Using the backscatter for this purpose probably leads to a detection of faulty ceilometers before the malfunction is evident from the cloud base data. Furthermore the backscatter signal gives information on instrument characteristics, e.g. the overlap function of the bi-axial optical system of the LD40. This is illustrated in Figure 5, which shows the averaged backscatter profiles of 6 ceilometers during situations with small backscatter values homogeneously increasing with altitude below 500m and without clouds below 1000m nor precipitation. The agreement with the standard Vaisala LD40 overlap factor is good, except below 125m where the output resolution of the backscatter data is too poor, but individual instruments can vary up to $\pm 20\%$. Possibly, the signal to noise ratio as a function of altitude might be evaluated and monitored in a similar way.

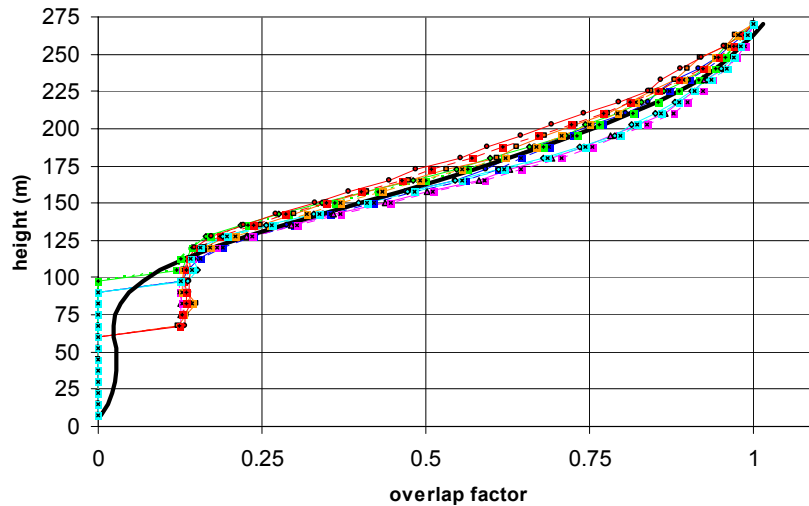


Figure 5: Overlap factors of 6 LD40 ceilometers derived from backscatter data and the standard Vaisala LD40 overlap function.

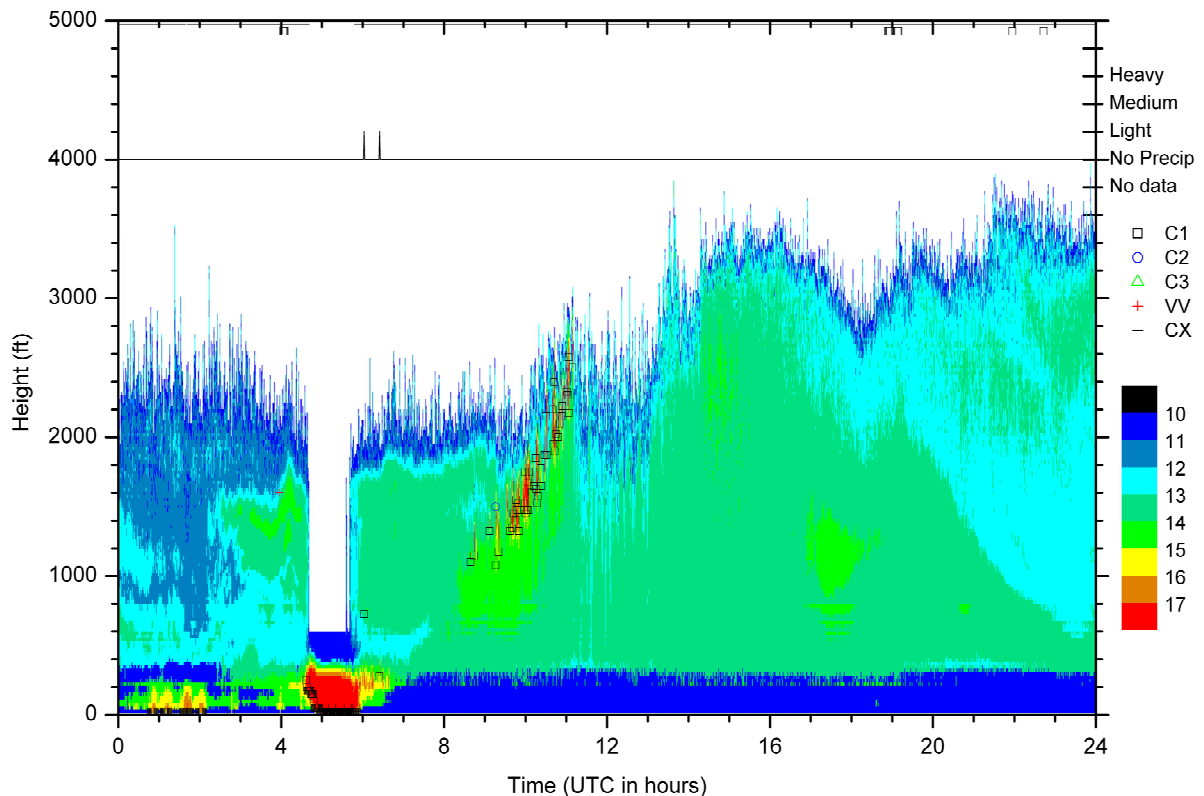


Figure 6: LD40 backscatter $\ln[P(r)*r^2]$ during fog for De Bilt on September 11, 2001. Backscatter is not given above the SNR=1 height and the first cloud base is denoted by a square.

An example of the backscatter profile during fog is given in Figure 6. In that case the LD40 reports a cloud base of 25ft. This occurs between 2-3UT and 5-6UT. The backscatter data indicates that the fog at 2-3UT is rather shallow since the SNR=1 height is hardly affected and some structures can be observed above the fog layer. One might even expect that the sky is clear whereas the currently used automated report would give either overcast or vertical visibility below 100ft depending on whether the MOR is more then 1km or not (Wauben et al. 2006). Around 5-6UT a situation occurs when the ceilometer cannot penetrate the fog layer and the sky is truly obscured. Both fog events show enhanced backscatter values prior and after the cloud base reports during fog. Hence the backscatter gives a forewarning of the coming fog event and information of the disappearance of the fog layer that cannot be observed in the cloud base data. Note, however, that in most cases we observed so far cases of shallow fog could not clearly be identified from the backscatter data and the onset or lifting of fog can sometimes also be observed in the cloud base data. It is not yet known whether forewarning of fog events by enhancement of backscatter values might give rise to false alarms. These issues will be investigated in an upcoming test of fog and low clouds nowcasting

techniques at Schiphol Airport. This test at Schiphol will also give more detailed information on the evaluation of the low MLH derived from the LD40 ceilometer since a SODAR is operated at Schiphol. Figure 7 shows a MLH derivation for this SODAR using the method of Emeis et al. (2008). In fact, we derived the MLH from the SODAR reflectivity data for all 4 frequencies and 3 zenith angles. Figure 7 gives the median and the range of all 12 evaluations. The latter may serve as a quality check of the SODAR MLH determinations. The case shown in Figure 7 illustrates the suitability of the SODAR for detection of a low MLH.

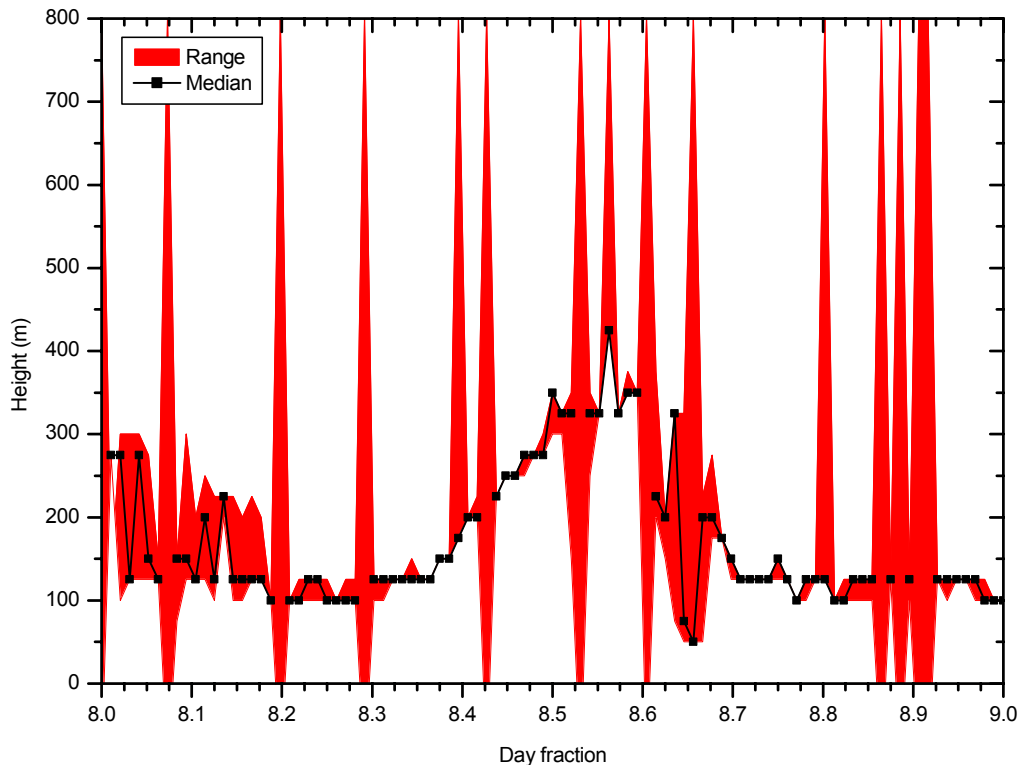


Figure 7: SODAR MLH determination for Schiphol on February 8, 2008.

This work was partly funded by the project Integrated observations and modelling of Greenhouse Gas budgets at the national level in the Netherlands (ME2), which is executed in the frame of the programme Besluit Subsidies Investerings Kennisinfrastructuur – Klimaat voor Ruimte (BSIK-KvR).

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