# Mixing layer height and air pollution levels in urban area

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## ABSTRACT

Ceilometers are applied by KIT/IMK-IFU to detect layering of the lower atmosphere continuously. This is necessary because not only wind speed and direction, but also atmospheric layering and especially the mixing layer height (MLH) influence exchange processes of ground level emissions. It will be discussed how the ceilometer monitoring information is used to interpret the air pollution near the ground.

The information about atmospheric layering is continuously monitored by uninterrupted remote sensing measurements with the Vaisala ceilometer CL51, which is an eye-safe commercial mini-lidar system. Special software for this ceilometer provides routine retrievals of lower atmosphere layering from vertical profiles of laser backscatter data.

An intensive measurement period during the winter 2011/2012 is studied. The meteorological influences upon air pollutant concentrations are investigated and the correlations of air pollutant concentrations with ceilometer MLH are determined. Benzene was detected by the department of Applied Climatology and Landscape Ecology, University of Duisburg-Essen (UDE) with a gas chromatograph during the measurement period. The meteorological data are collected by UDE and the monitoring station Essen of the German national meteorological service DWD. The concentrations of the air pollutants NO, $NO_2$ and $PM_{10}$ are provided by the national air pollution network LANUV.

**Keywords:** Air pollution, remote sensing, ceilometer, mixing layer height, volatile organic compounds

## 1. INTRODUCTION

The increased local emissions only cannot explain high air pollution episodes in urban areas, especially during the cold season. The mixing layer height (MLH), as well as wind speed and direction, are important factors which influence exchange processes of ground level emissions. It will be discussed how the knowledge of MLH is supporting the understanding of processes directing air quality. This variable controls the vertical space for rapid mixing of near-surface pollutants.

It was demonstrated that the lowest stable layer or inversion limits the vertical exchange of primary pollutants emitted at or near the surface (Schäfer et al., 2006)[1] and thus controls the near-surface pollutant concentrations. Because MLH is a consequence of vertical temperature (inversion), wind (vertical shear) and moisture profiles (strong decrease) in the lower atmosphere, remote sensing is a suitable tool to monitor MLH (Emeis et al., 2004[2]; Emeis and Schäfer, 2006[3]). Monitoring of MLH was performed like during other measurement campaigns in urban and sub-urban areas (Hannover, Munich, Budapest; see Schäfer et al., 2006[1]; Alföldy et al., 2007[4] and Schäfer et al., 2011[5]) and at the airports Zurich, Mexico City International Airport and Athens International Airport (see Helmis et al., 2011[6]) by a ceilometer. A Vaisala LD40 was operated during the campaigns mentioned before and two Vaisala ceilometers CL31 are running in Augsburg now (Emeis et al., 2012)[7]. During the campaign in Essen which is reported here a Vaisala ceilometer CL51 was applied at the weather monitoring station of Campus Essen of University Duisburg-Essen (UDE). These are eye-safe commercial mini-lidars and designed originally to detect cloud base heights and vertical visibility for aviation safety purposes. These measurements of the vertical aerosol distribution are routinely retrieved for MLH by a software which was improved continuously and compared with radiosonde data. The MLH was continuously measured by the CL51.

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## 2. MEASUREMENTS AND METHODOLOGY

The detection of MLH by Vaisala ceilometers is described in more detail in Münkel, 2007[8]. The CL51 is a compact mini-lidar with a diode laser of 910 nm wavelength capable to cover an altitude range higher than 4000 m. The lowest detectable layers are around 50 m. The instruments run in fully automated, hands-off operation mode. Laser power and window contamination are permanently monitored to provide long-term performance stability. The heights of the near surface aerosol layers and the MLH are analyzed from optical vertical backscatter profiles (Emeis et al., 2008)[9]. The minimum range resolution is 10 m. The eye-safety class is 1M. The ceilometer backscatter profiles are usually used to detect vertical visibility and cloud characteristics. To detect the heights of the near surface aerosol layers and the MLH the gradient method is used. The minima of the vertical gradient (the term 'gradient minimum' is used here to denote the steepest gradient or most negative value of the gradient) is given as an indication of a layer upper boundary and gradient minimum nearest to the ground is taken as MLH (Emeis et al., 2007)[10]. Multiple layer detection is important for air quality also if residual layers are present during the late night (examples are shown in Figure 1). Air pollutants emitted during the day before can be captured in the residual layer over night and then contribute to air quality on the next day after the nocturnal surface inversion breaks down during the morning hours. An averaging over time and height enables the suppression of noise-generated artefacts. A sliding averaging is done and minimum accepted attenuated backscatter intensities are set. The ceilometer retrieval algorithm works appropriately during nearly cloudless conditions.

A comparison of MLH retrieval results from ceilometer with those from SODAR (Sound Detection And Ranging) wind profile and RASS (Radio Acoustic Sounding System) temperature profile measurements is described in Emeis et al, 2004[2] and 2012[7] as well as in a presentation by Schäfer et al. at this conference too.

The air pollutants NO, $NO_x$, and $PM_{10}$ are provided from the monitoring air pollution network of the Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (LANUV). An urban station which is strongly influenced by traffic (Gladbecker Str., kerb site) and a station in the sub-urban background 100 m away from a highway (Schuir) are selected.

In addition to the monitoring air pollution network, in situ concentration measurements of benzene were performed at Gladbecker Str. Benzene concentration was measured every half hour by a GC955 instrument from Synspec b.v. Sampling was done during 20 min of each half hour and benzene was enriched on Tenax TR before it was analyzed by a GC-PID system.

The weather characterisation including wind speed and wind direction are taken from the weather monitoring station at Campus Essen of UDE. The Campus is located close to the city centre. The radiosonde data shown in Figure 1 - 3 were taken from the monitoring station Essen of the German national meteorological service (called Deutscher Wetterdienst, DWD) and are available in the internet: http://weather.uwyo.edu/upperair/sounding.html.

These air pollutant and meteorological measurements are the basis to study the meteorological influences upon air quality in Essen. An intensive measurement period during the winter 2011/2012 from 28/12/2011 until 17/04/2012, including benzene measurements from 28/02/2012 until 28/03/2012, was studied.

Half-hourly-mean values of benzene concentration and one-hourly-mean values of NO, $NO_2$ and $PM_{10}$ concentrations and MLH data were determined and applied for the correlation analyses of data. An estimation of the total error of the correlation values is necessary to demonstrate the reliability of the determined correlation coefficients. The concentrations of NO, $NO_x$, $PM_{10}$ and benzene are measured with a standard error in the order of 5 % ($S_1$ = 0.05) during mean urban pollution conditions. The determination of MLH from ceilometers data has an error of about 10 % ($S_2$ = 0.10) if MLH is within the detection range. Thus, the overall error of correlation between the concentrations and MLH can be estimated from the following equation

$$\text{Overall Standard Error} = 1 - \{(1 - S_1) \cdot (1 - S_2)\}$$

which is giving a value of 14.5 % for NO, $NO_2$, $PM_{10}$ and benzene. Only such correlation coefficients between concentrations and MLH which are higher than this value are significant i.e. showing dependence between these data.

# 3. RESULTS

The results of MLH detection as well as the correlations of air pollutant concentrations with MLH will be shown.

### 3.1 Mixing layer height from ceilometer measurements

At first typical daily courses of the MLH will be discussed. In Figure 1 a case with a residual layer during the late night, an increasing MLH during the day with maximum at about 6 pm and the formation of a near surface layer in the evening, so that residual layer is formed, is presented (22/03/2012). A day with similar layering and temporal variation of MLH but some clouds is shown in Figure 2 (19/03/2012). In this case clouds are thin and ceilometer algorithm is still able to determine MLH. The cloud upper boundary is taken as layer upper boundary. Figure 3 shows a day with very low clouds so that the ceilometer cannot provide information in higher altitudes above the cloud cover (28/02/2012). In this case data from radiosonde measurements were considered. Since clouds seem to be a result of surface inversion of virtual potential temperature, and vertical wind profile indicates an increase of wind speed in the height of clouds, cloud base was taken as MLH. During cloudiness the determination of MLH values were checked individually as described above and cloud base was only taken as MLH if radiosonde data give reasonable clues.

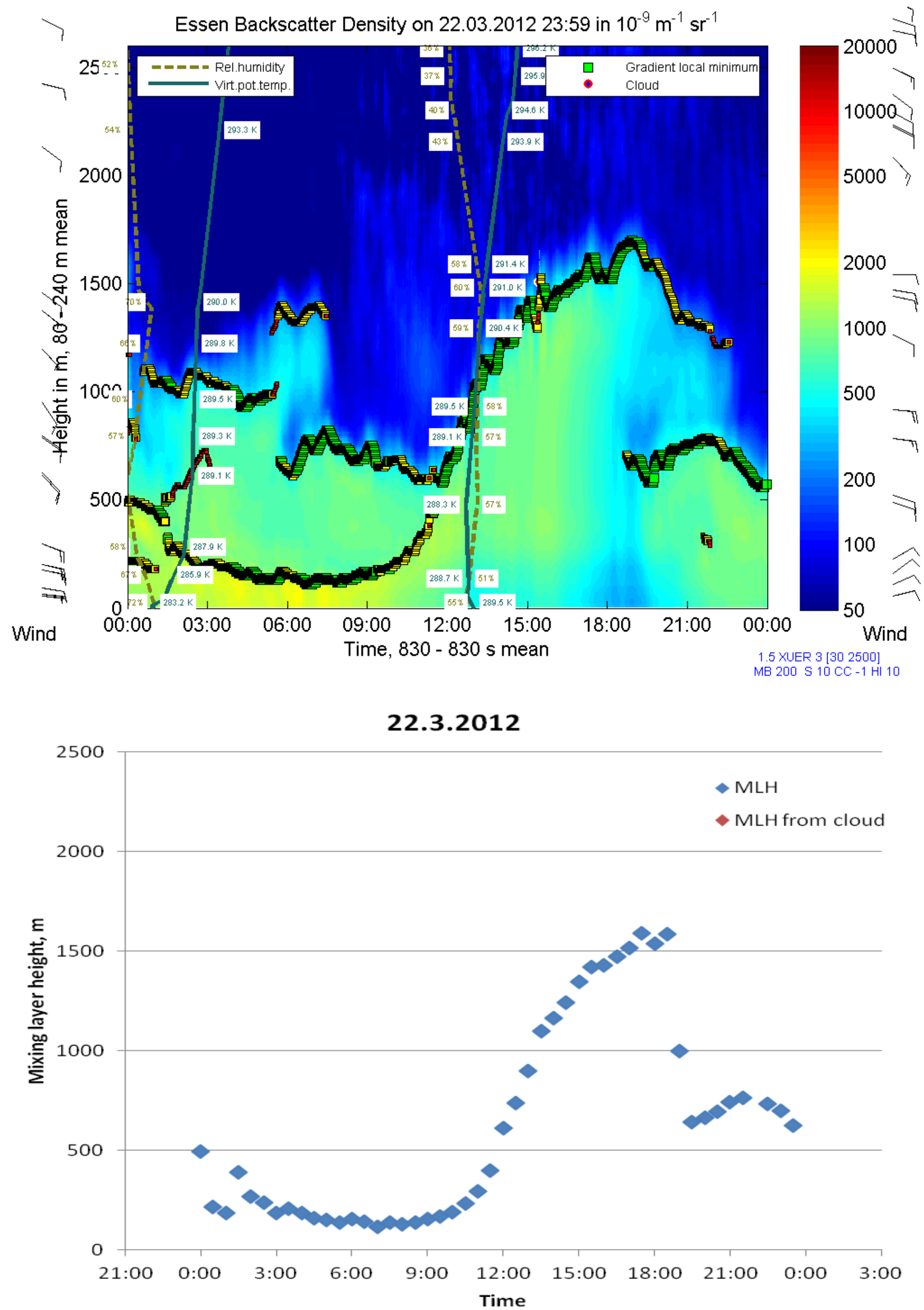
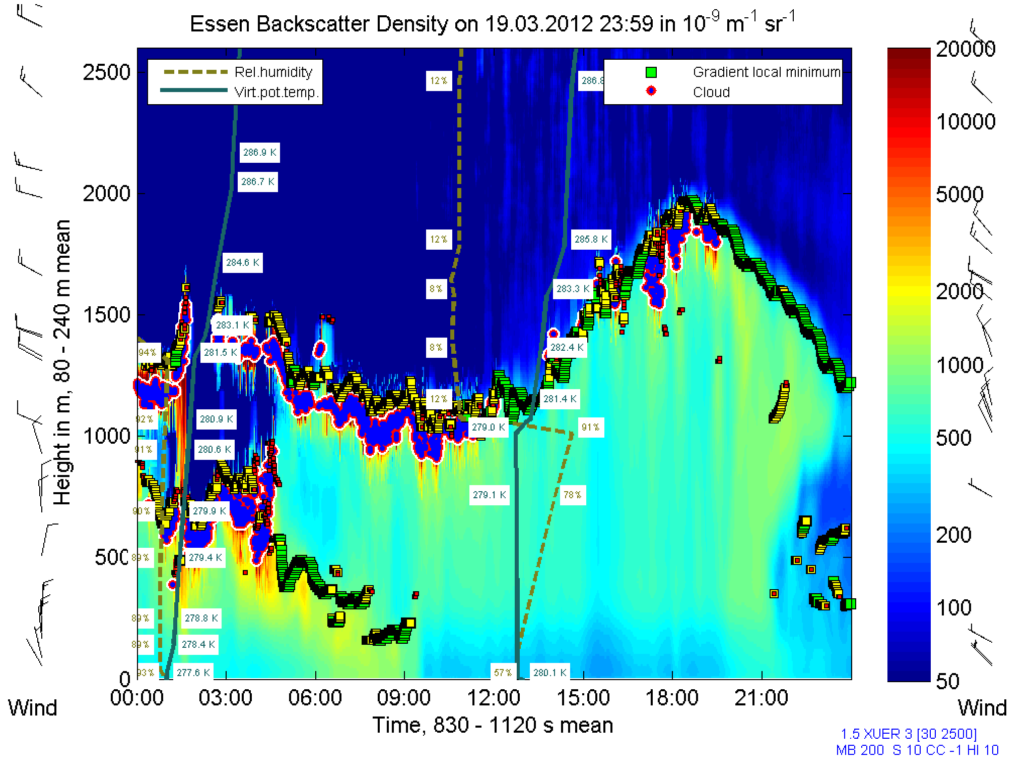



Figure 1. Daily course of ceilometer backscatter intensity together with two relative humidity and virtual potential temperature from radiosonde measurements (performed by DWD, station Essen, http://weather.uwyo.edu/upperair/sounding.html), left, and mixing layer height (MLH) determined from gradient analyses of backscatter intensity, right, on 22/03/2012. Blue diamonds are 30-min-averages of MLH.



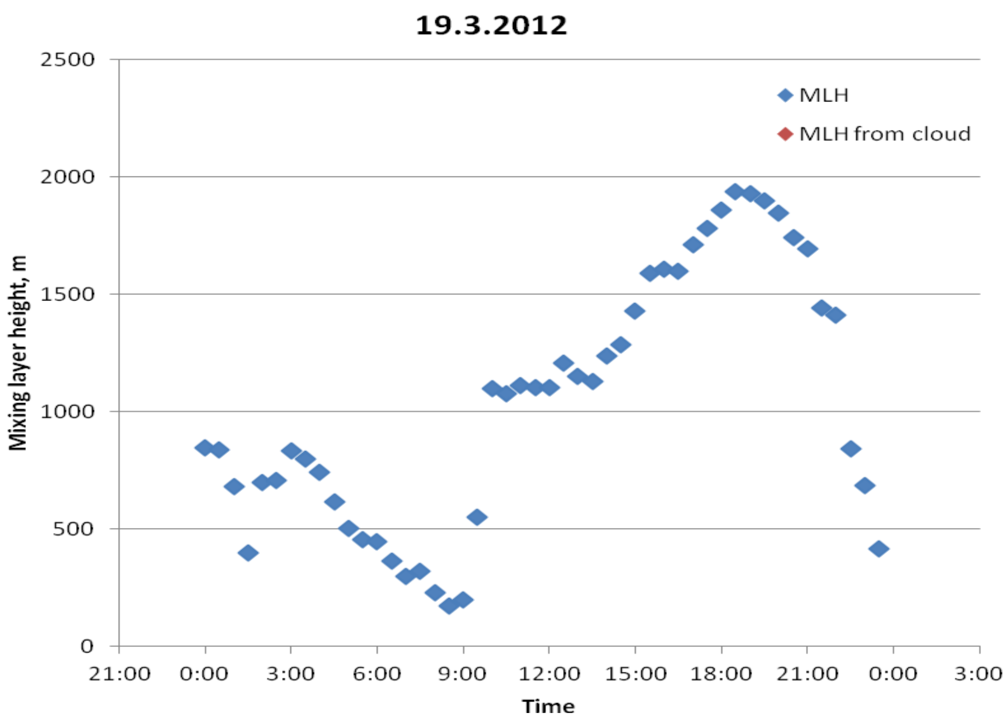




Figure 2. Daily course of ceilometer backscatter intensity detecting some clouds together with two relative humidity and virtual potential temperature from radiosonde measurements (performed by DWD, station Essen, http://weather.uwyo.edu/upperair/sounding.html), left, and mixing layer height (MLH) determined from gradient analyses of backscatter intensity, right, on 19/03/2012. Blue diamonds are 30-min-averages of MLH.

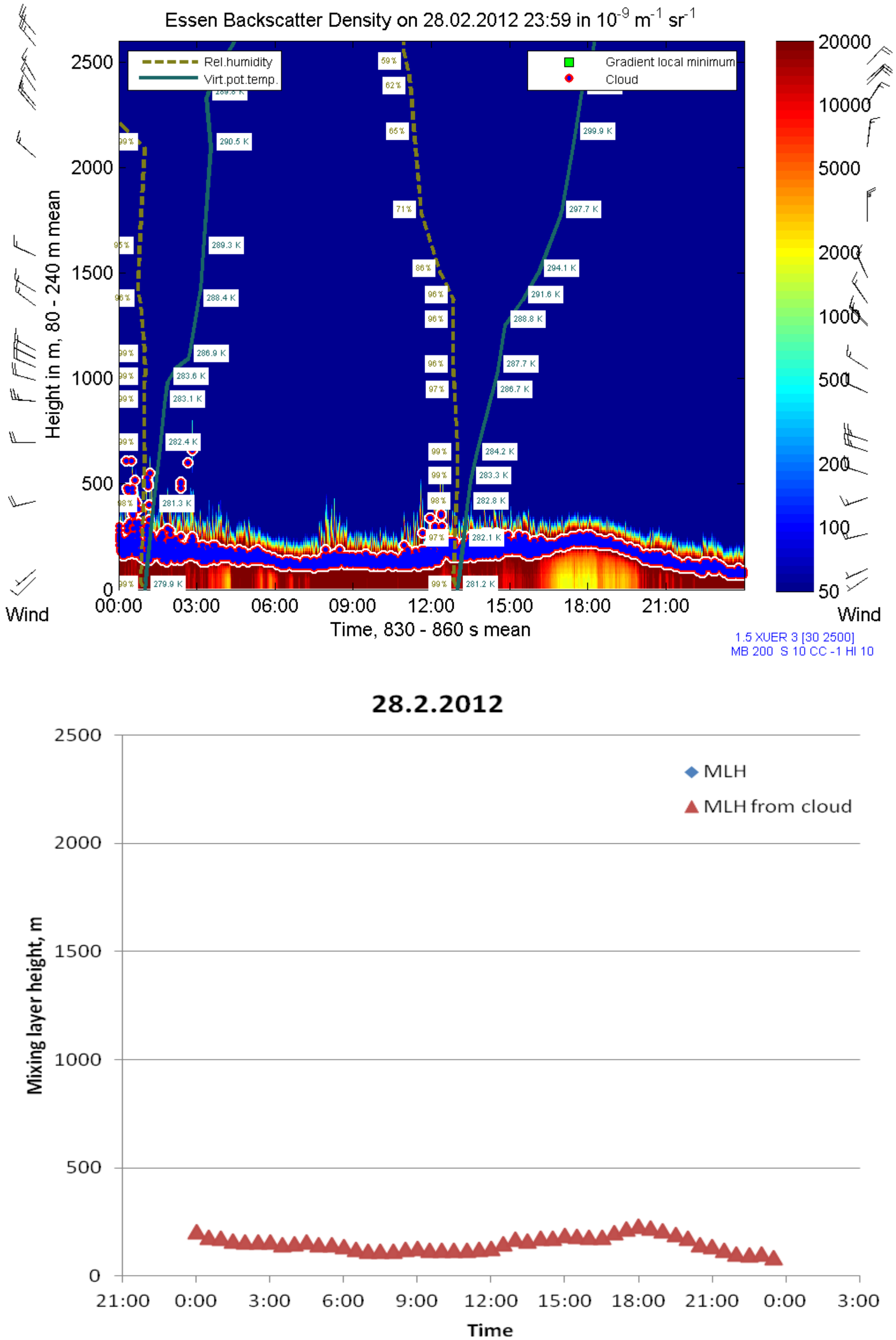
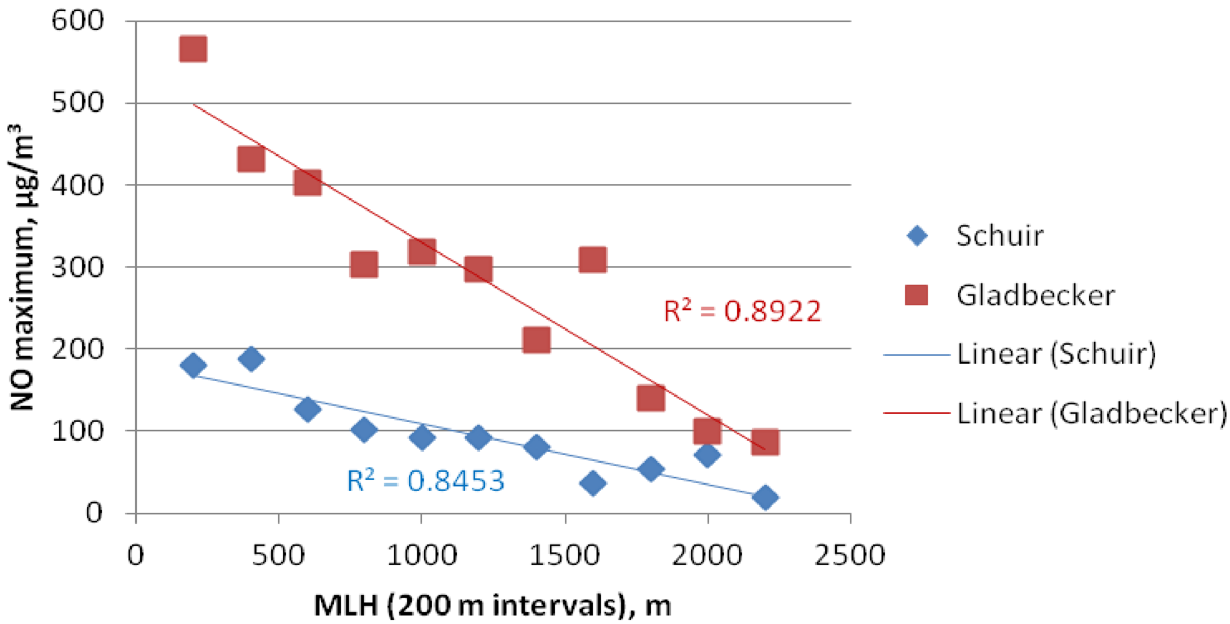
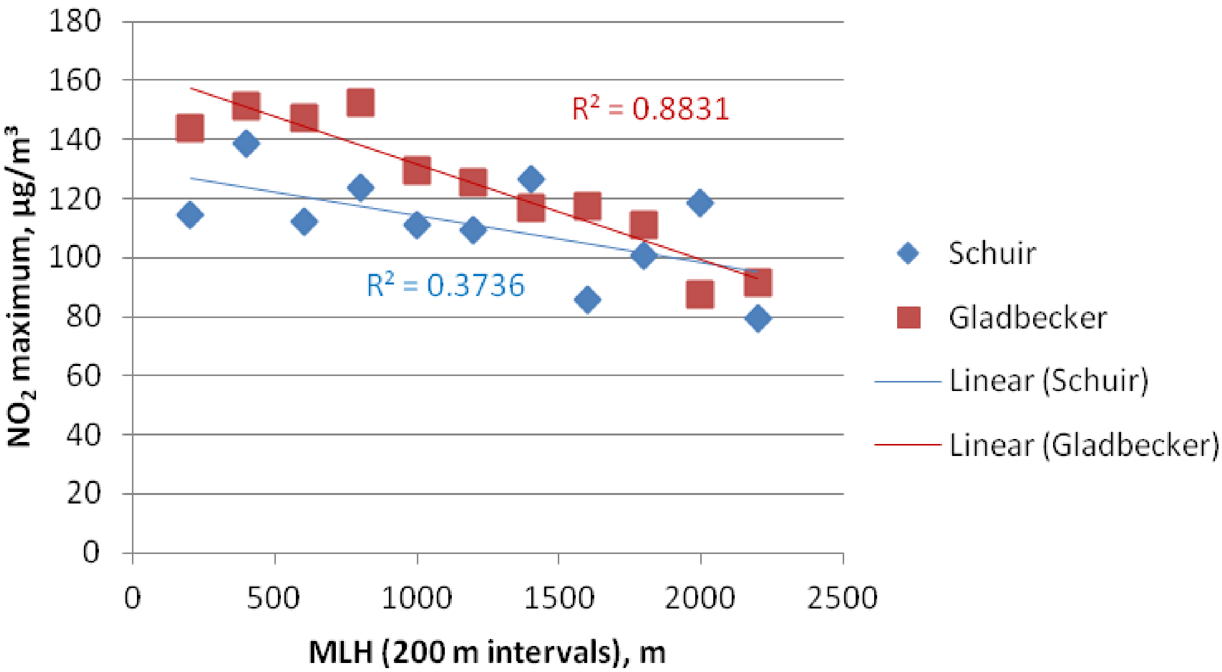



Figure 3. Daily course of ceilometer backscatter intensity together with two relative humidity and virtual potential temperature from radiosonde measurements (performed by DWD, station Essen, http://weather.uwyo.edu/upperair/sounding.html), left, and mixing layer height (MLH) determined from cloud base as a natural boundary, right, on 28/02/2012. Red triangles are 30-min-averages of cloud base taken as MLH.

### 3.2 Correlation of urban air pollution with mixing layer height from ceilometer

Applying the classification scheme of Sturges ($K = 1 + 3.32 \log N$, where K is the number of classes and N is the total number of observations; e.g. Bahrenberg, 1999[11]) 11 classes and a class width of 179 m was found so that 200 m intervals of MLH instead of the original 10 m intervals were used for the correlation analyses. The best correlations were found by using maximum concentration of pollutants within the 200 m MLH intervals during the observation period. In Figure 4 the results for the maximum of NO, $NO_2$ and $PM_{10}$ concentrations from both stations Schuir (sub-urban background site) and Gladbecker Str. (kerb site) are shown. All correlations are significant.





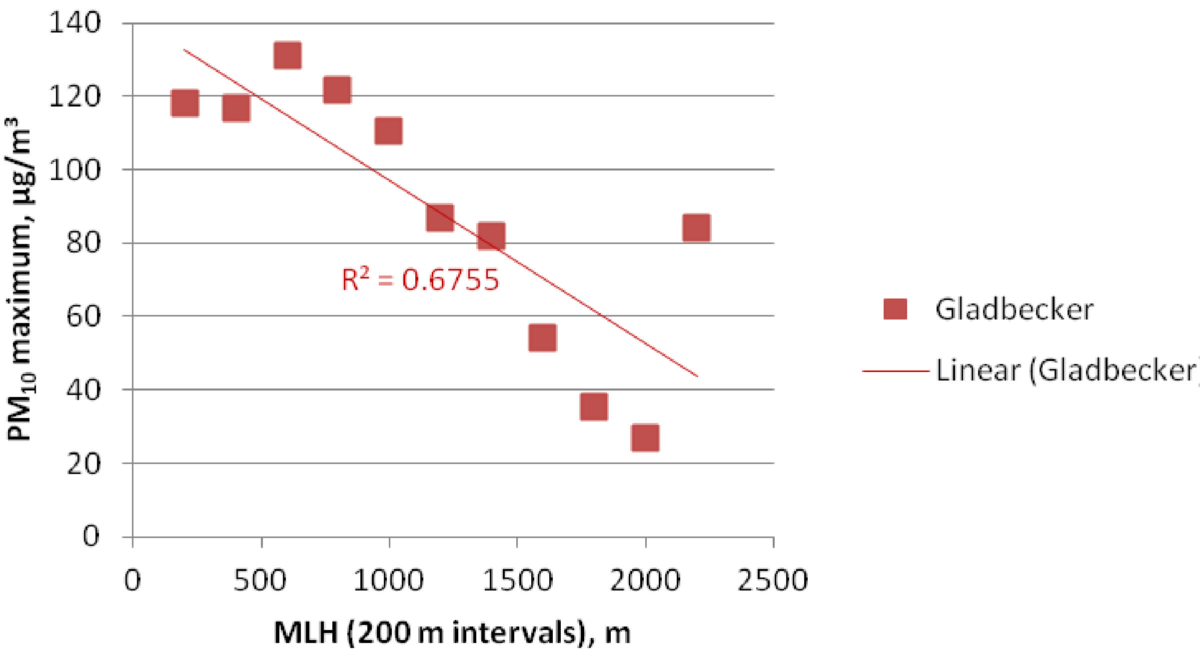




Figure 4. Correlations of the maximum of NO (above), $NO_2$ (middle) and $PM_{10}$ (below) concentrations during the measurement campaign from both stations Schuir (sub-urban background site; no $PM_{10}$) and Gladbecker Str. (kerb site) with 200 m intervals of mixing layer height (MLH) determined from ceilometer measurements.

The same type of correlation for benzene from Gladbecker Str. with MLH is shown in Figure 5 which is significant also.

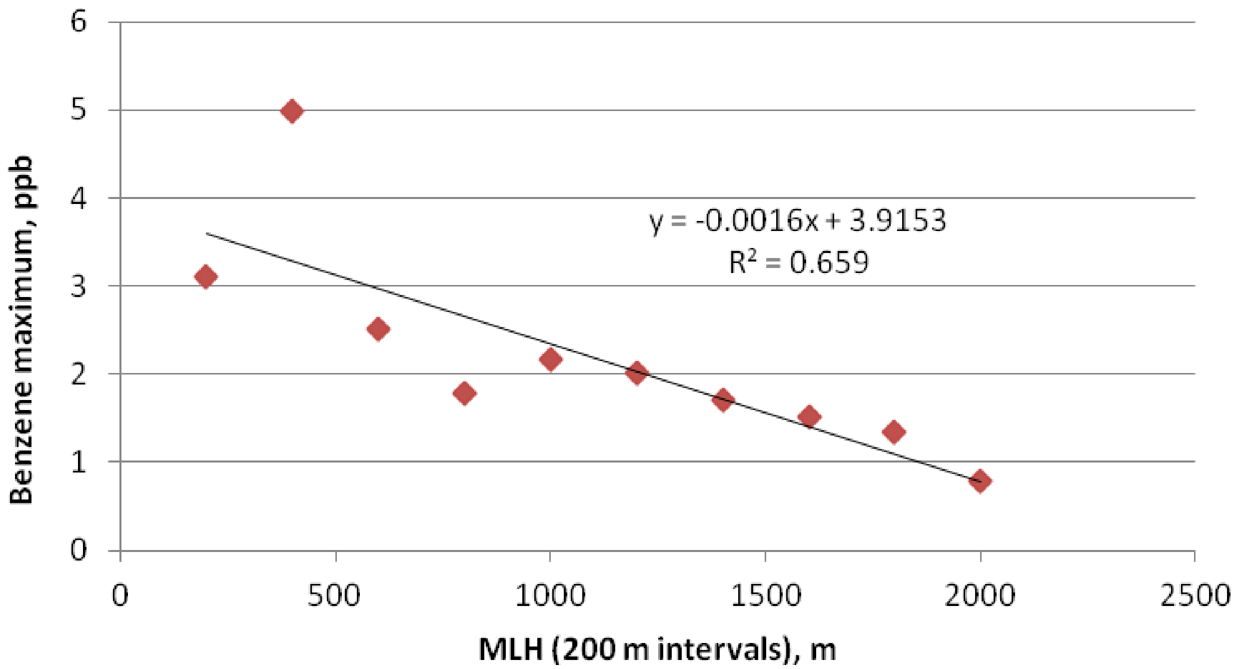



Figure 5. Correlations of the maximum of benzene concentrations during the measurement campaign from Gladbecker Str. with 200 m intervals of mixing layer height (MLH) determined from ceilometer measurements.

## 4. DISCUSSION, CONCLUSION AND OUTLOOK

The air quality is not only affected by the emissions and chemical transformations, but also by the meteorological conditions. The influences of advection and convection as well as the MLH must be considered. A nearly continuous measurement of MLH is possible by ceilometers - such instruments are frequently available today.

High air pollutant loads near the surface are coupled with MLH during winter mainly. It can be concluded that an important part of the variance of the observed NO, $NO_2$, $PM_{10}$ and benzene concentrations is caused by the MLH i.e. that the influence of MLH upon these air pollutant concentrations is significant.

The most appropriate correlation analysis of concentrations with MLH is the investigation of maximum concentrations within the 200 m MLH intervals during the observation period. The correlation coefficients are much higher than those for mean concentrations within the 200 m MLH intervals or original half-hourly or hourly data. This shows that really high air pollution concentrations are supported by low MLH. It is a new result that investigations of these maximum concentrations of air pollutants in the street canyon provide higher correlation coefficients than in the sub-urban background. In the case in the street canyon in Hannover the original hourly mean or daily mean values were used as described in Schäfer et al., 2006[1] but these correlations were not significant i.e. the emissions dominate the air pollutant concentration. Here it is shown that the maximum air pollutant concentrations are caused not only by emissions but by meteorological conditions i.e. the MLH, too.

The significant influences of MLH upon air pollutant concentrations in the sub-urban background are in good agreement with the results for urban and rural background stations in the region of Munich and Hannover (Schäfer et al., 2006[1]), in Augsburg and Munich (Schäfer et al., 2011[5]) as well as in Budapest (Alföldy et al., 2007[4]). It was found there from the investigation of the original hourly mean or daily mean values that mainly during winter the MLH determines the concentration of air pollutants near the surface by about 50 % in areas which are not influenced by strong emissions and during time periods without strong vertical mixing and advection.

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