On a relation between particle size distribution and mixing layer height

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ABSTRACT

Ceilometers are applied to detect layering of the lower atmosphere continuously. This is necessary because not only wind speeds and directions 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 can be used to determine the MLH influence upon the particle size distribution (PSD) which is detected near the ground.

The information about atmospheric layering is continuously monitored by uninterrupted remote sensing measurements with the Vaisala ceilometers LD40 and CL31 which are eye-safe commercial lidar systems. Special software for these ceilometers provides routine retrievals of lower atmosphere layering from vertical profiles of laser backscatter data. The meteorological data are collected by the air pollution monitoring station of the Bavarian State Agency of Environment (LfU) at the southern edge of Augsburg and at the airport at the northern edge of Augsburg by the German National Meteorological Service (DWD). PSD are measured at the aerosol measurement station in the centre of Augsburg by the Cooperative Health Research in the Region of Augsburg (KORA).

The two intensive measurement periods during the winter 2006/2007 and 2007/2008 are studied. The weather situations are characterized, the meteorological influences upon air pollutant concentrations like wind speed and wind direction are studied and the correlations of ceilometer backscatter densities and MLH with PSD are determined.

Keywords: Air pollution, remote sensing, ceilometer, mixing layer height, particle size distribution

1. INTRODUCTION

Particulate matter and especially ultrafine particles (UFP) are of high health risk. This is mainly due to emissions and chemical particle formation processes but also to meteorological influences. Wind speeds and directions as well as mixing layer height (MLH) are important factors which influence exchange processes of ground level emissions (Schäfer et al., 2006[1]; Alföldi et al., 2007[2]; Schäfer et al., 2011[3]).

Especially the knowledge of MLH can contribute to the understanding and analysis of air pollution episodes because air pollutants emitted from the ground can accumulate up to the MLH. If the MLH is located near to the ground air pollution can be high due to a strongly limited air mass dilution. The continuous knowledge of MLH is supporting the understanding of processes directing air quality (Emeis and Schäfer, 2006[4]). Remote sensing offers continuous measurements and it can be applied to monitor MLH (Emeis et al., 2004[5]; Emeis et al., 2011[6]). Here we focus on

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monitoring of MLH with ceilometers which we performed in urban and sub-urban areas (see Schäfer et al. (2006)[1]) and at airports (see Schäfer et al., 2010[7]).

It will be discussed how the knowledge of the meteorological parameters and MLH is supporting the understanding of processes directing particle size distribution (PSD).

2. MEASUREMENTS AND METHODOLOGY

The MLH was continuously monitored by uninterrupted remote sensing measurements with ceilometer, SODAR and RASS in Augsburg.

Augsburg, a town with about 265 000 inhabitants (in 2007), 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 large-scale 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 Vaisala ceilometers LD40 and CL31 were used which are eye-safe commercial lidar systems (see Münkel, 2007[8]). These are compact eye-safe mini-lidars 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 (biaxial LD40) or 50 m (monoaxial 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 minimum range resolution is 7.5 m (LD40) or 5 m (CL31). The eye-safety class is 1M. The ceilometer backscatter profiles are used to detect lower cloud height usually. The two ceilometers are installed at the northern edge and in the centre of Augsburg (see Figure 1).

The heights of the near surface aerosol layers and the MLH are analysed by a gradient method from optical vertical backscatter profiles (Emeis et al., 2008[9]). 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 and for the upper edge of up to 4 more layers above (Emeis et al., 2007[10]). 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 (Emeis et al., 2008[9]).

A comparison of the different measurement results of these remote sensing systems during simultaneous measurements was performed (Emeis et al., 2004[5]; Emeis et al., 2009[11]; Emeis et al., 2011[6]). In the absence of low clouds and precipitation and during broken clouds ceilometers can estimate the MLH fairly well. The aerosol structures seen in lower layers by the ceilometer agree well with the temperature inversions measured by the RASS as well the profiles of relative humidity and virtual potential temperature measured by radiosondes.

The meteorological data were collected by the monitoring station of the Bavarian Environment Agency (LfU) at the southern edge, and the German National Meteorological Service (DWD) at the northern edge, as well as at the aerosol measurement station in the centre of Augsburg (see Figure 1) by the Cooperative Health Research in the Region of Augsburg (KORA) where the particle size distribution of UFP was measured with a Twin Differential Mobility Particle Sizer (Pitz et al., 2008[12]).

The two intensive measurement periods during the winter 2006/2007 and 2007/2008 are studied.

3. RESULTS

Mixing layer heights

Two examples of measurement results of the ceilometer Vaisala CL31 in the centre of Augsburg to observe the vertical aerosol distribution, together with radiosonde data (wind vector, relative humidity and potential virtual temperature) from the meteorological observatory Oberschleißheim, are shown: on February 16th, 2007 in Figure 2 and on February

16th, 2008 in Figure3. The time is given as local time. The backscatter intensity is presented in different colours. The MLH is given by blue squares.

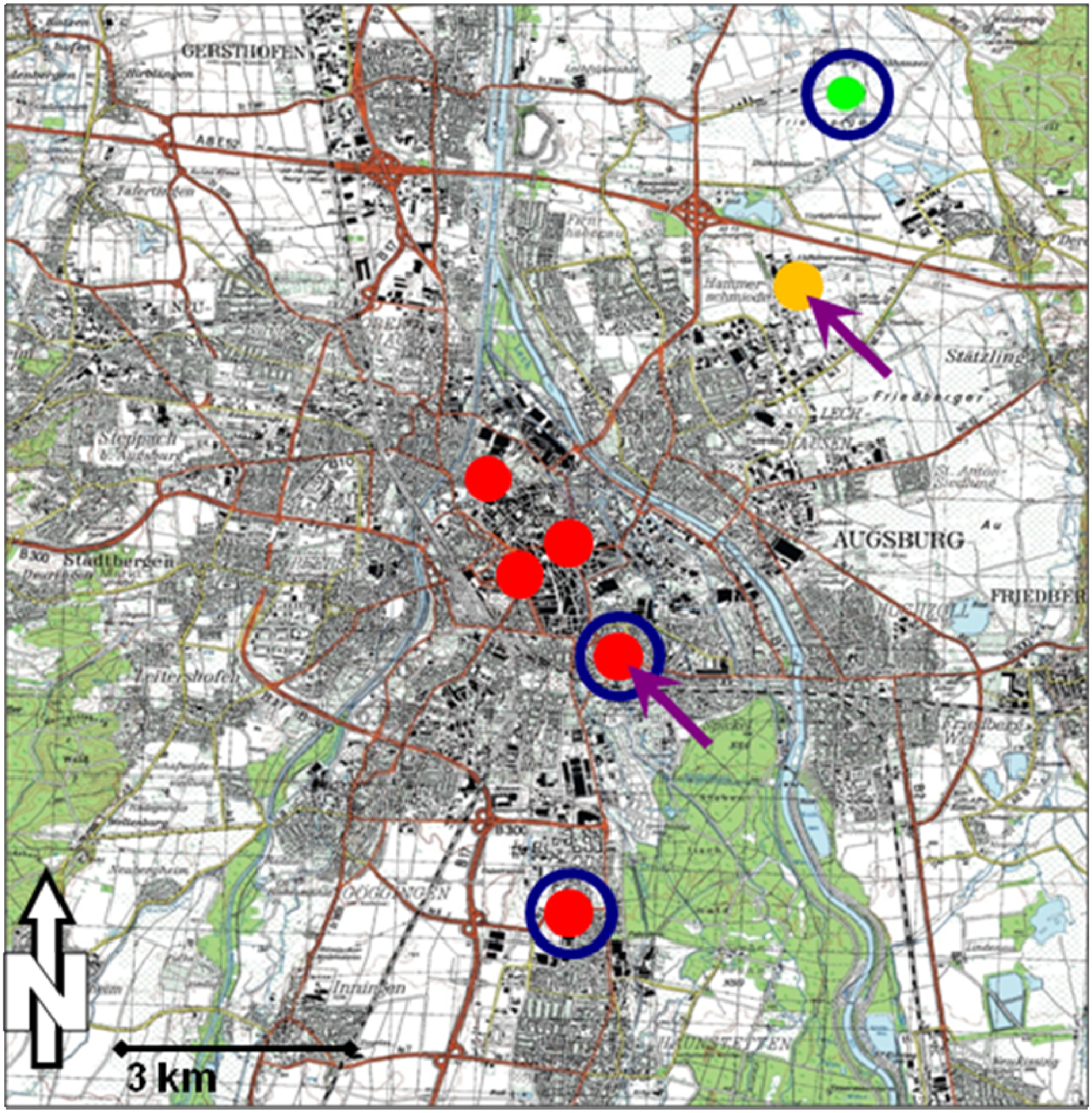

Figure 1: Measurement stations of particles and trace gases in Augsburg (red and yellow circles). The Twin Differential Mobility Particle Sizer (red circle) and a ceilometer CL31 (arrow) are operated at the aerosol measurement station in the centre of Augsburg near the Fachhochschule (FH) by the Cooperative Health Research in the Region of Augsburg (KORA). All other stations marked by red circles are operated by the Bavarian Environment Agency (LfU). The second ceilometer CL 31 (arrow) is at the station near the motorway A8 in the North (yellow circle) operated by the IMK-IFU. The meteorological measurement station of the German National Meteorological Service (DWD) is the green circle with blue ring in the North (Augsburg Airport). All weather stations are marked by blue rings.

In most cases decreasing relative humidity and increasing potential virtual temperature with height (radiosonde data) correlated well with the height of the near-surface layer determined from ceilometer data. Both days are examples of wintertime stable atmospheric conditions. The daytime conditions are characterised by a well-mixed boundary layer due to convection, but during the night a near-surface layer (MLH often below 500 m) prevents rapid dilution of emitted air pollutants.

On February 16th, 2007 during the night a near-surface layer and a residual layer in about 800 m height are detected. During the morning hours the MLH increased, so that around noon the MLH reaches the height of the residual layer and a common mixing layer is formed which reaches at 14:00 a maximum. During the evening a new layer above ground is formed.

On February 16th, 2008 it is cloudless too and a near-surface layer which exists during the night is increasing in the morning. The maximum of the mixing layer is in the afternoon. In the evening the mixing breaks down and a near-surface layer is formed which is similar to that during the night before.

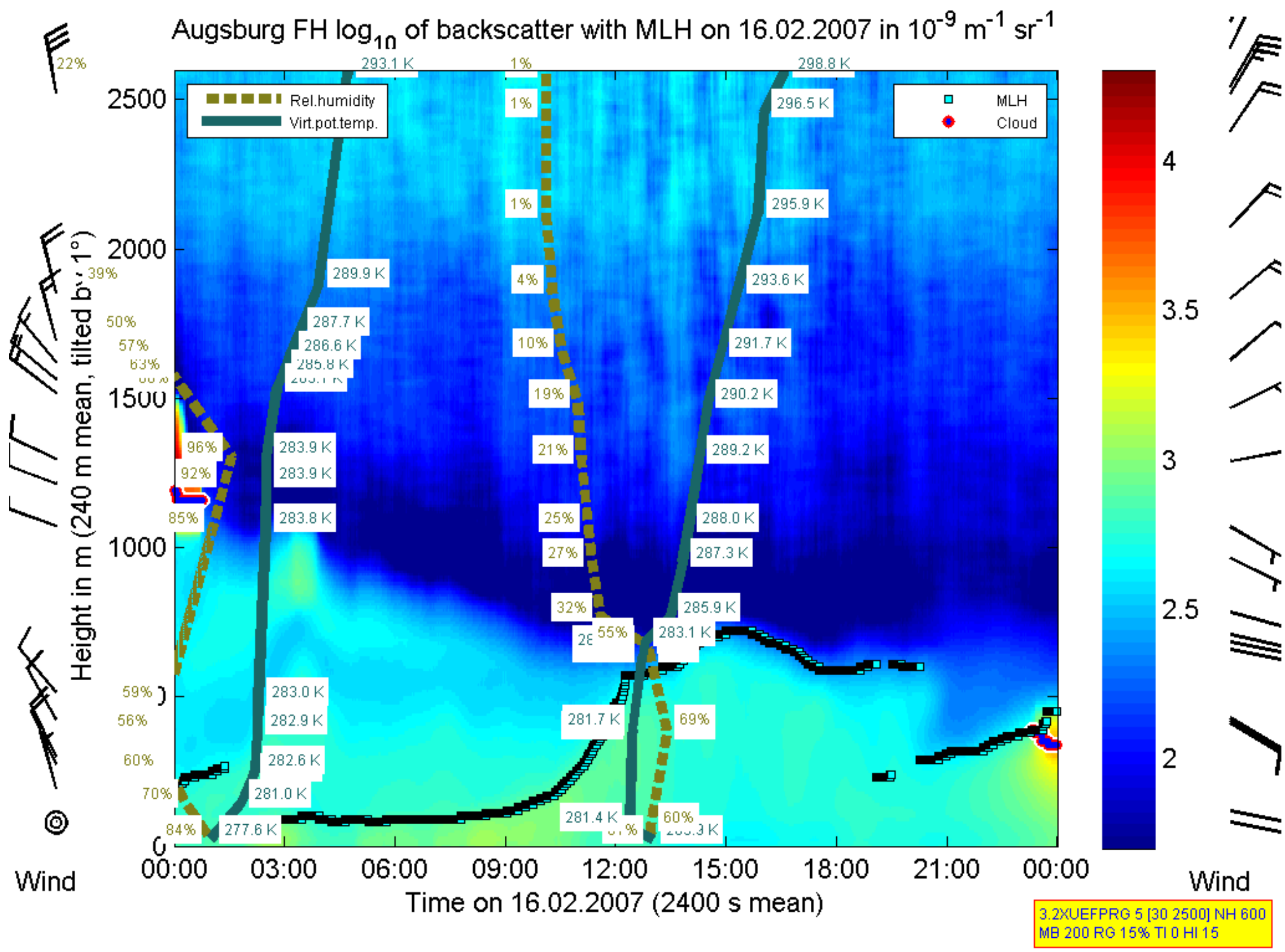

Figure 2: Ceilometer backscatter densities on February 16th, 2007. Gradient local minima are indicated by black framed green rectangles and cloud base heights by blue circles. The lowest gradient minimum reported marks the MLH. The radiosonde data from Oberschleißheim near München at midnight and noon are included: wind barbs (left for midnight, right for noon), relative humidity and virtual potential temperature (values at the profiles).

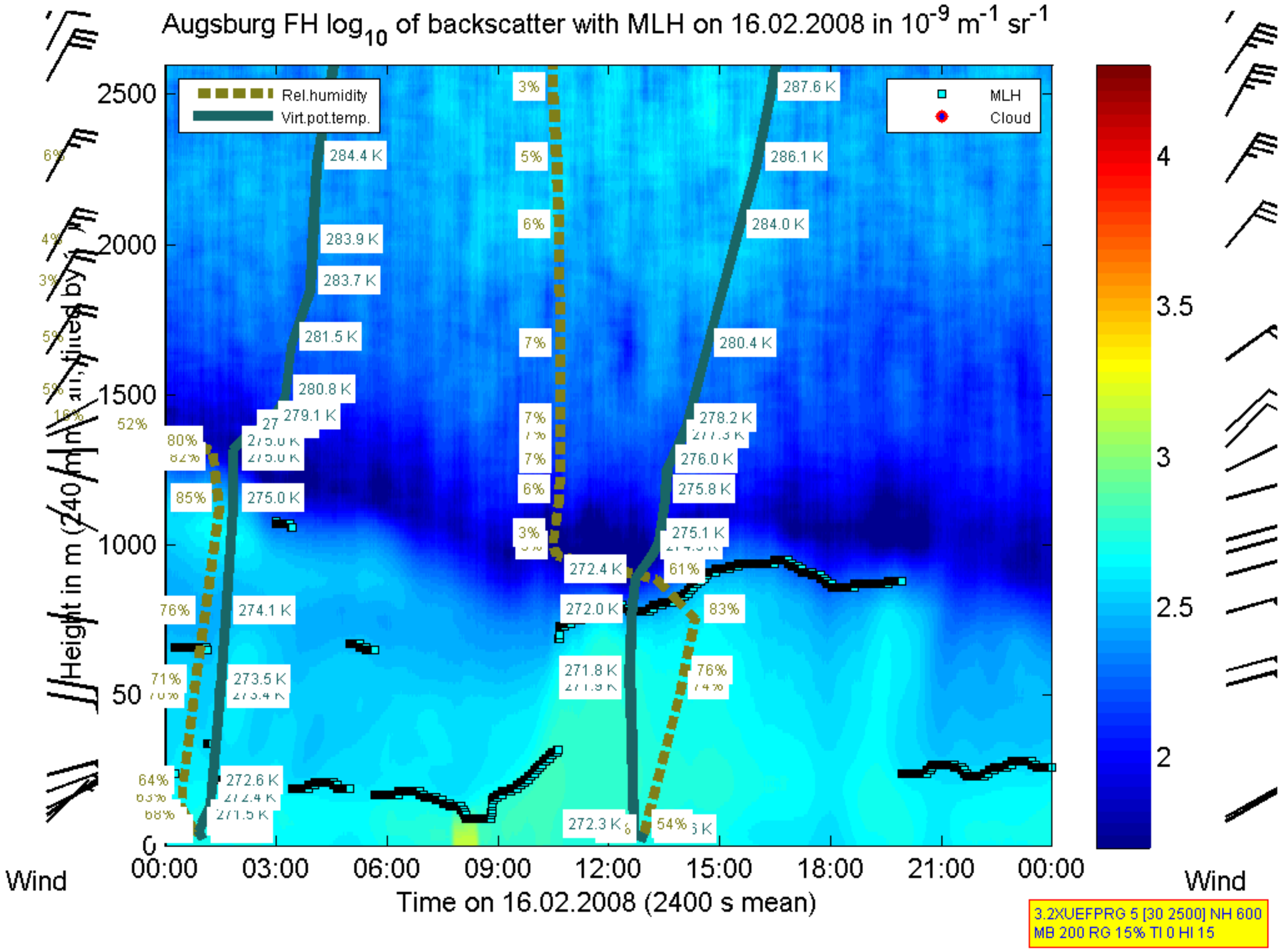

Figure 3: Ceilometer backscatter densities on February 16th, 2008. Gradient local minima are indicated by black framed green rectangles and cloud base heights by blue circles. The lowest gradient minimum reported marks the MLH. The radiosonde data from Oberschleißheim near München at midnight and noon are included: wind barbs (left for midnight, right for noon), relative humidity and virtual potential temperature (values at the profiles).

Daily variation of the particle number concentration

The daily variation of the UFP and particle number concentration (NC) is shown in Figures 4 and 5 and has the following behaviour:

3 - 10 nm: relatively constant,

10 - 100 nm: strong daily course,

100 - 500 nm: weak daily course and

>500 nm: intensity of daily course decreases.

This is caused by UFP and particle formation processes which are dependent from the emission characteristics and humidity.

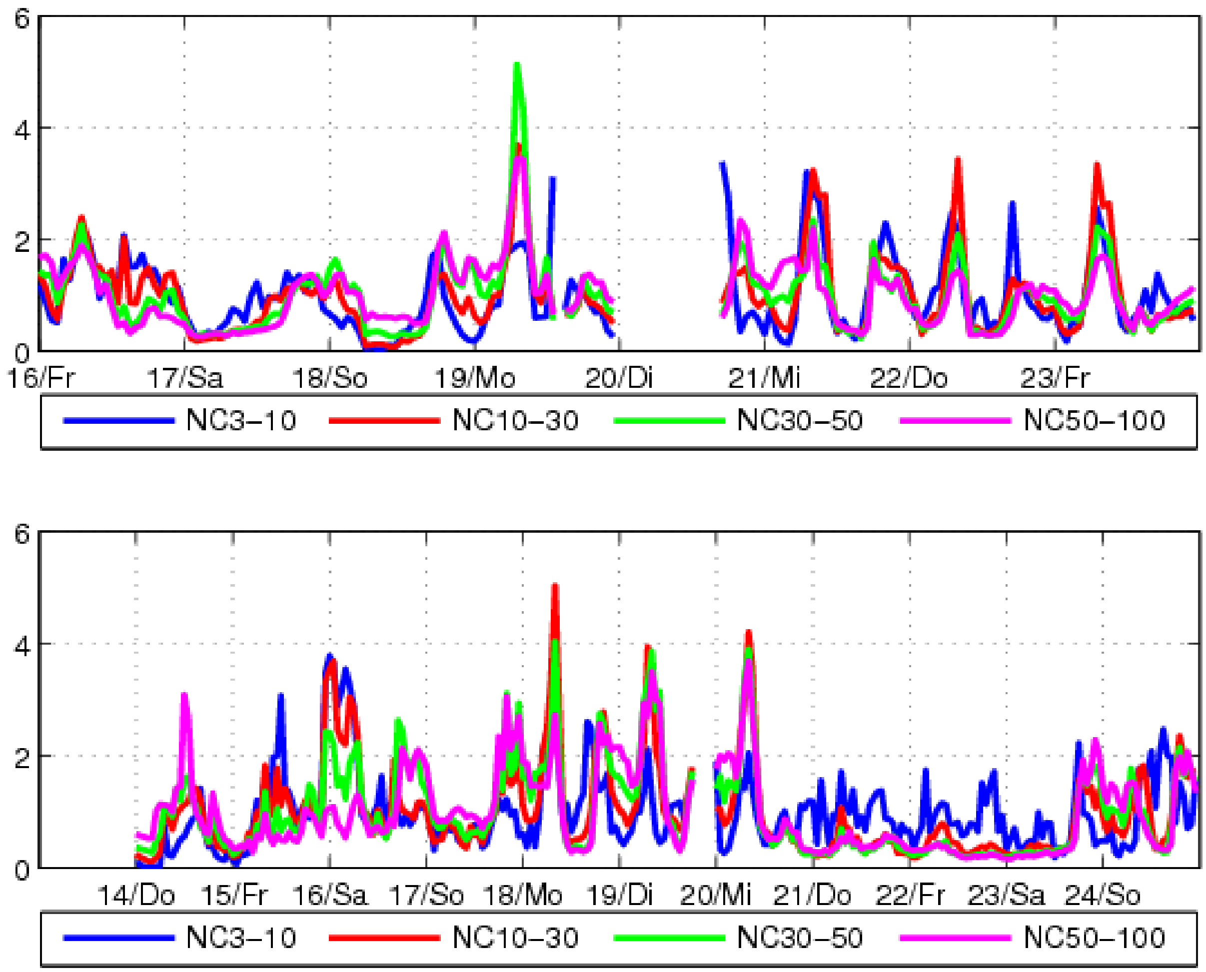

Figure 4: Temporal variation of UFP number concentrations (NC) in different size modes (3 – 10 nm, 10 – 30 nm, 30 – 50 nm, 50 – 100 nm) at FH (inner city of Augsburg) during the campaigns 16 - 23 February 2007 (above) and 14 – 24 February 2008 (below).

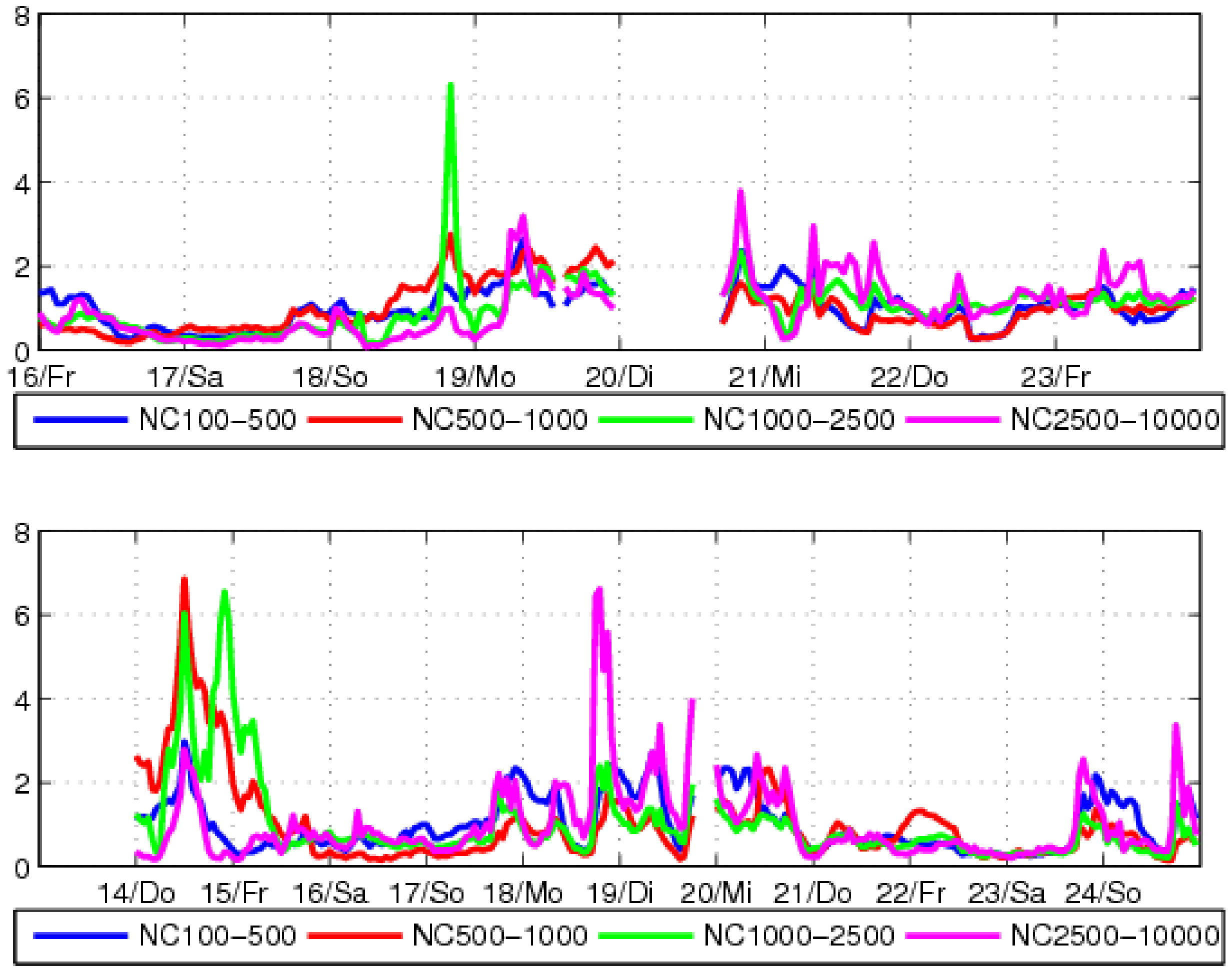

Figure 5: Temporal variation of particle number concentrations (NC), normalized with their mean values, in different size modes (100 – 500 nm, 500 – 1000 nm, 1000 – 2500 nm, 2500 – 10000 nm) at FH (inner city of Augsburg) during the campaigns 16 - 23 February 2007 (above) and 14 – 24 February 2008 (below).

The daily course of MLH from ceilometer CL31 measurements at FH (inner city of Augsburg) during the campaigns together with lower cloud heights is shown in Figure 6. About half of the time is cloudless and there was no precipitation. During the night MLH values lower than 500 m and during the day MLH values lower than 1000 m dominate.

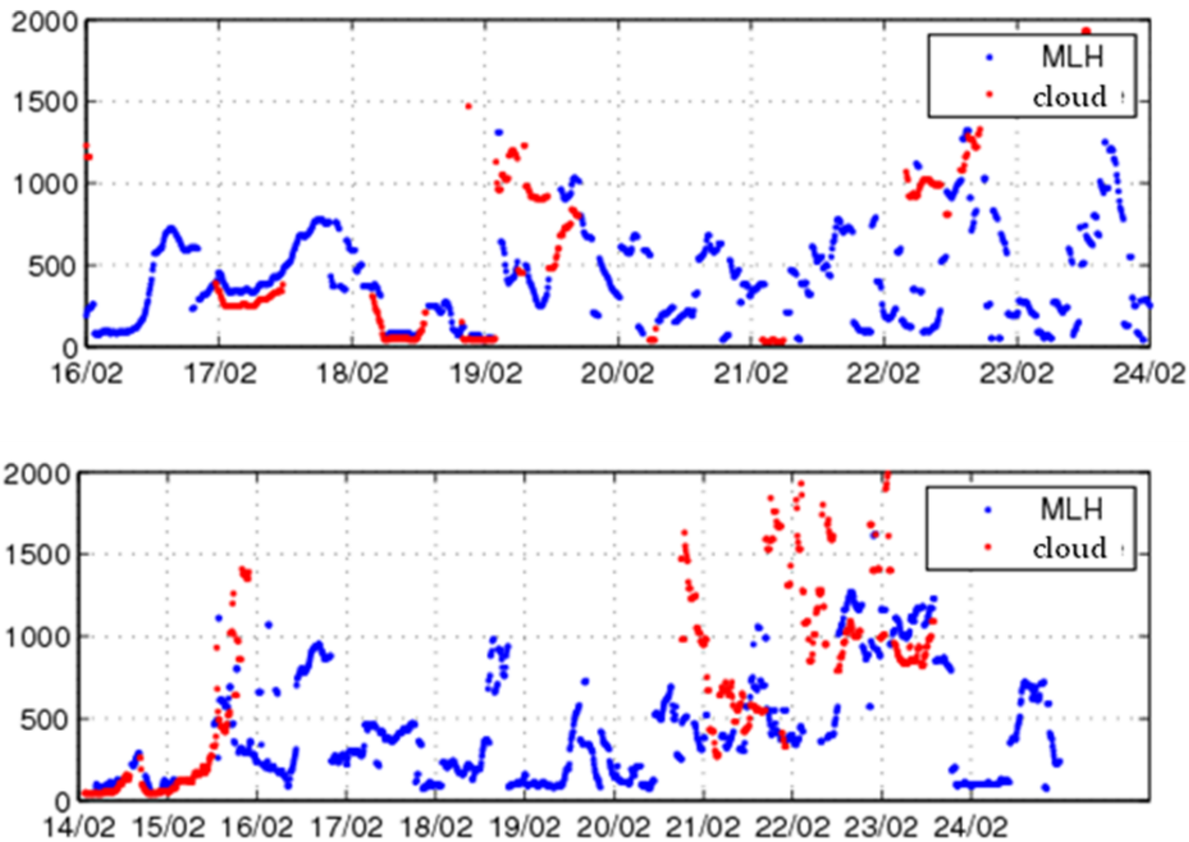

Figure 6: Temporal variation of mixing layer height (MLH, blue) and cloud height (red), both in [m], from ceilometer CL31 measurements at FH (inner city of Augsburg) during the campaigns 16 – 23 February 2007 (above) and 14 -24 February 2008 (below).

The wind speed (Figure 7) is generally in the inner city about half of that measured at the edge of the city in the North and South which is 8 m s^{-1} maximum. The daily course is characterized by lower wind speeds during the night than during the day.

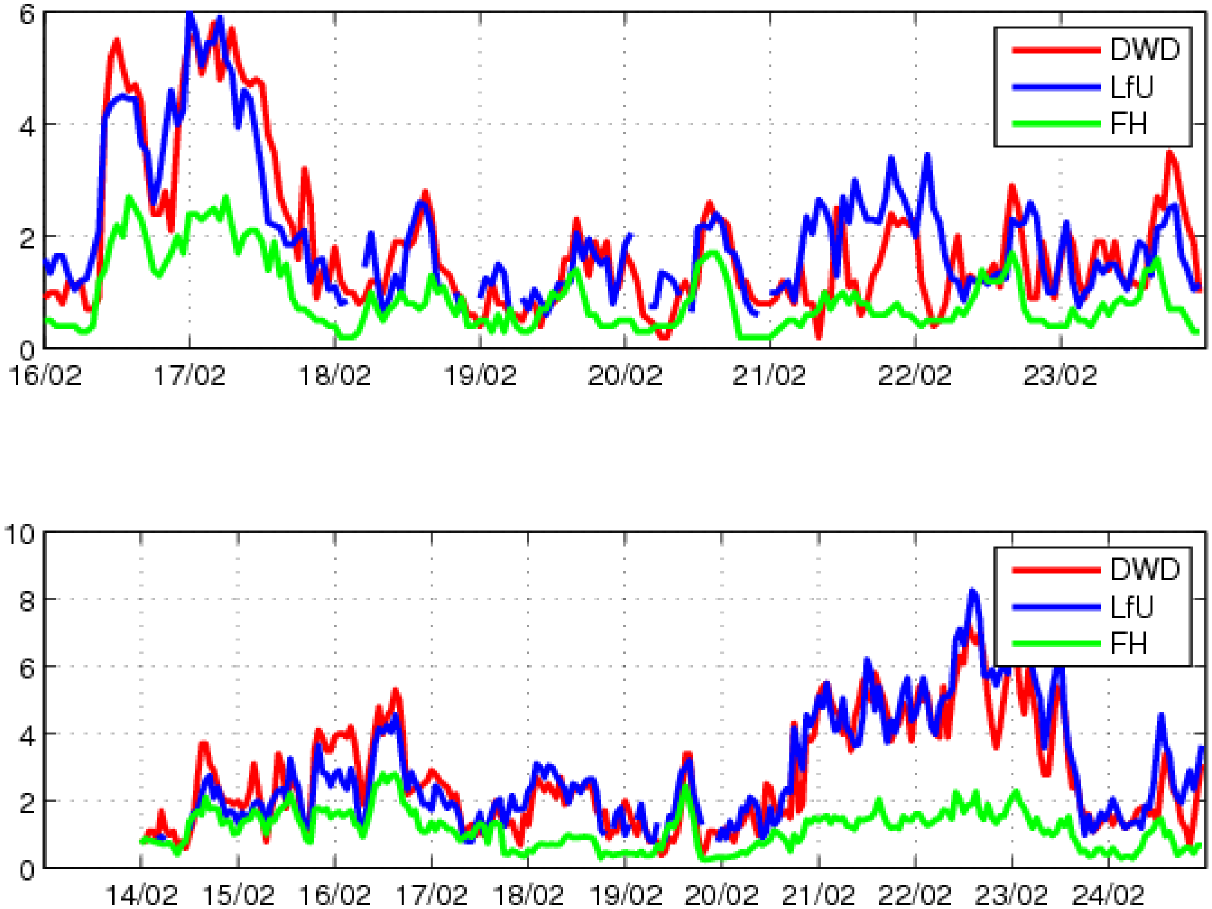

Figure 7: Temporal variation of wind speed in [m s^{-1}] during the campaigns 16 – 23 February 2007 (above) and 14 – 24 February 2008 (below) at the three different stations across the city area: FH inner city, LfU outer city in the South and DWD at Augsburg airport in the North.

In Figure 8 the relative humidity is shown which is 30 % minimum. During the day the relative humidity is minimum and during the night maximum.

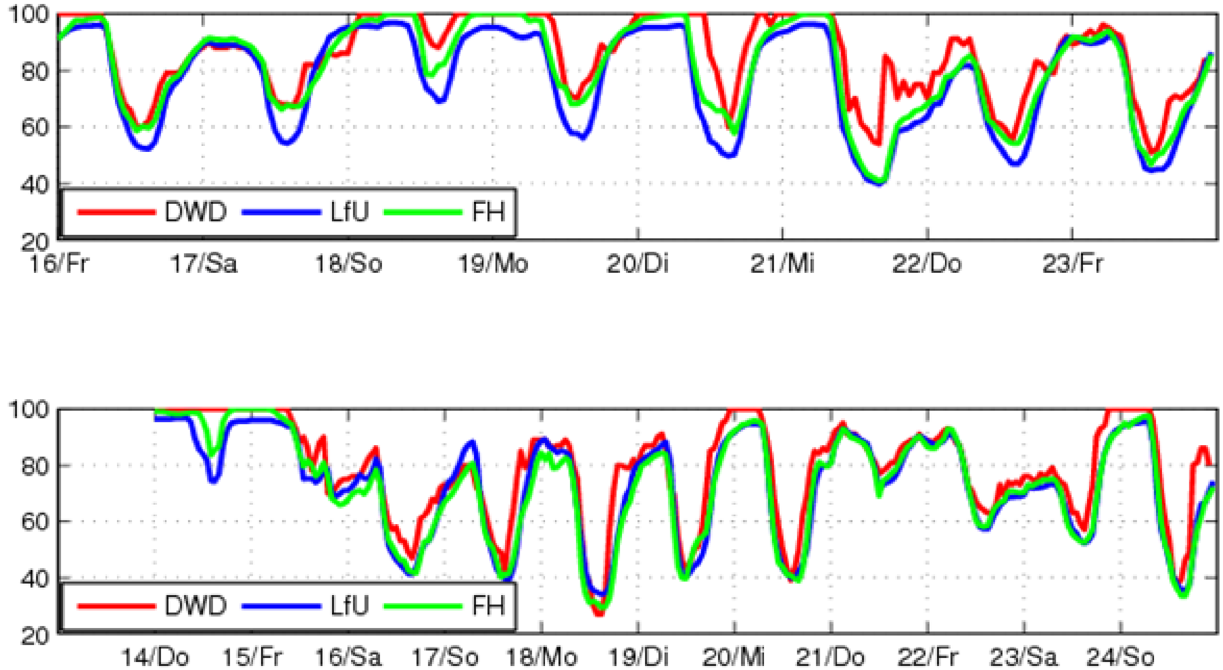

Figure 8: Temporal variation of different relative humidity in [%] during the campaigns 16 - 23 February 2007 (above) and 14 – 24 February 2008 (below) at the three different stations across the city area: FH inner city, LfU outer city in the South and DWD at Augsburg airport in the North.

Table 1: Correlation coefficients R^2 of mixing layer height (MLH), temperature (Temp), wind direction (W dir), Wind speed (W speed) and relative humidity (RH) with particle number concentrations in different size ranges (all hourly mean data).

		3 - 10	10 - 30	30 - 50	50 - 100	100 - 500	500 - 1000	1000 - 2500	2500 - 10000
2007	MLH	0.010	0.023	0.063	0.121	0.110	0.026	0.000	0.001
2008	MLH	0.000	0.146	0.242	0.350	0.455	0.185	0.161	0.069
2007	Temp	0.001	0.020	0.132	0.265	0.236	0.080	0.010	0.087
2008	Temp	0.002	0.170	0.282	0.298	0.223	0.078	0.107	0.019
2007	W dir	0.041	0.011	0.009	0.005	0.003	0.051	0.037	0.000
2008	W dir	0.041	0.149	0.155	0.111	0.028	0.024	0.122	0.023
2007	W speed	0.001	0.046	0.141	0.258	0.377	0.198	0.152	0.166
2008	W speed	0.005	0.111	0.227	0.354	0.423	0.098	0.109	0.191
2007	RH	0.001	0.029	0.161	0.323	0.357	0.195	0.002	0.016
2008	RH	0.025	0.009	0.021	0.054	0.108	0.232	0.161	0.003

Correlations

Particles of different sizes are influenced differently by the meteorological parameters and MLH. The daily variation of the particle NC is coupled directly with the MLH and wind speeds (see Table 1). A significant correlation of the hourly-mean values of particle NC in the size range 100 – 500 nm with MLH (R^2=0.46 for hourly mean data in 2008) and wind speeds (R^2=0.42 for hourly mean data in 2008) is found: the higher the MLH the lower the NC and the higher the wind speed the lower the NC. The correlation coefficients for particles of bigger as well as smaller size are lower (see Table 1). During the day the correlation coefficients are smaller than during the night i.e. during well mixed conditions the influence of meteorological parameters and MLH upon particles is not much different for particles of different sizes.

4. DISCUSSION, CONCLUSIONS, OUTLOOK

The origin of smaller particles (UFP) in the atmosphere is emission. These particles accumulate, coagulate and nucleate in the atmosphere rapidly to bigger particles. These processes are mainly the reason that particles of small sizes have relatively low correlations with wind speeds and MLH. Mainly during winter the MLH determines near-surface concentration of air pollutants by about 50 % in areas not influenced by strong emissions and during time periods without strong vertical mixing and advection.

Bigger particles (e.g. NC 500 - 1000 nm) are influenced by humidity and formation of secondary particles. These processes reduce the influence of wind speeds and MLH also.

All these results correspond with the findings of a study for the period 2005-2006 with NC 3 – 10,000 nm and MLH from radiosonde data (Schäfer et al., 2009[13]; Schäfer et al., 2011[3]).

Finally, the influences of emissions, transports and mixing of the lower atmosphere (MLH) upon particle NC are more complex than for trace gas concentrations (Schäfer et al., 2006[1]).

These studies will be continued to get a better understanding of episodes with high particle NC in different size ranges. Due to the strong daily variation of MLH their continuous observation with high and known accuracy is required.

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