Remote sensing of meteorological parameters to study their influences upon air quality in urban areas at the example of Augsburg

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ABSTRACT

The mixing layer height was continuously measured in Augsburg by remote sensing methods like ceilometer, sodar and RASS. The information about the mixing layer height is used to study the processes influencing air quality. The air pollution data are taken from the monitoring network and an additional in situ measurement station. High-pollution episodes during the winters 2006/2007 and 2007/2008 were investigated. The correlations of air pollutant concentrations with mixing layer height were determined which are significant.

1. INTRODUCTION

High air pollution episodes in urban areas often occur in the cold season and can not only be ascribed by increased local anthropogenic emissions. The mixing layer height (MLH) is an important factor which influences 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 [1] and thus controls the near-surface pollutant concentrations. Because MLH is a consequence of vertical temperature and moisture profiles in the lower atmosphere, remote sensing is a suitable tool to monitor MLH [2, 3]. Monitoring of mixing layer height was performed as during other measurement campaigns in urban and suburban areas (Hannover, Munich, Budapest; see [1]) and at the airports Zurich, Mexico City International Airport and Athens International Airport by the Vaisala ceilometer LD40 [4]. In Augsburg two Vaisala ceilometers CL31 were operated also. 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.

Further, MLH was determined by remote sensing with the Doppler-sodar (sound detection and ranging) DSD3x7 from Metek (see also [1]). Vertical wind profiles and turbulence parameters up to 1300 m maximum were measured by this method too.

Third, a RASS instrument (i.e. a sodar with an electromagnetic extension) provides the detection of the temperature profile too. The air temperature is detected by the observation of the propagation of the acoustic sodar pulses with a radar. The temperature calculation from the sound speed is corrected for the vertical wind speed.

The MLH was continuously measured by these uninterrupted remote sensing techniques.

2. MEASUREMENTS AND METHODOLOGY

The Vaisala Ceilometers LD40 and CL 31 applied here are described in more detail in [5]. It are compact minilidar with a diode laser of 855 nm (LD40) or 905 nm (CL31) wavelength capable to cover an altitude range higher than 4000 m. The lowest detectable layers are around 150 m (LD40) or 50 m (CL31). 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 [6]. The minimum range resolution is 7.5 m (LD40) or 5 m (CL31). 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 most negative value of the gradient) is given as an indication of MLH or upper edge of up to 5 lifted layers [7]. 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 MLH retrieval algorithm works appropriate during nearly cloudless conditions.

MLH was determined solely from sodar data as the minimum of the height of the ground-based echo layer and the height of an elevated echo maximum (if present). The top of the lowest stable layer, the lifted inversion and the top of the turbulent layer are given. If the MLH was higher than the instrument’s range it could not be determined from sodar data and the MLH was set at this range. These problems caused an ambiguity of MLH parameters if the MLH is large. Details on the determination and statistical evaluations of the resulting MLH are reported in [8].

From RASS measurements, in principle, MLH can either be determined from the temperature profiles or from the electro-magnetic backscatter intensity [6]. The latter depends on temperature and moisture fluctuations in the atmosphere. The derivation of MLH from the temperature profile requires a good vertical resolution of the profile which is mainly available only from the RASS. But even if the inversion layer at the

top of the boundary layer is thick enough, due to the high attenuation of sound waves in the atmosphere, a RASS can measure the temperature profile only up to about 1 km. Therefore, in the case of a deeper atmospheric boundary layer (ABL), MLH was determined from a secondary maximum of the electro-magnetic backscatter intensity which marks the occurrence of the entrainment zone at the ABL top. Thus, with this instrument combination the whole diurnal cycle of MHL is ideally monitored by interpreting the temperature profile at night-time and by analyzing the electro-magnetic backscatter intensity profile during daytime.

A comparison of ceilometer results with sodar and RASS measurements is described in [2] and in a presentation by Emeis et al. at this conference too. Multiple layer detection is important if residual layers are available during the late night. These conditions enable the contribution of air pollutants emitted during the day before during mixing around noon to the current air quality.

These remote sensing instruments were operated at three different sites: at the northern edge (CL31 or LD40, RASS), in the middle (CL31) at the Fachhochschule (FH) and at the southern edge of the town (sodar) at the Landesamt fuer Umweltschutz (LfU).

In addition to the monitoring air pollution network in situ concentration measurements of CO, NO, NO_x, and O_3 inside a van as well as PM_{10} were performed together with wind measurements at the northern edge of the town. These air pollutant measurements are the basis to study the meteorological influences upon air quality in Augsburg. Mainly intensive measurement periods during the winter 2006/2007 and 2007/2008 were studied. The weather situations are characterised, the meteorological influences like wind speed and wind direction are studied and the correlations of air pollutant concentrations with MLH are determined.

One-hourly-mean values were determined from all these data 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_x, CO and PM_{10} are measured with a standard error in the order of 5 % (S_1 = 0.05). The determination of MLH from soadar and 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

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

which is giving a value of 14.5 % for NO, NO_2, CO and PM_{10}. 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

It was found that the lowest stable layer or inversion limits the vertical exchange of primary pollutants emitted at or near the surface [1] and thus controls the near-surface pollutant concentrations. Multiple layer detection is important if residual layers are available during the late night. These conditions enable the contribution of air pollutants emitted during the day before during mixing around noon to the current air quality. Therefore it is interesting to analyze how the air quality of a town like Augsburg (about 265 000 inhabitants in 2007) is influenced by MLH. Augsburg is situated about 60 km west-north-west of Munich in a rural area on the river Lech. The Lech is flowing north from the Alps (about 100 km south of Augsburg) towards the Danube in a shallow valley, which is about 10 km wide and about 100 m deep. Under synoptically calm conditions with weak pressure gradients we observe light winds from the south at night and from the north to north east at daytime. At the presence of stronger pressure gradients the winds do not deviate much from the large-scale synoptic winds. Prevailing wind direction of such cases is from the south west.

The selected winter periods for data analysis are: 16 – 23 February 2007 and 14 – 24 February 2008. Hourly-mean values and daily-mean values are considered in the following. The data of the MLH retrievals of the ceilometer at the FH and of the air pollutant concentration measurements by the monitoring network at the southern edge of the LfU are used for the correlations. Other stations of the monitoring network are not considered because these are within streets (curb side stations).

3.1 Mixing layer heights

A typical daily course of the MLH is given in Figure 1. The relative humidity, the virtual potential temperature and wind vectors from radiosonde measurements in Oberschleißheim by DWD at 00:00 and 12:00 local time are given too. At 16/02/2007, 12:00 the decreasing relative humidity and increasing potential virtual temperature with height agreed well with the height of the near-surface layer detected from ceilometers data (600 m).

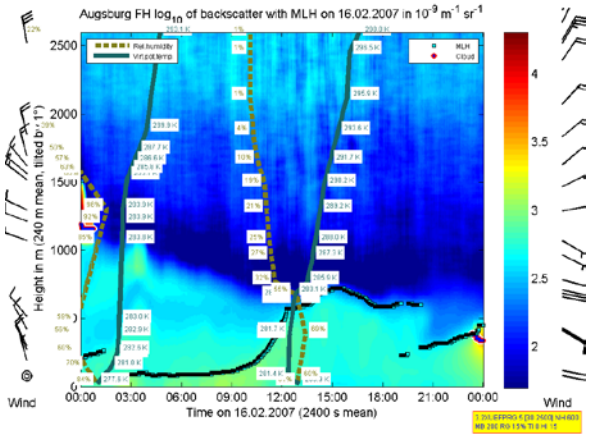

Figure 1. *Measurement results of ceilometer Vaisala CL31 at FH to observe the vertical aerosol distribution together with radiosonde data (wind vector, relative humidity and potential virtual temperature) from the meteorological observatory Oberschleißheim on 16 February 2007. The mixing layer height is given from the local minimum of the gradient of the backscatter data of the ceilometer. The time is given as local time. The backscatter intensity is presented in different colours (see right part of the figure).*

A further example from the winter measurements in 2008 is given in Figure 2 (16/02/2008). There is also a

good coincidence between the decreasing relative humidity and increasing potential virtual temperature measured by the radiosonde at 12:00 and the MLH determined from the ceilometers backscatter intensities.

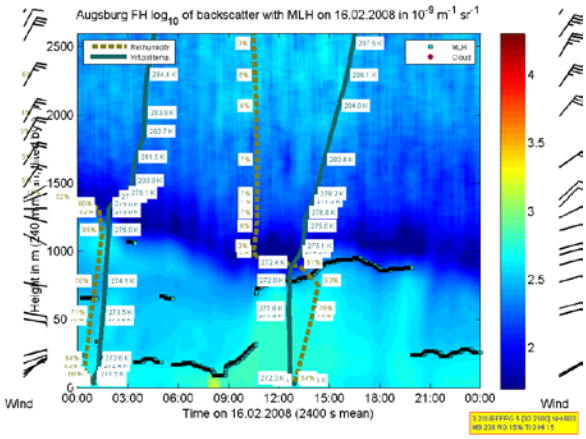

Figure 2. *Measurement results of ceilometer Vaisala CL31 at FH to observe the vertical aerosol distribution together with radiosonde data (wind vector, relative humidity and potential virtual temperature) from the meteorological observatory Oberschleißheim on 16 February 2008. The mixing layer height and backscatter intensity are given as in Figure 1. The time is given as local time.*

3.2 Correlations of air pollutant concentrations with mixing layer height

The significant correlations of the hourly-mean values of concentrations (y, in µg/m^3) and MLH (x, in m) during winter 2007 are the following:

CO: $y=716.3 \cdot e^{-0.001 \cdot x}$, $R^2=0.15$ (see Figure 3);

NO: $y=18.3 \cdot e^{-0.002 \cdot x}$, $R^2=0.16$.

The influences of the MLH upon pollutant concentrations are relevant for CO and NO only.

During winter 2008 the correlations are the following:

CO: $y=-0.53 \cdot x+727.7$, $R^2=0.20$ or $y=665.4 \cdot e^{-0.001 \cdot x}$, $R^2=0.36$ (see Figure 4);

NO: $y=-0.03 \cdot x+31.4$, $R^2=0.16$ or $y=14.9 \cdot e^{-0.003 \cdot x}$, $R^2=0.33$;

NO_2: $y=-0.03 \cdot x+43.9$, $R^2=0.28$ or $y=43.1 \cdot e^{-0.001 \cdot x}$, $R^2=0.40$;

PM_{10}: $y=-0.03 \cdot x+44.5$, $R^2=0.26$ or $y=43.4 \cdot e^{-0.001 \cdot x}$, $R^2=0.40$ (see Figure 5).

Consequently, the influence of the MLH upon the CO, NO, NO_2 and PM_{10} concentrations is relevant during winter 2008. In all cases an exponential dependence of the concentrations on MLH shows a better correlation.

In comparison there are more low MLH values in the winter 2008 case than in the winter 2007 case. This can be the reason that the correlation coefficients in winter 2007 are much higher than in winter 2008.

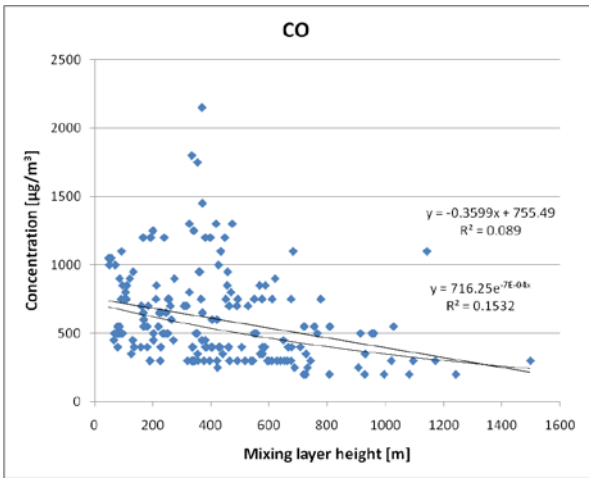

Figure 3. *Correlation of the hourly-mean values of CO concentrations and mixing layer heights during winter 2007. The parameters of a linear and exponential regression function and the square of the correlation coefficients are given.*

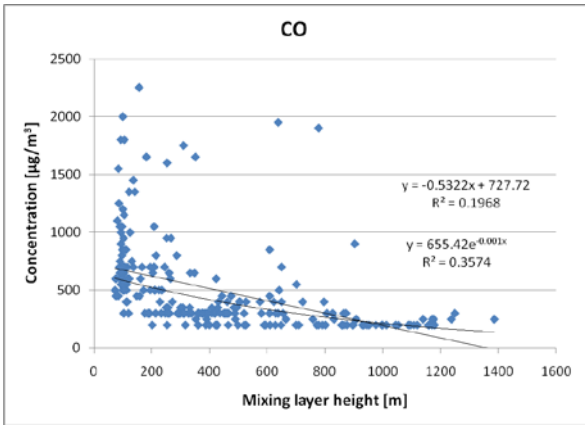

Figure 4. *Correlation of the hourly-mean values of CO concentrations and mixing layer heights during winter 2008 (same layout as Figure 3).*

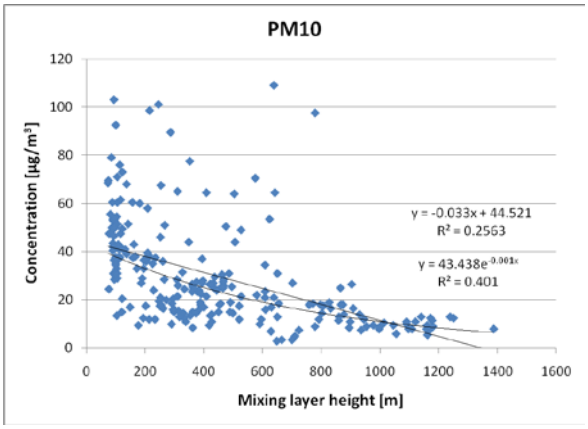

Figure 5. *Correlation of the hourly-mean values of PM_{10} concentrations and mixing layer heights during winter 2008 (same layout as Figure 3).*

The significant correlations of the daily-mean values are the following:

CO: $y=-0.67 \cdot x+775.1$, $R^2=0.49$ or $y=832.6 \cdot e^{-0.001 \cdot x}$, $R^2=0.49$ (see Figure 6);

NO: $y=-0.05\cdot x+36.6$, $R^2=0.41$ or $y=43.7\cdot e^{-0.004\cdot x}$, $R^2=0.41$;

NO_2: $y=-0.05\cdot x+50.3$, $R^2=0.66$ or $y=55.5\cdot e^{-0.002\cdot x}$, $R^2=0.69$;

PM_{10}: $y=-0.06\cdot x+54.8$, $R^2=0.60$ or $y=60.2\cdot e^{-0.002\cdot x}$, $R^2=0.72$ (see Figure 7).

All these daily-mean correlations are of higher significance than the hourly-mean correlations.

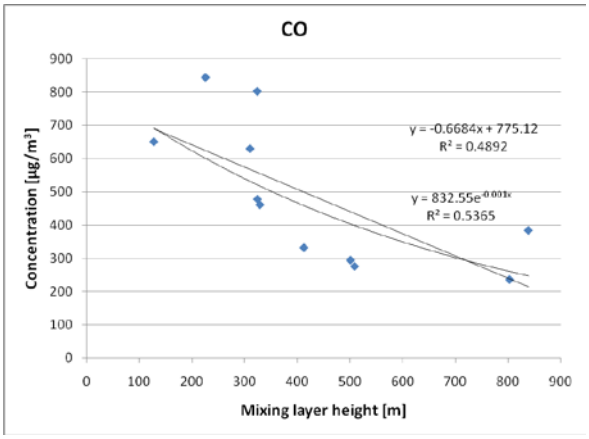

Figure 6. *Correlation of the daily-mean values of CO concentrations and mixing layer heights during winter 2008 (same layout as Figure 3).*

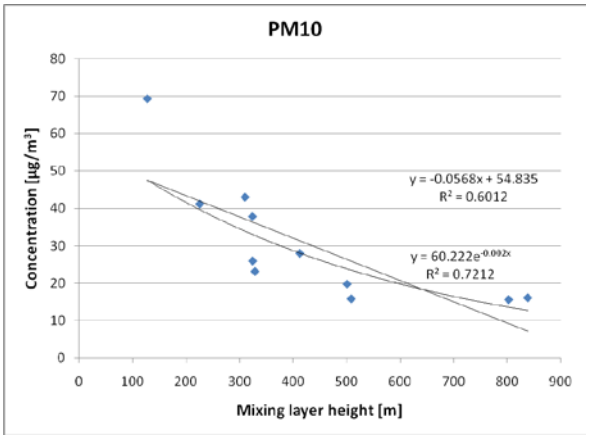

Figure 7. *Correlation of the daily-mean values of PM_{10} concentrations and mixing layer heights during winter 2008 (same layout as Figure 3).*

The correlation coefficients are higher for NO_2 than for NO. This is caused by the higher amount of primary emitted NO than NO_2 so that the MLH has a bigger influence on NO_2 than on NO.

4. CONCLUSIONS

The air quality is not only determined by the emissions and chemical transformations mainly within the frame of the ozone chemistry 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 these winter cases. It can be concluded that an important part of the variance of the observed CO, NO, NO_2 and PM_{10} concentrations is caused by the MLH i.e. that the influence of MLH upon these air pollutant concentrations is significant. The most appropriate temporal averaging period for the correlation of concentrations with MLH is a daily mean. This is caused by missing data during certain weather situations like well-mixed conditions and some very rapid temporal variations of MLH.

The significant influences of MLH upon air pollutant concentrations are in good agreement with the results described in [1] for urban and rural background stations in the region of Munich and Hannover. It was found there 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. It was found in [1] also that during relative high MLH the correlation coefficients are comparable low (as here during the winter 2007 case). Also the findings described here that an exponential dependence of the concentrations on MLH shows a better correlation than a linear dependence is in agreement with the findings in [1]. This is a hint for a non-perfect mixing of a pollutant in the boundary layer caused by continuous emissions near the ground.

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