Smart Air Quality Network for spatial high-resolution monitoring in urban area

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ABSTRACT

A pragmatic, data driven approach, which for the first time combines existing in situ and remote sensing data sets with a networked mobile air pollutant measurement strategy in the urban space is an objective of the Smart Air Quality Network (SmartAQnet) project. It aims to implement an intelligent, reproducible, finely-tuned (spatial, temporal), yet cost-effective air quality measuring network, initially in the model region of Augsburg, Germany. Central to this is the development and utilization of partial, already existing (but not yet combined) data on the one hand and the collection and integration of relevant missing data on the other hand. Unmanned aerial vehicles (UAV) with low-weight meteorological sensors and particle counter are used to monitor the three-dimensional dynamics of the lower atmosphere. Ground-based remote sensing by ceilometer for mixing layer height detection as well as a Radio-Acoustic Sounding System (RASS) for temperature and wind profile measurements at the University campus complete the new network architecture and UAV height profiling of atmospheric parameters.

The SmartAQnet research initiative focuses on the subject of data access and data-based applications. Such complex monitoring provides the basis of deeper process understanding of air pollution exposure. The network architecture is shown and first results about spatial variation of meteorological influences upon air pollution exposure is presented using ceilometer, UAV and the existing monitoring network data.

Keywords: air quality, environmental sensing, exposure, emissions, ceilometer, UAV

1. INTRODUCTION

The investigations of individual air pollution exposure and health risks suffer from a lack of available data. Currently, air pollutants are measured by a measurement network of rare spread dedicated techniques corresponding to EC guidelines. Remote sensing instruments onboard of ground-based, mobile and airborne platforms close some gaps only due to strong

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limitations in spatial and temporal coverage. This incomplete data basis does not allow to study and simulate all cause-and-effect chains between quality of air, which we breath, and the built and natural environment.

The project Smart Air Quality Network (acronym: SmartAQnet, http://www.smartaq.net/), funded by the German Federal Ministry of Transport and Digital Infrastructure - Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), is based on a pragmatic, data driven approach, which for the first time combines existing in situ data sets of the four state air quality monitoring stations (LÜB stations, https://www.lfu.bayern.de/luft/immissionsmessungen/index.htm) in Augsburg (Bourgesplatz, Karlstrasse, Königsplatz, LfU) with remote sensing and a networked mobile air pollutant measurement strategy in the urban space. An introduction to the project was given by Budde et al. (2017a)[1] already. Central to these objectives is the development and utilization of partial, already existing (but not yet combined) data on the one hand and the collection and integration of relevant missing data on the other hand. These data are used also to develop a small-scale emission inventory as basis for chemistry-transport modelling on the small scale and determination of space-time fields of aerosol distribution by geo-statistic interpolation and further statistical methods. Also, a semi-empirical numerical scheme as part of an air quality management system (Street Increment methodology) has been applied in Augsburg to demonstrate currently available data processing algorithms (Moussiopoulos et al., 2018a)[2].

The hardware development for new network sensors is based on optical sum (nephelometry) and / or individual particle analysis (optical particle counting). Optimally, both measurement tasks are realized by an inexpensive nephelometer which is called here scout (autonomous, mobile smart dust measurement device that is auto-calibrated to a high-quality reference instrument within an intelligent monitoring network). The architecture to build up a test network in the model region Augsburg, Germany, is developed. The data architecture of the project implements a complete Internet of Things Stack using the latest Smart Data technologies (see Budde et al. (2017a)[1]).

Further, unmanned aerial vehicles (UAV) with low-weight weather parameter sensors and particle counter are used to monitor the three-dimensional dynamics of the lower atmosphere. In a fixed sounding program several flights per week are performed at the University campus.

Ground-based remote sensing by ceilometer for mixing layer height (equivalent boundary layer height (BLH) is used here) detection (see Emeis et al. (2004)[3], Wiegner et al. (2014)[4]) as well as a Radio-Acoustic Sounding System (RASS) for temperature and wind profile measurements (see Emeis et al. (2009)[5], Emeis et al. (2012)[6]) at the University campus complete the new network and UAV height profiling of atmospheric parameters. Such complex monitoring provides the basis of deeper process understanding of air pollution and evaluation data for small-scale chemistry-transport modelling (see Schäfer et al. (2005)[7], Schäfer et al. (2006)[8], Schäfer et al. (2011)[9], Schäfer et al. (2016)[10], Wagner, Schäfer (2017)[11]).

First results about spatial variation of meteorological influences upon air pollution exposure will be shown and discussed using ceilometer, UAV and the existing monitoring network data.

2. NETWORK ARCHITECTURE AND METHODOLOGY

2.1 Network architecture

Consistency and also intelligent communication of mobile measuring devices (for example validation and self-calibration) are included. The site selection criteria for 50 scouts and 5 reference meters were defined as following:

- Integration into the available air quality monitoring network of the Bavarian State Agency for Environment – Landesamt für Umwelt (LfU),
- Coverage of the whole Augsburg area (see Fig. 1),
- Regular siting for spatial representativity,
- Detection of emission hot spots (road traffic, residential heating).

The site characterization includes these topics:

- Lan or WLAN network availability,
- Electricity availability,
- Local spatial representativity.

A concept for the SmartAQnet network phase 1 has been drafted with the idea of a Central Activity Zone (CAZ) centred around an existing state air quality monitoring station at Königsplatz of a 2 km x 4 km area (see Figure 1 in red) and including the University campus. The CAZ provides the opportunity to test deployment and calibration strategies with new sensors (scouts) and existing sensors and 5 reference meters, as well as upload and processing of data on the SmartAQnet server during an intensive observation month (IOM), which is planned for in September/October 2018. Figure 1 includes the modelling domains also for transport modelling by GRAL in blue and for wind field modelling by GRAMM in green (Oettl, Uhrner, 2011)[12].

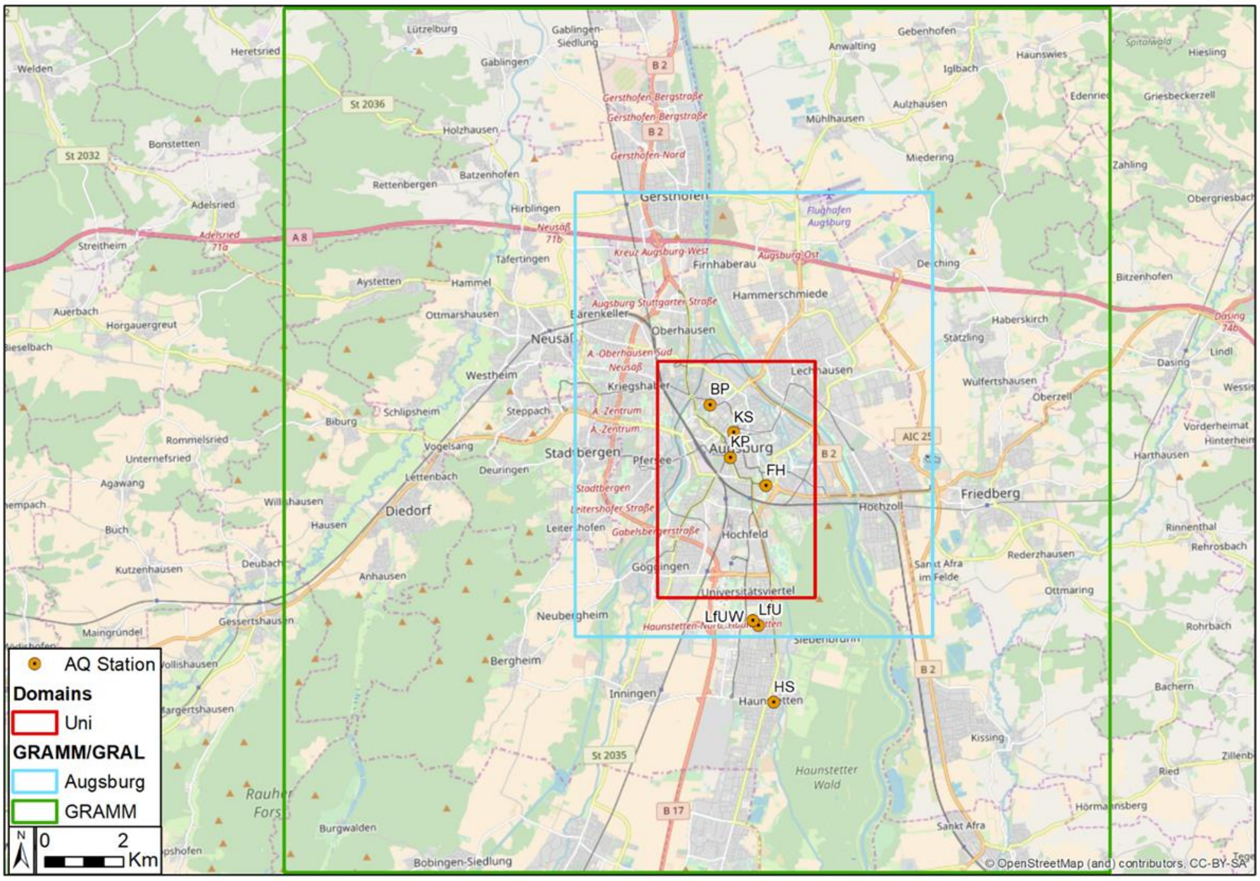

Figure 1. Augsburg with the state air quality monitoring (LÜB) stations BP – Bourgesplatz, KS – Karlstrasse, KP – Königsplatz, LfU – Landesamt für Umwelt, LfUW – weather station at Landesamt für Umwelt and HS – Haunstetten, FH – the Aerosol station of the German Research Center for Environmental Health (HMGU), the area of the Central Activity Zone (CAZ) in red, the area for transport modelling by GRAL in blue, the area for wind field modelling by GRAMM in green.

Additionally, bicycles are equipped with sensors for meteorological parameters and PM. Data are collected together with GPS information. The bicycle routes complete the spatial coverage of in situ sensors of the new network and include stops of about 5 minutes at reference instruments, monitoring stations and scouts.

A prototype backpack for walking measurements was constructed using sensors for fine and ultrafine particles as well as particle sampling for chemical analyses of particles in the laboratory by GC-MS analytical method in addition to a GPS tracker and a Point of View (POV) camera. The particle counters enable to trace ambient PM concentrations' changes. A MicroAethalometer enables BC measurements and despite the very low detected concentrations, spatial and temporal variation can be clearly realized.

Finally, a regional background site with a reference instrument will be set up south-east of Augsburg city at the edge of the GRAL area.

2.2 In situ sensors

The scouts are prototype instruments - inexpensive nephelometers EDM80 Nephs (see Figure 2) which are extremely fast and include an intelligent signal evaluation through extensive comparison measurements to reference devices. They are characterized by a low signal-to-noise ratio, which can additionally be significantly altered by environmental influences.

The EDM164 for PM_{10}, $PM_{2.5}$ and PM_1 concentration measurements is used as reference meter.

Figure 2. Prototype nephelometer EDM80 Neph called here scout (autonomous, mobile smart dust measurement device that is auto-calibrated to a high-quality reference instrument within an intelligent monitoring network) installed at the state air quality monitoring station Karlstrasse.

Low-cost sensors are added in the network at fixed sites and by means of smartphones of citizen. The possibilities and challenges of bringing experts together with laypersons will also be investigated (see Budde et al. (2017b)[13] for first results).

2.3 UAV

UAV are equipped with low-weight weather parameter sensors and particle counter which are used to monitor the three-dimensional dynamics of the lower atmosphere. A meteobox with three temperature and humidity sensors (SHT75, P14rapid and Temod-I²C) is. Particulate matter is measured with an Alphasense OPC-N2. To reduce the influence of the UAV body, special sensor inlets and pumps are installed.

Daily UAV morning profiles at the University campus (see Figure 3) are flown by fixed-wing UAV and copter to detect:

- PM_{10} concentrations,
- Relative humidity,
- Temperature.

Figure 3. Location for the fixed-wing UAV (left, spiral rise) and copter (right, straight rise) height profiling at the campus of the University of Augsburg.

2.4 Ceilometers

Three ceilometers which are mini-lidar will be operated at a North-South profile through the urban area for BLH detection. The locations (see Figure 1) are at the University campus, at the HMGU Aerosol station and near Bourgesplatz at a monastery garden. BLH can be determined fairly well by ceilometers in the absence of low clouds and precipitation and during scattered clouds (Wiegner et al., 2014)[4]. Measurements have been performed with *VAISALA* ceilometers CL31 and CL51. The instrument characteristics are: one lens design with a diode laser of 910 nm wavelength, capable to cover an altitude range higher than 4000 m; eye-safety class 1M; fully automated; hands-off operation mode; permanent monitoring of laser power and window contamination for long-term performance stability; averaging over time and height for suppression of noise generated artefacts; sliding averaging and set of minimum accepted attenuated backscatter intensities; typical range resolution 10 m; lowest detectable layers around 50 m; temporal averaging 10 min or one hour. The heights of the near surface aerosol layers are analysed by a gradient method from optical vertical backscatter profiles routinely with a MATLAB-based software (Münkel et al., 2011)[14]. The minima of the vertical gradient (the term 'gradient minimum' is used here to denote the most negative value of the gradient) are given as an indication of the BLH and for the upper edge of up to 4 more layers above.

2.5 Radio Acoustic Sounding System (RASS)

A RASS for temperature and wind profile measurements (Emeis et al., 2009)[5] is running at the University campus to complete the new network. The *METEK* RASS used here (Schäfer et al., 2012)[15] is a Doppler-RASS or SODAR-RASS that measures continuously profiles of wind speed, wind direction, variance of the vertical wind component and of acoustic temperature with a vertical resolution of 20 m up to a height of 540 m. BLH is 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. From RASS measurements, in principle, BLH can either be determined from the temperature profiles or from the electro-magnetic backscatter intensity (Emeis et al., 2012)[6]. The latter depends on temperature and moisture fluctuations in the atmosphere.

3. FIRST MEASUREMENT RESULTS

3.1 Example day 22/03/2018

On 22/03/2018 at 6 UTC flights with a fixed-wing UAV (Figure 3 left) and a copter (Figure 3 right) were carried out at the University campus. The starting place from the copter was on top of the University roof a few meters next to the ceilometer CL51. Three ascents were performed up to a height of 200 m asl. On top of the fixed-wing the meteobox is installed. The same meteobox is installed on the copter and particulate matter is measured additionally. The aim of these measurements was to compare the particulate matter measurements by the copter with the backscatter signal from the ceilometer. In Figure 4 the backscatter signal of the ceilometer for the whole day is shown. For each layer the calculated height is given together with a quality index, where 3 is the best level (Figure 4 top). At 6 UTC the BLH calculated with the ceilometer backscatter signal data is about 100 m, which matches to the meteorological conditions measured by the UAVs - there is a temperature inversion in the height from 70 up to 150 m agl. Until 9 UTC there is a more or less pronounced mixing layer in about 100 m agl. This part of the boundary layer is layered stable and the particulate matter concentration in this area is high (Figure 4 bottom). Here the PM_{10} concentrations measured at the nearby LÜB station LfU fluctuated between 23 and 30 µg/m³. After 9 UTC the mixing layer rises up and the particulate matter concentration decreases. At 15 UTC it begins to rain. Here the PM_{10} concentration increases slightly until 17 UTC due to particle growing with high humidity.

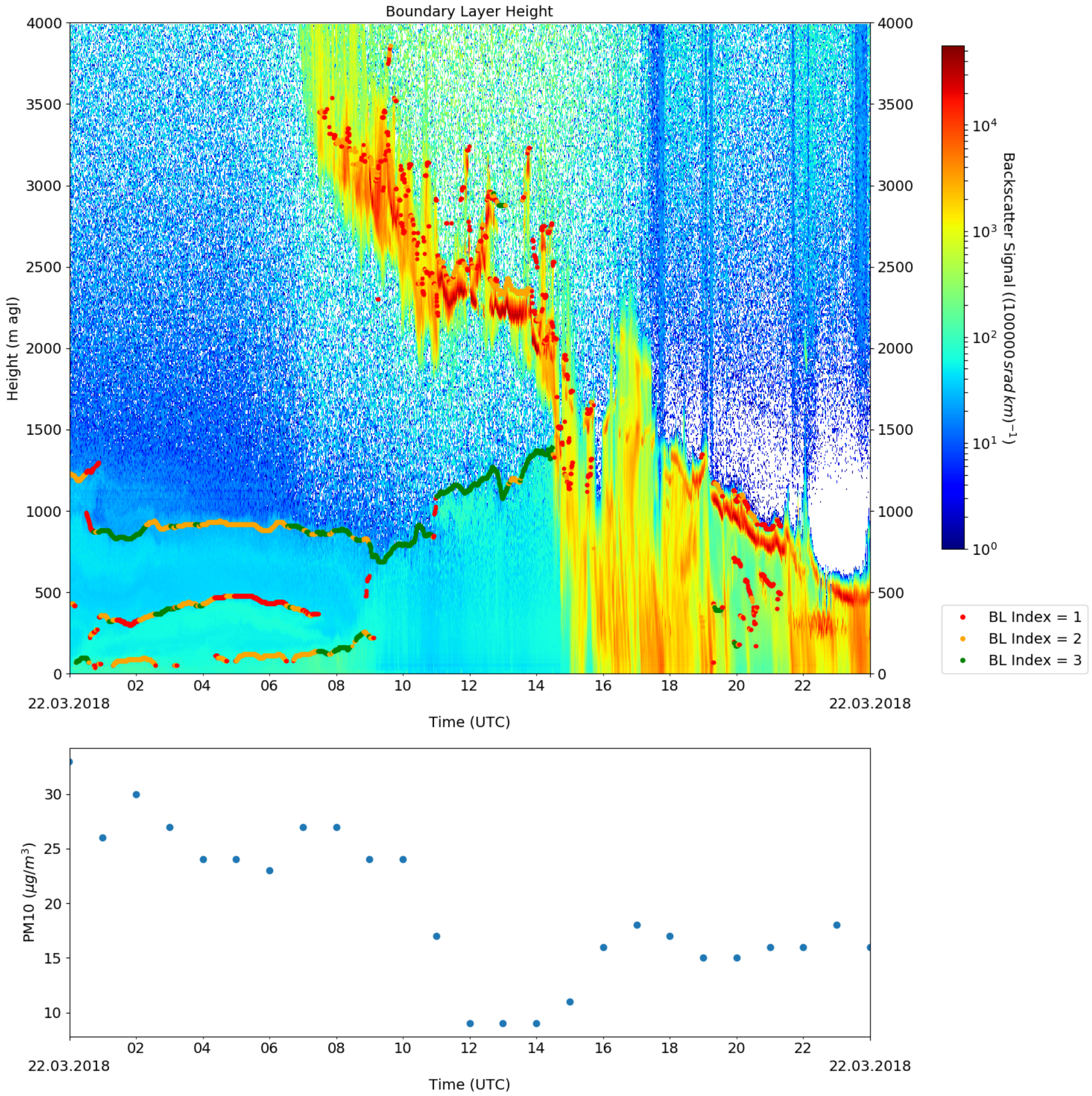

Figure 4: Top: Backscatter signal from the ceilometer on 22/03/2018 and layer heights with three quality levels (red: BL Index=1, orange: BL Index=2 and green: BL Index=3 (best quality)). Bottom: PM_{10} concentration at the LÜB station LfU on 22/03/2018.

In Figure 5 the results of relative humidity and temperature measured during the fixed-wing flights (5a), backscatter intensity measured by the ceilometer and PM_{10} concentration detected during the fixed-wing flights (5b) and scatterplot of PM_{10} concentration and backscatter intensity (5c) at 10 UTC are shown. There is a temperature inversion in 580 m asl which corresponds well with a strong decrease of backscatter intensity and PM_{10} concentration above this height. The nearly constant temperature profile above 650 m asl agrees also with a nearly constant backscatter intensity and PM_{10} concentration above this height. The trends from particulate matter concentration und backscatter signal are similar (Figure 5b) and the correlation coefficient is 0.983 (Figure 5c).

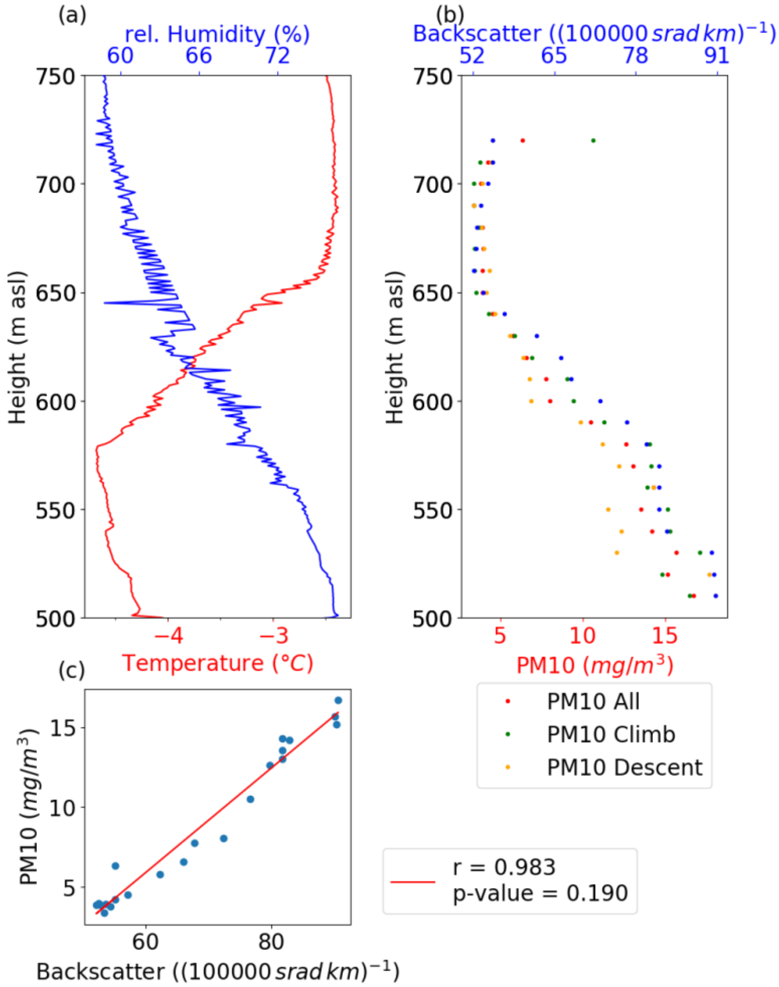

Figure 5: (a) Temperature red) and rel. humidity blue) in different heights measured by the fixed-wing flights, (b) PM_{10} concentration averaged over 10 m sections in the altitude (red: all, green: only during the climb, orange: descent), measured by the Alphasense OPC-N2 of the copter and backscatter signal (blue) averaged over the flight time, measured by the ceilometer CL51, (c) Scatterplot of the data shown in (b).

3.2 Comparison of PM_{10} concentrations at the four LÜB stations and BLH measured with a ceilometer

The PM_{10} concentrations at the four LÜB stations in Augsburg (Bourgesplatz – urban background site, LfU – urban background site, Karlstrasse – traffic site, Königsplatz – traffic site) are measured in hourly resolution. The ceilometer CL51 backscatter intensities, used to detect up to three layers with quality levels, are applied and the first height with the BL-Index 3 is analyzed. Data were evaluated from 15/10/2017 until 31/07/2018 and averaged hourly values were used. The histogram of the calculated BLH in 100 m intervals is shown in Figure 6 and the highest number of BLH is at 400 m agl. Figure 7 shows the boxplot of the daily course of BLH in one-hour intervals with highest BLH at 14:00 UTC and lowest BLH between 03:00 and 06:00 UTC.

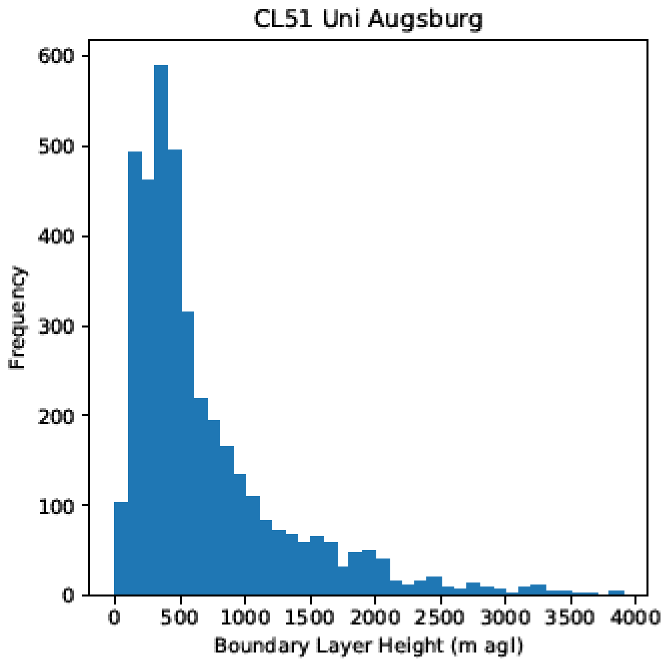

Figure 6: Histogram of the calculated boundary layer height in 100 m intervals determined from ceilometer backscatter intensities.

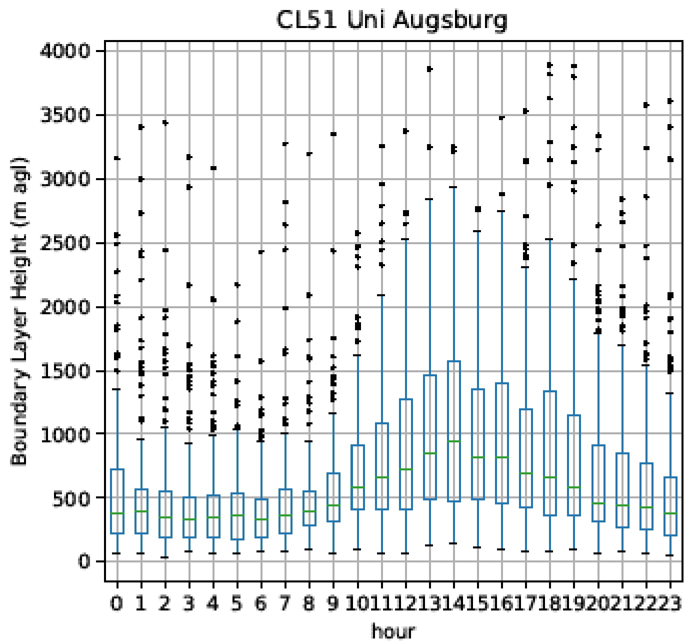

Figure 7: Boxplot of the daily course of the boundary layer height in one-hour intervals of UTC determined from ceilometer backscatter intensities.

For the comparison of PM_{10} concentrations and BLH 200 m intervals were used for the BLH (see Wagner, Schäfer (2017)[11]). There is a linear relationship between PM_{10} concentration and BLH. Especially when considering the maximum values, the BLH is low during high PM_{10} concentrations. When considering the mean values, the linear relationship can be seen up to a BLH of about 1200 m. Above this height, the number of detected layers is lower (see Figures 8 - 11). Also Figures 8 - 11 bottom left illustrates the correlation between high BLH values and low PM_{10} concentrations. Here the PM_{10} concentrations were divided into three categories (<20 µg/m³, 20 - 50 µg/m³, >50 µg/m³). This allocation is based on the classification of the air quality classes of the LfU, whereby two classes have always been combined. PM_{10} values above 50 µg/m³ are rather rare (see Figures 8 - 11 bottom right), and in most cases the BLH is below 1000 m and the median is below 500 m (see Figures 8 - 11 top left).

Figures 8 - 11 top right show corresponding PM10 concentrations. Here the classical course of the BLH is reflected, whereby PM_{10} concentrations increase in the morning, decrease during the day and increase again in the evening. The course of PM_{10} concentration is exactly the opposite of the daily BLH course. Median PM_{10} concentrations are minimum around 15 UTC and maximum during the night.

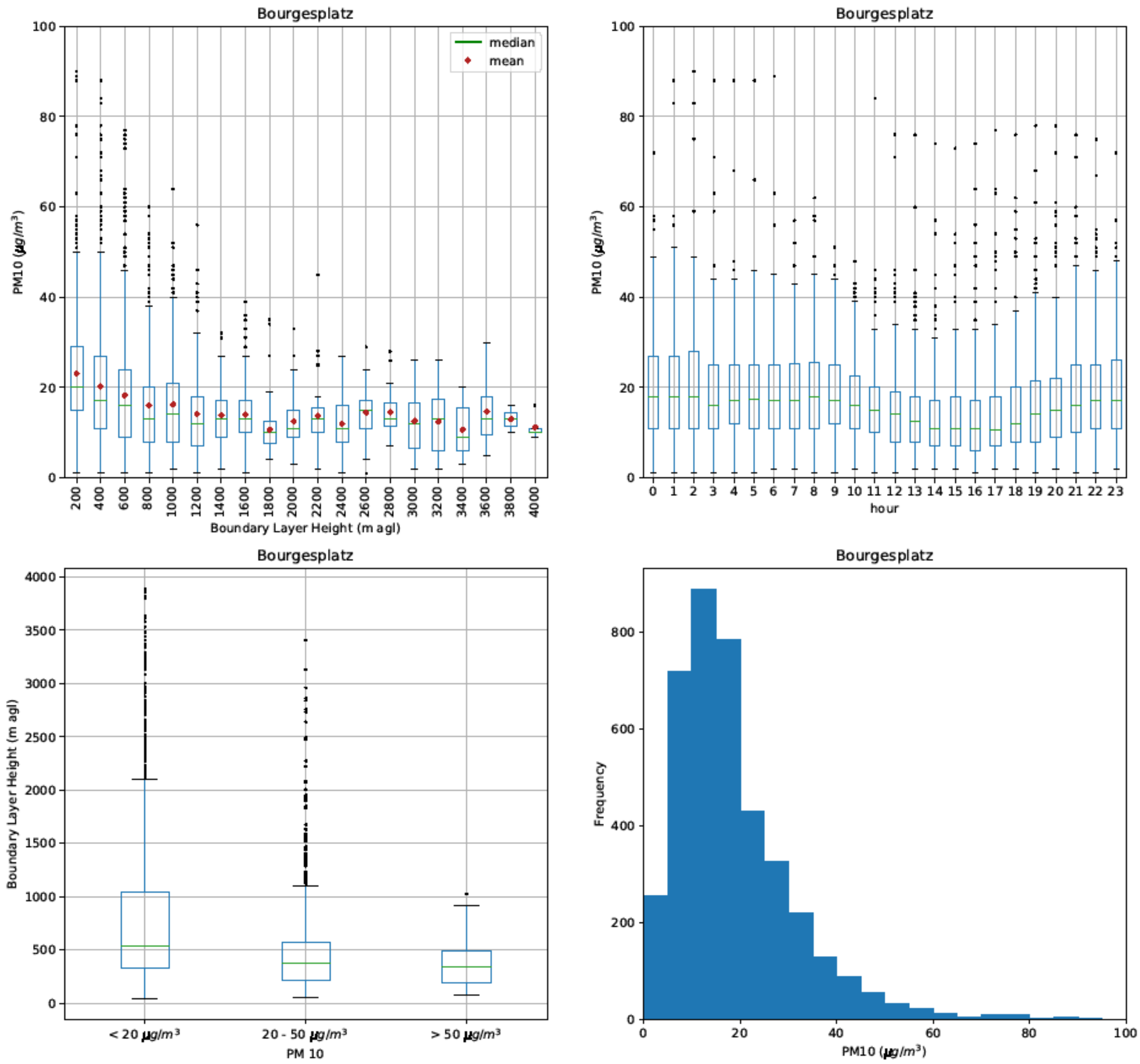

Figure 8: Analyses of the PM_{10} concentration data at the LÜB station Bourgesplatz (urban background) together with boundary layer height (BLH). Top left: PM_{10} concentrations for different BLH, divided into 200 m intervals. Top right: Boxplot of the daily course of PM_{10} concentrations in one-hour intervals. Bottom left: Boxplot of the BLH grouped into three categories of PM10 concentrations. Bottom right: Histogram of PM_{10} concentrations in 5 µg/m³ intervals.

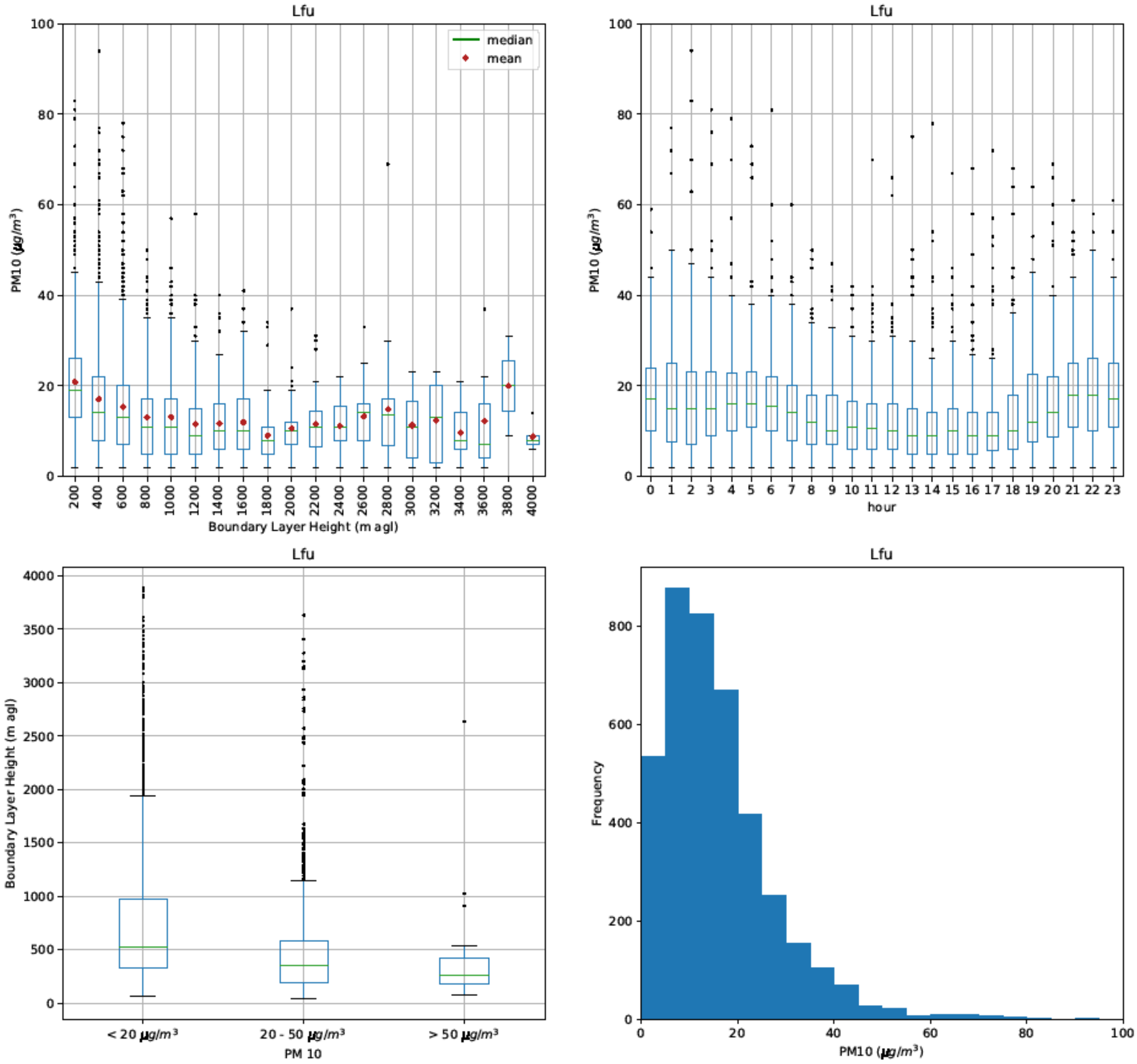

Figure 9: Analyses of the PM_{10} concentration data at the LÜB station LfU (urban background) together with boundary layer height (BLH). Top left: PM_{10} concentrations for different BLH, divided into 200 m intervals. Top right: Boxplot of the daily course of PM_{10} concentrations in one-hour intervals. Bottom left: Boxplot of the BLH grouped into three categories of PM_{10} concentrations. Bottom right: Histogram of PM_{10} concentrations in 5 µg/m³ intervals.

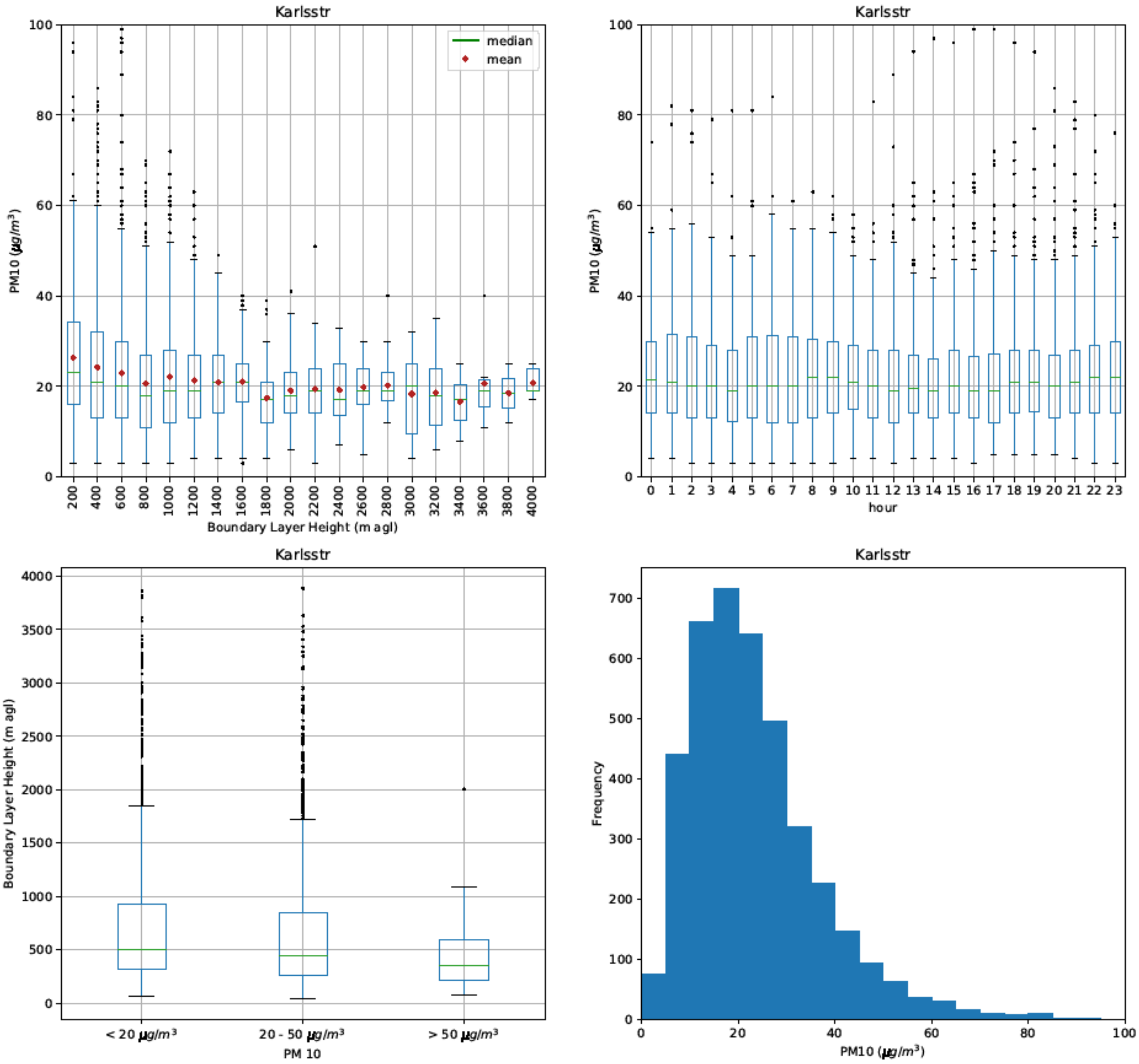

Figure 10: Analyses of the PM_{10} concentration data at the LÜB station Karlstrasse (traffic site) together with boundary layer height (BLH). Top left: PM_{10} concentrations for different BLH, divided into 200 m intervals. Top right: Boxplot of the daily course of PM_{10} concentrations in one-hour intervals. Bottom left: Boxplot of the BLH grouped into three categories of PM_{10} concentrations. Bottom right: Histogram of PM_{10} concentrations in 5 µg/m³ intervals.

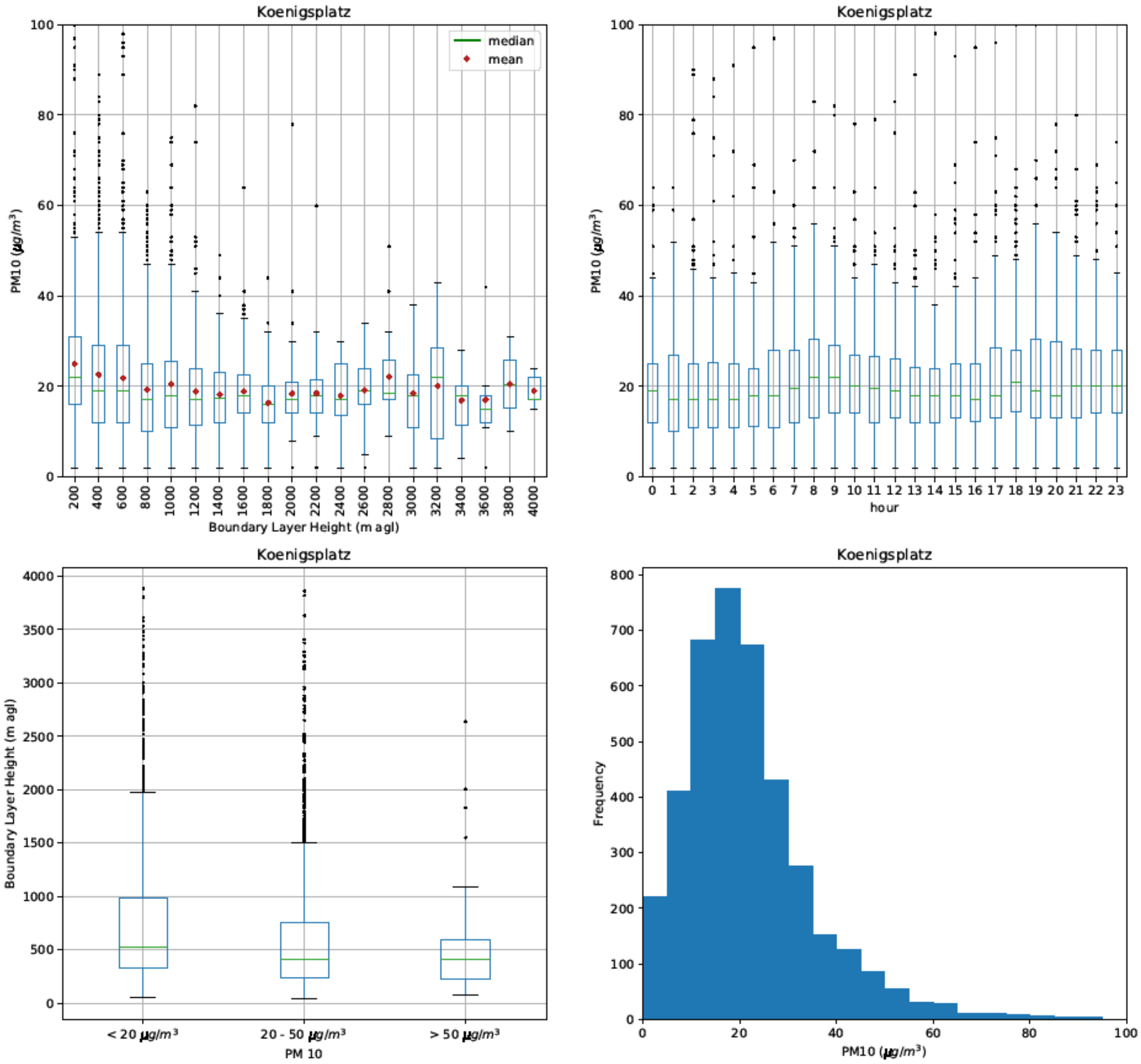

Figure 11: Analyses of the PM_{10} concentration data at the LÜB station Königsplatz (traffic site) together with boundary layer height (BLH). Top left: PM_{10} concentrations for different BLH, divided into 200 m intervals. Top right: Boxplot of the daily course of PM_{10} concentrations in one-hour intervals. Bottom left: Boxplot of the BLH grouped into three categories of PM_{10} concentrations. Bottom right: Histogram of PM_{10} concentrations in 5 $\mu g/m^3$ intervals.

4. DISCUSSION

The general agreement of profile characteristics of temperature and relative humidity from UAV as well as ceilometer backscatter and BLH corresponds to findings from comparison between radiosonde data at Oberschleissheim (about 50 km east-south-east of Augsburg) and ceilometer monitoring (see Emeis et al. (2012)[6]). It is an advantage that UAV observations are more flexible than radiosonde soundings so that UAV flights can be performed consequently nearer to ceilometer measurements.

The inter-comparison of backscatter intensity measured by the ceilometer and PM_{10} concentration detected during the fixed-wing flights is a new result. The conclusion that the trends from particulate matter concentration und backscatter signal are similar, shown by a correlation coefficient of 0.983, supports the ability of ceilometers to detect atmospheric layers and BLH (see Wiegner et al. (2014)[4]).

The significant anti-correlation between daily courses of BLH and PM_{10} at the four LÜB stations agree with earlier results too (see Schäfer et al. (2006)[8], Schäfer et al. (2011)[9], Schäfer et al. (2016)[10], Wagner, Schäfer (2017)[11]). It is a result of the analyses with these data of different monitoring sites (urban background and traffic) in one city that the BLH influence at the urban background sites is higher than at the traffic sites (Figures 8 – 11 top left). At a traffic site the emissions dominate over the BLH influence (Wagner, Schäfer, 2017)[11] (Figures 8 – 11 bottoms left) so that the concentrations are generally higher (Figures 8 - 11 top right, bottom right).

5. CONCLUSIONS

The inter-comparison of different air pollution monitoring stations in Augsburg to detect the spatial variation of the BLH influence upon air quality shows, that there are differences so that the influence of emissions upon air quality is different too. This supports the core of the SmartAQnet project which is a feasibility study aimed at investigating the potential of wide-spread distributed aerosol measurements with intelligent measurement networks of heterogeneous sensors in urban areas. The aim of the project is to perform data analyses from a reproducible, space-time adapted and cost-effective air quality measurement network in which the state air quality monitoring stations are included. Finally, the data availability and quality for end users will be improved for

- the overall air quality,
- the personal exposure i.e. information for health care,
- health research,
- air quality forecast,
- traffic management.

This means a comprehensive determination of PM by a measurement network of fixed and mobile heterogenous sensors, which are continuously operated, remote sensing by ground-based methods at some sites, mobile in situ measurements and numerical simulations of spatial and temporal PM concentrations on a small scale are required. Such working tasks are commonly up to date because these are performed in similar projects (Moussiopoulos et al., 2018b)[16].

6. OUTLOOK

The data analyses from a reproducible, space-time adapted and cost-effective air quality measurement network will include the comparison and evaluation of summary data for Augsburg with the results of numerical simulations. To follow this task the model GRAMM/GRAL is set-up for small-scale transport modelling (see Figure 1). First results of calculated PM_{10} concentration fields are available on the basis of earlier emission inventories. Later the planned PALM4U chemistry-transport simulations of air pollution (http://www.uc2-program.org/) on the basis of the spatial high-resolved emission inventory will be performed. The following conclusions from modelling for spatially high-resolved measurements are planned:

- Evaluation of data from multilayer, heterogenous measurement network for air pollutants and application of available data of air quality for Big-Data-Analyses to improve data quality,
- Comparison of measurement data with results of small-scale chemistry-transport modelling for evaluation of background conditions, initialisation and model validation,
- Inverse modelling to determine emission source strengths / hot spots,
- Application of results of small-scale simulation of air pollution to reduce space-time gaps of measurement network,
- Improvement of small-scale simulation of air pollution to forecast air quality,
- Development of space-time fields of aerosol distribution by geo-statistic interpolation and further statistical methods for measured data.

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