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ABSTRACT

Ground-based remote sensing by three ceilometers for mixing layer height detection over Augsburg as well as a Radio-Acoustic Sounding System (RASS) for temperature and wind profile measurements at the campus of Augsburg University are applied together with UAV height profiling with low-weight meteorological sensors and particle counter to monitor the three-dimensional dynamics of the lower atmosphere. Results about meteorological influences upon spatial variation of air pollution exposure are presented on this data basis which is more than one year long. Special focus is on the information about atmospheric layering as well as mixing and transport conditions for emitted particulate matter. Better understanding of these complex processes support knowledge about quality of air, which we breath, and especially high air pollution episodes and hot spot pollution regions.

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

1. INTRODUCTION

The Smart Air Quality Network (SmartAQnet) project is aimed at appropriation of individual air pollution exposure and health risks data by integration of existing in situ instrument, spatially high-resolved network, unmanned aerial vehicle (UAV) sounding and remote sensing data sets by a new air pollutant monitoring strategy in the urban space. The project SmartAQnet, funded by the German Federal Ministry of Transport and Digital Infrastructure - Bundesministerium für Verkehr und digitale Infrastruktur (BMVI) under grant no. 19F2003B will reduce gaps in currently available spatial and temporal air pollution data coverage. The architecture to build up a test network is realized in the model region Augsburg, Germany, including a consistent and also intelligent communication of measuring devices by a complete Internet of Things Stack using the latest Smart Data technologies. An introduction to the project was given at SPIE by Budde et al. (2017)[1] and a first data presentation by Redelstein et al. (2018)[2].

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For the first time 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) are combined with remote sensing and a networked air pollutant measurement strategy with middle- and low-cost sensors in the urban space. Remote sensing instruments at the ground and airborne platforms with in-situ sensors (unmanned aerial vehicle – UAV, also named rotorcraft and copter) close some gaps whereas there are strong limitations in spatial and temporal coverage. UAV are equipped with low-weight weather parameter sensors and particle counter to monitor the three-dimensional dynamics of the lower atmosphere. In a fixed sounding program at every day on 07:00 am flights are performed at the Augsburg University campus.

Ground-based remote sensing by ceilometer for mixing layer height (MLH, 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 Augsburg 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 characteristics relevant for air pollution exposure will be shown and discussed using ceilometer, RASS and UAV.

2. INSTRUMENTATION AND METHODOLOGY

The ceilometers *Vaisala* CL31 and CL51 are mini-lidar with one optical axis (Emeis, 2010)[12] for usually vertical visibility and cloud characteristics detection which allows for observations from a few tens of metres up to several kilometres above ground with an eye-safe diode laser of 910 nm wavelength, a vertical resolution of about 10 m and a lowest detectable layer at around 50 m. The instruments are sited at a North-South profile through the urban area of Augsburg, Germany: near Bourgesplatz at a monastery garden, at the HMGU Aerosol station and at the university campus (see Figure 1). 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, 2007[13]; Emeis et al., 2008[14]; Münkel et al., 2011[15]). The minima of the vertical gradient (the most negative value of the gradient) are given as an indication of the BLH and for the upper edge of up to 3 more layers above (Emeis et al., 2007)[16]. An averaging over time (10 min or one hour) and height enables the suppression of noise generated artefacts. A sliding averaging is done and minimum accepted attenuated backscatter intensities are set. The BLH retrieval algorithm works appropriately during nearly cloudless conditions.

Figure 1. Ceilometers *Vaisala* CL51 at the roof of the Building of the Institute of Geography of the University of Augsburg.

The *METEK*-RASS used for direct comparisons at the university campus (see Figure 2) is a Doppler-RASS (Emeis, 2010)[12] that measures profiles of wind speed, wind direction, variance of the vertical wind component by analysing the Doppler shift of the acoustic signal with frequency of 1,600 Hz and of acoustic temperature by electro-magnetic wave sounding at 474 MHz of the acoustic disturbance in the atmosphere with a vertical resolution of 20 m from about 60 m up to a height of 540 m. The acoustic signal power is reduced down to 15 % normally due to noise protection of people at the university campus. Power is enhanced up to 60 % only during special periods. In consequence to this reduction the range is up to about 100 m normally and sometimes up to about 200 m. The temperature determined from RASS measurements depends on the air humidity, so the UAV data must be converted into the so-called acoustic temperature for comparison. 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 derivation of BLH from the temperature gradient profile requires a good vertical resolution of the profile, which is mainly available from the RASS and is done here. BLH is taken from all these measurements as upper boundary height of the first detected layer above ground or near-surface layer.

Figure 2. Radio-Acoustic Sounding System (RASS) which is installed at the campus of the University of Augsburg about 300 m north of the ceilometer.

The rapid development of microcontroller and small sensor technology has established the use of UAV in the exploration of boundary layer phenomena (e.g. Reuder et al., 2009[17]; Anderson and Gaston, 2013[18]). The advantage of UAV measurements over remote sensing instruments is to measure in-situ with a high spatial resolution. The UAV systems used are a self-constructed fixed-wing aerial vehicle, with a wing span of 1.4 m and a take-off weight of 1.3 kg, and a rotorcraft of type DJI Matrice 600 pro (see Figure 3). The 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 installed, the main sensor is the SHT75 produced by Sensirion. On the fixed-wing the sensors are placed in a radiation protection tube, which is angled at the front and the back in order to avoid radiation if sun is low on the horizon. Sensor ventilation is achieved only passively by the airspeed. On the hexacopter the sensors are mounted in a vertical radiation protection tube directly below one of the six rotors in order to achieve strong ventilation. Particulate matter is measured with an Alphasense OPC-N2

Daily UAV morning profiles at the Augsburg University campus (see Figure 3) are flown by fixed-wing UAV or copter (see Figure 4) to detect:

- PM_{10} and $PM_{2.5}$ concentrations,
- Relative humidity,
- Temperature,
- Wind.

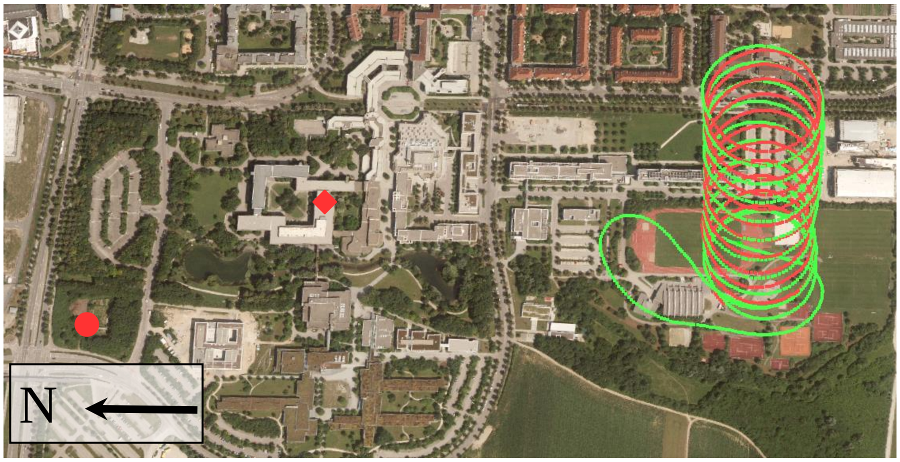


Figure 3. Location for the fixed-wing UAV (spiral rise) and copter profiling on the sportsground, ceilometer (diamond) and Doppler-RASS (circle) at the campus of the University of Augsburg.

Figure 4. Copter (left) and fixed-wing UAV (right) for height profiling at the campus of the University of Augsburg.

3. FIRST MEASUREMENT RESULTS

Regular UAV measurements at the campus of the University of Augsburg each day on 07:00 provide profiles of temperature (orange) and virtual potential temperature (blue) which are shown in Figures 5a) to 5e). At first a situation is shown with a clear BLH determined from ceilometer backscatter intensities and temperature inversion (upper boundary): both values agree with each other (Figure 5a). A day is demonstrated without a detected temperature inversion and BLH from ceilometer measurements (Figure 5b). In Figure 5c) a day is shown without a temperature inversion but a BLH detected from ceilometer measurements. The opposite is the case in Figure 5d) and in Figure 5e) a temperature inversion is detected between about 100 and 225 m and the BLH is determined by the parcel method at about 150 m which is in agreement with the ceilometer measurements (123 m).

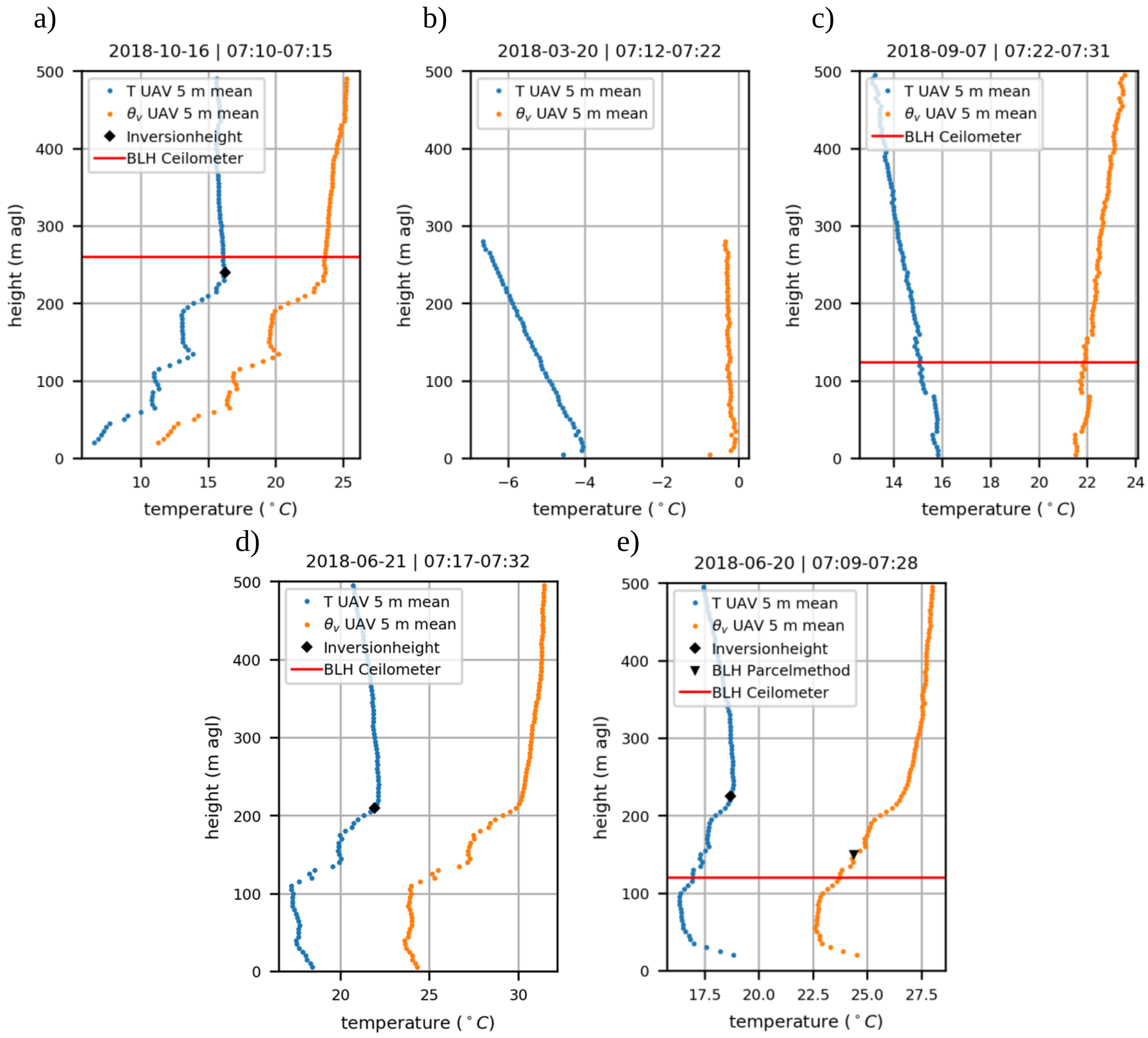


Figure 5a) – 5e). UAV measurements at the campus of the University of Augsburg of temperature profiles (orange) and virtual potential temperature (blue). Shown are boundary layer heights (BLH) determined from ceilometer backscatter intensities (red), upper boundary of inversions (diamond) and applied parcel method (triangle).

UAV measurements at the campus of the University of Augsburg of temperature and $PM_{2.5}$ profiles are given in Figure 6 left. The $PM_{2.5}$ concentration decreases above the temperature inversion indicating that the temperature inversion is the upper boundary of the near-surface well-mixed layer. Figure 6 right shows the diurnal variation of the BLH calculated from the ceilometer at the University of Augsburg on the same day. The first BLH is with 40 m height lower than the temperature inversion and the second BLH is in 350 m height. At this height there is also a small decrease in the PM2.5 concentration. At 09 UTC the BLH rises until sunset.

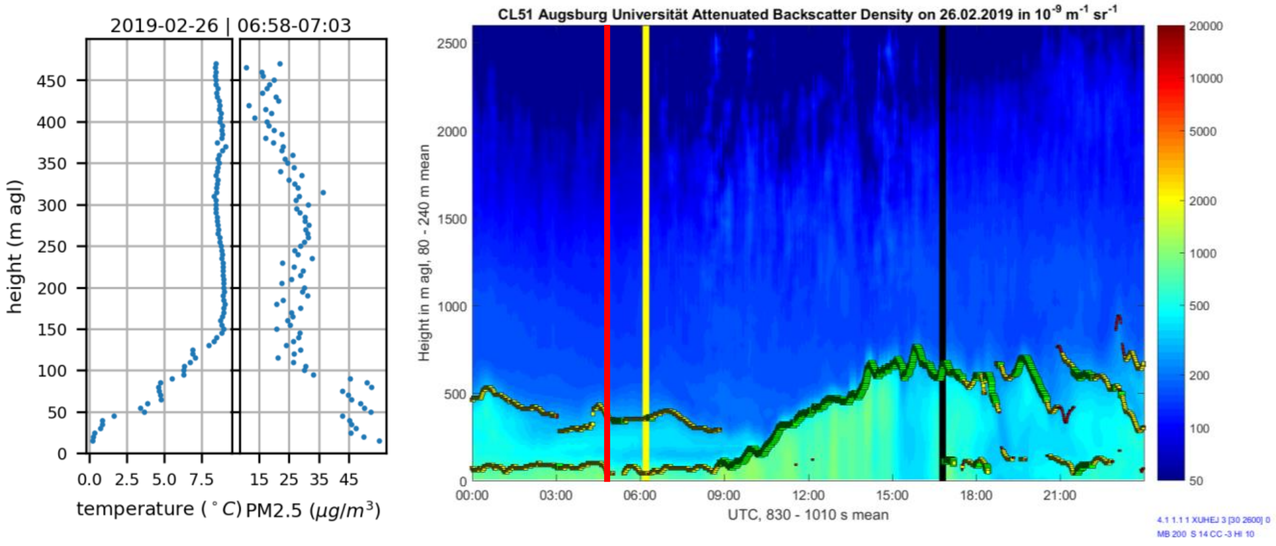
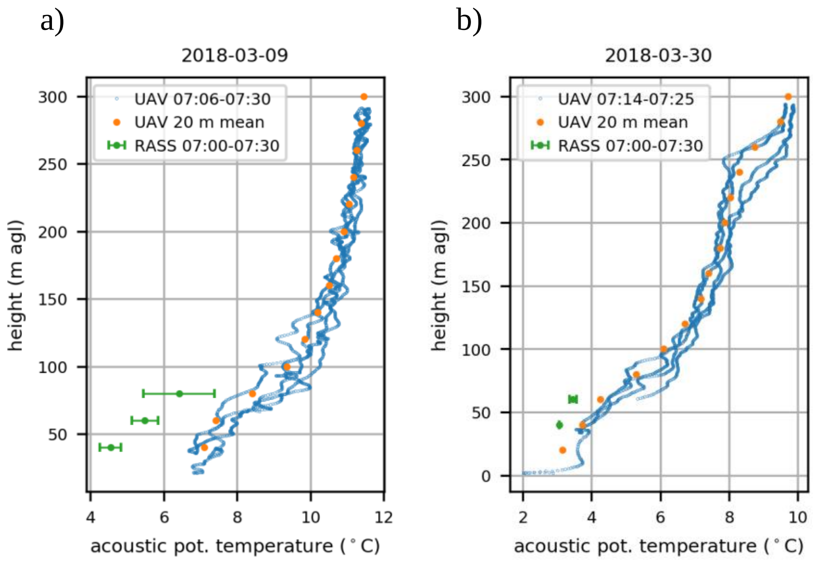


Figure 6, left. UAV measurements at the campus of the University of Augsburg of temperature and $PM_{2.5}$ profile. Right. Diurnal variations of the attenuated backscatter density and BLH from the CL51 at the campus of the University of Augsburg. Red line: UAV ascent, yellow line: sunrise, black line: sunset.

The comparison of the acoustic potential temperature from remote sensing by RASS and in situ measurements by UAV is shown in Figure 7. The data output by the RASS are 10 min mean values. The mean value of the data between 07:00 and 07:30 is shown here, with bars to the minima and maxima in that time. Figures 7a) and 7b) provide decreasing temperature with height but a slight shift of RASS temperatures to lower values is visible. Temperature inversions are demonstrated in Figures 7c) and 7d).



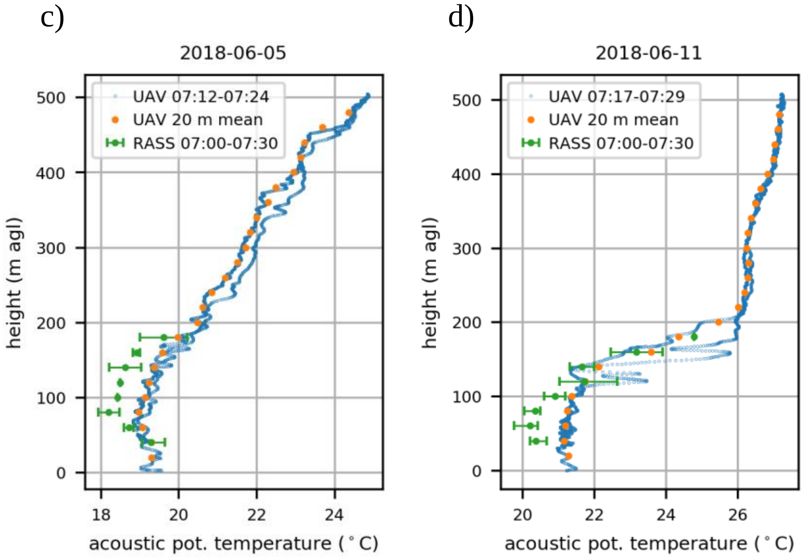


Figure 7a) – 7d). UAV measurements at the campus of the University of Augsburg of acoustic potential temperature profiles of original vertical resolution (blue) and 20 m mean (orange) as well as RASS measurements of acoustic potential temperature profiles (green). It is the mean between 7:00 and 7:30 shown, as well as the minima and maxima in this period with a bar.

4. DISCUSSION

The comparison between the boundary layer height calculation by measurements on the UAV and measurements with a ceilometer shows several similarities in different situations. This depends of course on the measurement methods used to determine the BLH, but also on the respective weather condition where the methods work better or worse.

The comparison of the profile of the acoustic potential temperature between RASS and UAV data shows good agreement in the examples. However, there is sometimes a difference of up to 2°C within the half hour shown in the RASS data. Furthermore, the RASS data quality depends on weather conditions and the acoustic sound power, which cannot be permanently strong in an inhabited area due to noise pollution. This means that the same measurement heights cannot always be achieved, which may also make it more difficult to determine the BLH.

5. CONCLUSIONS AND OUTLOOK

Measurements of vertical profiles with UAVs is a new concept in science, which has advantages and disadvantages compared to remote sensing devices. UAVs can be used flexibly, and the measuring instruments mounted on this platform can make in-situ measurements with a high vertical resolution. However, UAVs always require a pilot, so a high temporal resolution cannot always be given over long periods. A solution for obtaining temporally and spatially high-resolution data is the combination of these measurement methods. This measurement concept is pursued in the SmartAQnet project.

In order to make use of the different measurement methods, they should be compared with each other. Here a few examples were shown, which have different agreements. By comparing as many different situations as possible, a statistical evaluation is to be made, which may possibly also lead to an assessment of the differences in different weather situation classifications.

In the SmartAQnet project, an experimental particulate matter prediction platform based on neuronal networks will be developed. Here meteorological input variables play a major role, especially the lowest stratification of the atmosphere, which is sounded by the measuring instruments presented here (UAV, ceilometer and RASS). The temporal change of the lowest stratification cannot of course be observed by one UAV ascent in the morning, so that the remote sensing devices play an important role here. Possibly the backscatter intensity of the ceilometer can be used to estimate the particulate matter concentrations at different altitudes. Therefore, a previous comparison between UAV and ceilometer in different weather conditions is very important in order to be able to better assess the information of the data. The RASS gives important information about wind velocity and direction, as well as the BLH.

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REFERENCES

[1] Budde, M., Riedel, T., Beigl, M., Schäfer, K., Emeis, S., Cyrys, J., Schnelle-Kreis, J., Philipp, A., Ziegler, V., Grimm, H., Gratza, T., "SmartAQnet – Remote and In-Situ Sensing of Urban Air Quality." Proc. SPIE, 10424, 104240C-1–104240C-8 (2017).

[2] Redelstein, J., Budde, M., Cyrys, J., Emeis, S., Gratza, T., Grimm, H., Hank, M., Hinterreiter, S., Münkel, C., Pesch, M., Petersen, E., Philipp, A., Riedel, T., Riesterer, J., Schäfer, K., Schnelle-Kreis, J., Uhrner, U., Werhahn, J., Ziegler, V., Beigl, M., "Smart Air Quality network for spatial high-resolution monitoring in urban area." Proc. SPIE, 10786, 107860B-1 – 107860B-14 (2018).

[3] Emeis, S., Münkel, C., Vogt, S., Müller, W., Schäfer, K., "Determination of mixing-layer height." Atmos. Environ., 38, 2, 273-286 (2004).

[4] Wiegner, M., Madonna, F., Binietoglou, I., Forkel, R., Gasteiger, J., Geiß, A., Pappalardo, G., Schäfer, K., Thomas, W., "What is the benefit of ceilometers for aerosol remote sensing? An answer from EARLINET." Atmos. Meas. Techn., 7, 1979–1997 (2014).

[5] Emeis, S., Schäfer, K., Münkel, C., "Observation of the structure of the urban boundary layer with different ceilometers and validation by RASS data." Meteorol. Z., 18, 2, 149-154 (2009).

[6] Emeis, S., Schäfer, K., Münkel, C., Friedl, R., Suppan, P., "Evaluation of the interpretation of ceilometer data with RASS and radiosonde data." Bound.-Lay. Meteorol., 143, 25–35 (2012).

[7] Schäfer, K., Emeis, S., Hoffmann, H., Jahn, C., Müller, W., Heits, B., Haase, D., Drunkenmölle, W.-D., Bächlin, W., Schlünzen, H., Leitl, B., Pascheke, F., Schatzmann, M., "Field measurements within a quarter of a city including a street canyon to produce a validation data set." Int. J. Environ. Pollut., 25, 1/2/3/4, 201-216 (2005).

[8] Schäfer, K., Emeis, S., Hoffmann, H., Jahn, C., "Influence of mixing layer height upon air pollution in urban and sub-urban area." Meteorol. Z., 15, 647-658 (2006).

[9] Schäfer, K., Emeis, S., Schrader, S., Török, S., Alföldy, B., Osan, J., Pitz, M., Münkel, C., Cyrys, J., Peters, A., Sarigiannis, D., Suppan, P., "A measurement based analysis of the spatial distribution, temporal variation and chemical composition of particulate matter in Munich and Augsburg." Meteorol. Z., 21, 1, 47-57 (2011).

[10] Schäfer, K., Elsasser, M., Arteaga-Salas, J.M., Gu, J.W., Pitz, M., Schnelle-Kreis, J., Cyrys, J., Emeis, S., Prévôt, A.S.H., Zimmermann, R., "Impact of meteorological conditions on airborne fine particle composition and secondary pollutant characteristics in urban area during winter-time." Meteorol. Z., 25, 3, 267-279 (2016).

[11] Wagner, P., Schäfer, K., "Influences of meteorological parameters and mixing layer height upon air pollutant concentrations in urban area." Urban Climate, 22, 64–79 (2017).

[12] Emeis, S., [Measurement methods in Atmospheric Sciences – In situ and remote], Borntraeger, Stuttgart. 280 pp. (2010).

[13] Münkel, C., "Mixing height determination with lidar ceilometers - results from Helsinki Testbed", Meteorol. Z., 16, 451-459 (2007).

[14] Emeis, S., Schäfer, K., Münkel, C., "Surface-based remote sending of the mixing-layer height", Meteorol. Z., 17, 621-630 (2008).

[15] Münkel, C., Schäfer, K., Emeis, S., "Adding confidence levels and error bars to mixing layer heights detected by ceilometer," Proc. SPIE 8177, 817708-1 – 817708-9 (2011).

[16] Emeis, S., Jahn, C., Münkel, C., Münsterer, C., Schäfer, K. "Multiple atmospheric layering and mixing-layer height in the Inn valley observed by remote sensing", Meteorol. Z., 16, 415-424 (2007).

[17] Reuder, J., Brisset, P., Jonassen, M., Müller, M., Mayer, S., "The Small Unmanned Meteorological Observer SUMO: A new tool for atmospheric boundary layer research." Meteorol. Z., 18, 2, 141-147 (2009).

[18] Anderson, K., Gaston, K. J., "Lightweight unmanned aerial vehicles will revolutionize spatial ecology." Frontiers in Ecology and the Environment, 11: 138-146 (2013).