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Usefulness of UAV-mounted multisensors system for in situ atmospheric measurement: a case study from Wrocław, Poland

Anetta Drzeniecka-Osiadacz[1*], Tymoteusz Sawiński[1], Magdalena Korzystka-Muskała[1], Marek Kowalczyk[1], Piotr Modzel[1]

[1] Department of Climatology and Atmosphere Protection, Institute of Geography and Regional Development, University of Wrocław, LIFE-MAPPINGAIR/PL Project, Kosiby 8 Str., 51-621 Wrocław, Poland; anetta.drzeniecka-osiadacz@uwr.edu.pl (ADO), tymoteusz.sawinski@uwr.edu.pl (TS), magdalena.korzystka-muskala@uwr.edu.pl {MKM), marek.kowalczyk@uwr.edu.pl (MK), piotr.modzel@uwr.edu.pl (PM)

* Correspondence: anetta.drzeniecka-osiadacz@uwr.edu.pl

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Abstract: Air pollution, especially particulate matter (PM_x), is one of the most serious environmental threats worldwide. It is challenging in terms of both public health, impact on climate, and the reduction of visibility. The assessment of spatial variability of PM_x allows us to understand better the processes cause the smog episodes, and may also be an additional element for the validation the results of dispersion model. The study presents the results of measurements of basic meteorological parameters and air pollution involving the multi-sensors system. A Matrice 600 hexacopter with an installed environmental head was used as the measurement platform. This system enables us to measure the concentrations of $PM_{2.5}$, PM_{10}, air temperature and humidity.

Keywords: drone, atmospheric boundary layer, particulate matter measurements

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1. Introduction

Air pollution, especially particulate matter (PM), is considered as a major environmental threat worldwide [1,2]. Associations between ambient air pollution and adverse health effects are well documented, both for long-term [3,4] and short-term health impacts [5,6]. Particulate matter has a serious detrimental effect on the environment, damages the crop, causes climate change and reduces visibility [7-9]. High-resolution monitoring of air pollution concentration and meteorological conditions (temperature, humidity, wind, etc.) within the atmospheric boundary layer (ABL) [10] is crucial for various environmental applications [11]. It is important to understand the processes of surface-atmosphere interactions, which govern, e.g. high air pollution concertation events, and it is vital to measure the impacts of air pollution for human health [12] and the environment. Information about these parameters is usually limited to a few meters above the ground, moreover, the measurements are the most frequently carried out in stationary mode [13], sometimes extended with remote sensing technology [14,15]. Thus, mobile measurement involving with UAVs is an interesting supplement for ground-based measurement [16,17].

The development of unmanned aerial vehicles (UAVs) provides possibilities for atmospheric measurements within the ABL and seems to be useful for surveys in small areas [18]. Drones equipped with properly designed and constructed sensors are successfully used in measuring air pollution, greenhouse gases, and meteorological variables [19,20].

The main objective of the study is to present the ability of using UAVs in simultaneous research of air pollution concentration and meteorological parameters and to determine the variability of the PM concentration together with the ABL structure in the lower part of the atmosphere in various types of land use and with different emission structures.

2. Data and methods

2.1. Design of the hexacopter-based measuring system

The measuring head installed on the UAV is the original solution, configured to measure selected air pollutants (PM, O_3) and basic meteorological parameters (T, RH, P) during flight. In addition, the device records flight parameters such as geographic coordinates and altitude. The inlets of the sensors used in head are placed above the plane of the rotors to minimize the influence of turbulence caused by propellers. Low-cost PM (optical) and O_3 (electrochemical) sensors were installed in the head, the selection of which was preceded by research and tests. All data were validated against the higher quality data from Meteorological Observatory during the test stage. Measurement data are saved in the logger's memory placed on the UAV and continuously monitored on the monitor screen using radio transmission.

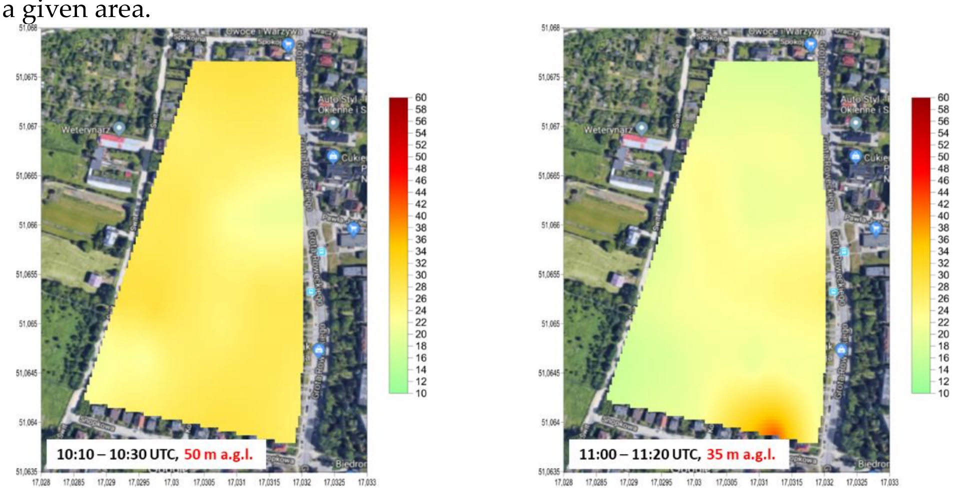
2.2. Field companies

The measurements using the drone were carried out in Wrocław, SW Poland. Wrocław, as many cities in Poland, suffers from poor air quality, especially during winter period. It is the result of the widespread use of coal and wood for domestic heating. Due to this reason, Polish cities are placed among regions with the worst air quality in the European Union [21].

In order to assess the spatial variability of the particulate matter concentration and meteorological conditions, measurement campaigns were performed in 3 locations representing urban, suburban (an area of detached houses and allotments) and rural locations. Measurements were carried out in horizontal and vertical modes. In the years 2019-2020, 9 such sessions were conducted, during each of them several flights were made (Table S1 in Supplementary material). The effective monitoring time during each flight was about 10-20 minutes. Background data including one-minute $PM_{2.5}$ and PM_{10} concentration, air temperature, humidity, wind speed and wind direction supplemented by sodar data were obtained from the Meteorological Observatory of the University of Wrocław.

2.2.1. Horizontal measurements

Horizontal measurements are carried out automatically in a selected area and at a certain height above the roof layer (Figure 1). The data are then presented in the form of spatial distributions of the analysed parameter. This enables the identification of the main sources of air pollution , as well as the assessment of the variability of air temperature in a given area.



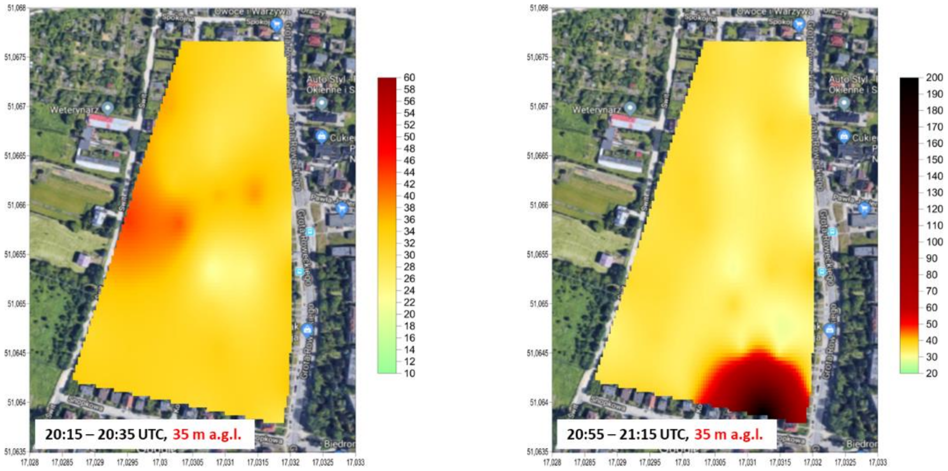


Figure 1. The examples of data processing and distribution of particulate matter concentration PM2.5 [μgm^{-3}] for different height achieved during one-day campaign.

2.2.2. Vertical measurements

Vertical transects over different type of land-use within the lowest 350 m are carried out several times during each survey in order to obtain temperature, humidity, and PM profiles. This approach allows us to assess the vertical distribution of these variables and compare the temperature profile with acoustic sodar data (Figure 2). Due to distortion of air made by rotors only ascending flights are used for further analysis.

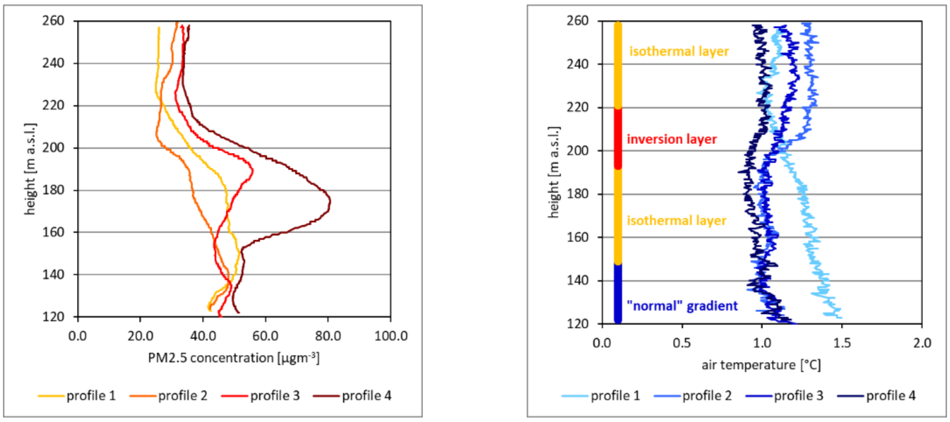


Figure 2. The example of visual interpretation of temperature and particulate matter vertical profiles from drone measurements.

3. Examples results

To assess the variability of the structure of the atmospheric boundary layer and distribution of particulate matter, we investigated in detail three selected measurement sessions. The first one was characterized by stable conditions during the night with a well-developed ground-based temperature inversion. The second one, carried out in November 2020, was characterized by a multi-layered night boundary layer with quite high dynamics. The last one from December 2020, was conducted during morning transition period.

The development of a stable, nocturnal boundary layer during calm wind conditions provides a gradual increase in air pollution concentration from combustion sources within the surface layer (Figure 4). After sunset, the inversion layer develops because of steadily dropping of temperature caused by radiative cooling of the ground. Such conditions also favour very strong gradients in the pollutant profile, maximum concentrations occur below the inversion layer, falling to almost 0 μgm^{-3} in the zone above ground-based layer. As indicated by the measurements carried out in the city centre (GS profiles), the increased roughness and the modification of radiation properties of surface contribute to the reduction of the temperature gradients within the inversion layers to about 70 m a.g.l. and the occurrence of an isothermal layer in the lower part of the ABL.

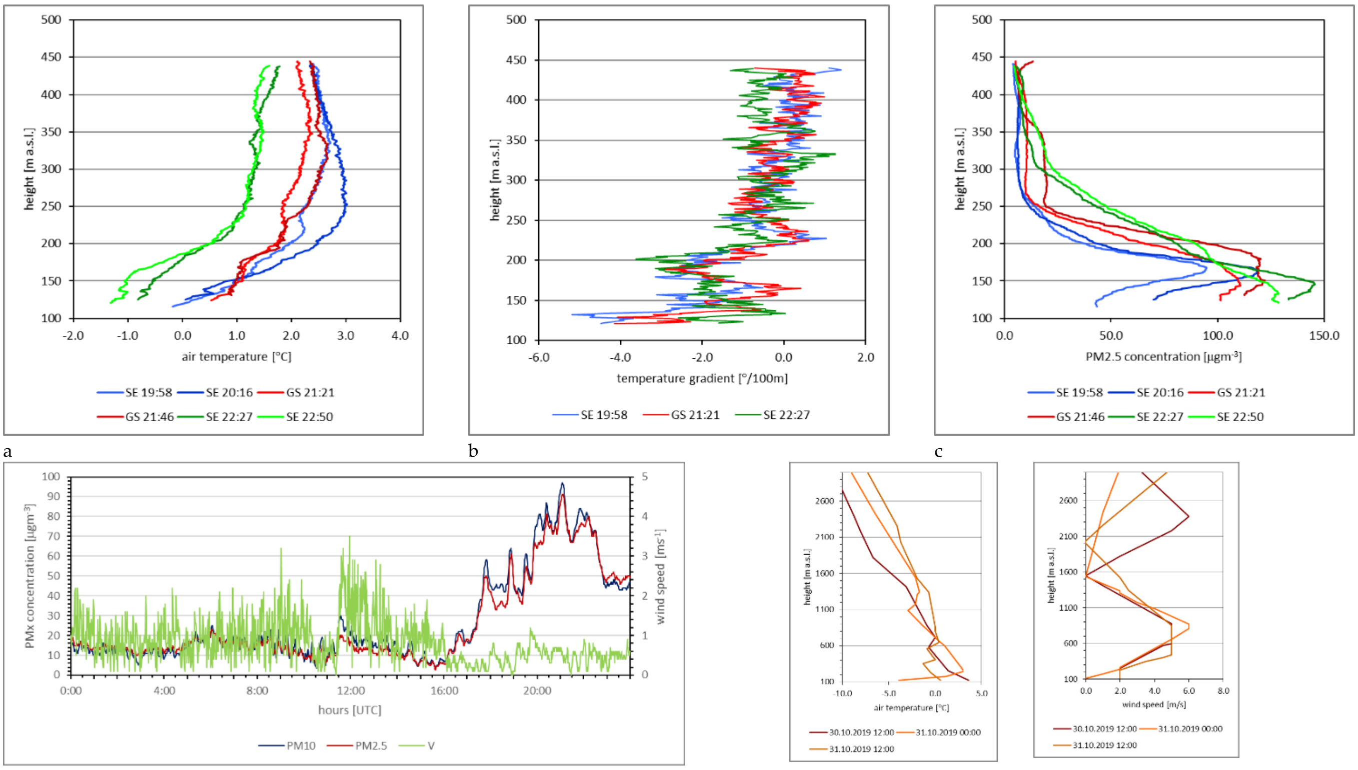
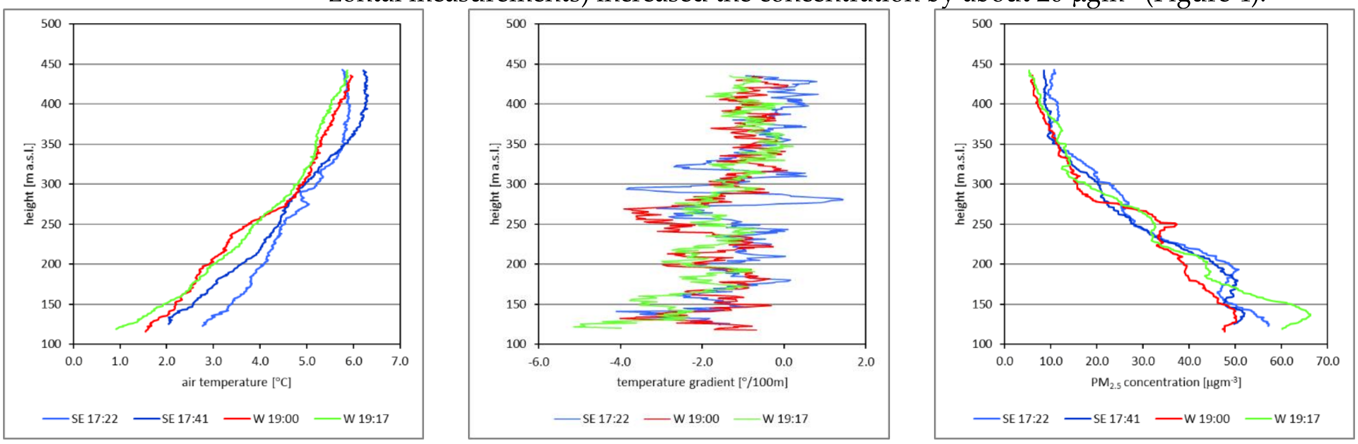


Figure 3. Vertical profile of air temperature, environmental lapse rates and $PM_{2.5}$ concentration (upper), diurnal distribution of PM_x and wind speed and vertical profile of temperature and wind speed from balloon sounding (www.weather.uwyo.edu/upperair/sounding.html). Flights on October 30, 2019.

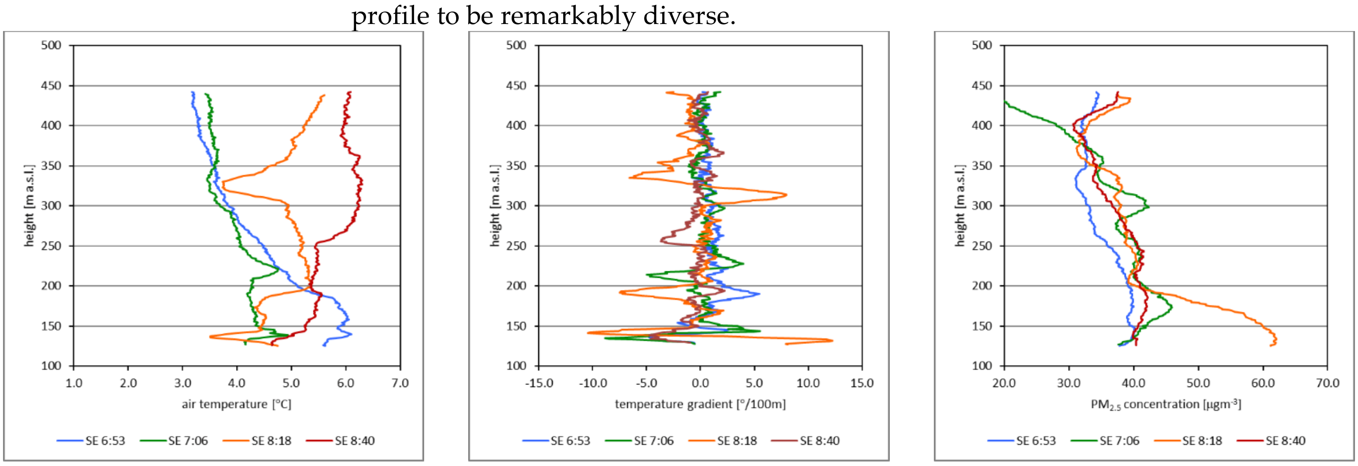
During the next field research, the concentration of PM was lower because of the less stable condition within the night ABL. As indicated by the sodar data, the inversion was characterized by a wavy structure caused by stronger mixing processes. The course of PM concentration in the vertical profile above two selected areas was very similar, except for the last flight. The advection of the plume from the emission sources (also visible in horizontal measurements) increased the concentration by about 20 μgm^{-3} (Figure 4).



a b c

Figure 4. Vertical profile of air temperature, environmental lapse rates and $PM_{2.5}$ concentration (a-c), diurnal distribution of PM_x and wind speed and sodar echogram (dark horizontal areas indicate inversion layer, so-called "spiky echoes" during day indicate convection) (d-e), results of horizontal profiling (f-g). Flights on November 24, 2020.

During the morning hours, the dynamics of PM concentrations vary from those of the evening or night conditions. First, the breaking of the night ABL leads to the formation of strong descending flows, which may cause an increase in PM concentrations close to the ground, below the elevated inversion (Figure 5). Moreover, the development of turbulence causes both the temperature and the PM concentration gradients in the vertical profile to be remarkably diverse.



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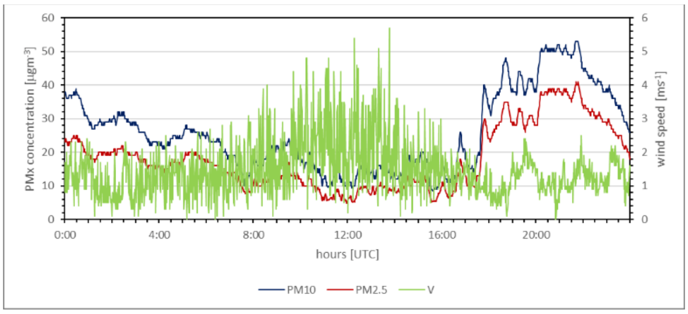

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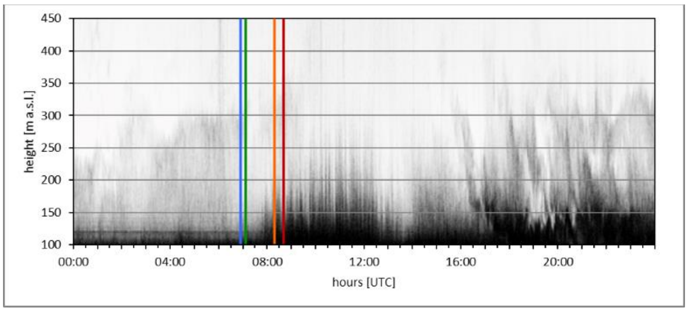

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Figure 5. Vertical profile of air temperature, environmental lapse rates and $PM_{2.5}$ concentration (a-c), diurnal distribution of PM_x and wind speed and sodar echogram (dark horizontal areas indicate inversion layer, so-called "spiky echoes" during day indicate convection) (d-e). Flights on December 17, 2020

3. Discussion and conclusions

Research on the atmospheric boundary layer involving sensors mounted on drones is an interesting alternative to traditional measurement platforms, such as profile in-situ measurements or remote sensing technics. They can be used in various environments, e.g., in polar regions, in varying terrain, or in urban areas [16,19,21].

The studies indicate, first of all, the influence of the boundary layer structure on the concentrations of pollutant and the strongly vertical variability of the parameters analyzed in the vertical profile (Figure S1), which was also confirmed in other studies [22]. The key issue to be solved is the appropriate design of the measurement system for comprehensive atmospheric studies [18], and in the case of using low-cost sensors, their proper calibration [23] to obtain reliable data with high resolution. The use of miniature solutions also allows measurements to be made up to a height of 1000 m above ground level [22], however, it seems that from the point of view of concentrations dynamics and the structure of the ABL, the lowest 300 - 500 m above ground is the most important, especially in urban areas [24].

The solution presented in the article, by simultaneous measurements of meteorological variables carried out according to the standards and air quality, allows for a detailed analysis of the influence of the structure of the ABL on air quality. It also complements remote sensing measurements, such as ABL sodar research. Thanks to the modular construction of the measuring head, in addition to basic equipment for measuring temperature, humidity, particulate matter, and ozone concentration selected devices could be added depending to the scientific needs.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: The description of the measurement campaigns; Figure S1: Whisker plots describing general characteristics of temperature (a) and particulate matter $PM_{2.5}$ (b) and PM_{10} from drone measurements during selected field researches.

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Conflicts of Interest: The authors declare no conflict of interest

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