Investigation of Vertical Particulate Matter Distribution using Low-cost Sensors in Istanbul, Turkey

Elif YAVUZ, S. Levent KUZU and Arslan SARAL

Abstract**—**Particulate matter ($PM_{2.5}$ and PM_{10}), which is one of the most important pollutants in the atmosphere, has serious effects on both human health and the environment. Air quality monitoring stations may not accurately represent pollutant gradients in a city due to the large spatial variability of these pollutants in urban environments, especially for traffic-related air pollutants such as $PM_{2.5}$. Recently, the use of Unmanned Aerial Vehicles (UAVs) in air quality applications is a new popular approach that is believed to overcome several limitations of existing methods. In this study, the vertical distribution of $PM_{2.5}$ and PM_{10} pollutants and the variation of meteorological parameters including temperature, relative humidity, and pressure were investigated in an urban area of Istanbul using low-cost sensors mounted on a UAV. Three field experiments were conducted on August 20, August 25, and September 3, 2021 using two different laser PM sensors, GROVE HM3301 and NOVA SDS011. The data was collected every 10 meters, with a 30-second hover, ranging in height from ground level to 100 m and the results were averaged for each altitude. According to the GROVE HM3301 and NOVA SDS011 measurement results at 100 m, PM_{10} concentrations decreased by about 15.5% and 9.4%, while $PM_{2.5}$ concentrations decreased by about 11.1% and 0.8%, respectively. The GROVE HM3301 PM_{10} and $PM_{2.5}$ measurement concentrations were found to be closer to each other, and the NOVA SDS011 particle sensor provided more sensitive measurement results. All the peak $PM_{2.5}$ and PM_{10} concentrations were found at the ground level except for the NOVA SDS011 $PM_{2.5}$ measurement results, where the maximum $PM_{2.5}$ concentration was observed at 80 m altitude. Temperature, pressure, and relative humidity were found to be negatively correlated with height.

Keywords**—**$PM_{2.5}$, PM_{10}, UAV.

I. Introduction

Particulate Matter ($PM_{2.5}$ and PM_{10}), often known as aerosol, is a term that refers to fine solid particles or liquid droplets that can range in size from 0.2 nanometers to 500 micrometers that are found in the ambient air. It is divided into two fractions; the coarse fraction (PM_{10}) refers to particles with a diameter between 2.5 to 10 microns, whereas the fine fraction ($PM_{2.5}$) refers to particles having a diameter of 2.5 microns or less. The particle size, characteristics, and contamination level of ambient particulate matter change dramatically depending on the variables of location, time, and source. Their sources can be natural, or anthropogenic activities such as traffic, manufacturing industries, and coal power plants [1]. They can also be formed in the atmosphere through chemical reactions of gases such as sulfur dioxide (SO_2), nitrogen oxides (NO_X), and some organic compounds [2].

Public health studies reveal that high PM levels have different effects on human health. These studies have demonstrated a significant association between particulate pollution exposure and health risks such as respiratory illnesses and cardiovascular diseases [3], [4]. Particularly, the size of the particles is directly linked to their potential to cause health problems. Fine particles ($PM_{2.5}$) pose the greatest health risk as they can penetrate deep into the lungs, while coarse particles (PM_{10}-$PM_{2.5}$) can irritate a person's eyes, nose, and throat. In addition to their health effects, aerosols can change albedo by absorbing and scattering solar radiation, which has a direct influence on the Earth’s climate. They can also have an indirect effect on climate by modifying the microphysical properties of clouds [5]. To measure the effects of atmospheric pollution on human health and the environment, detailed information about the characteristics of aerosol distribution and pollutant concentration is needed [6]. Air quality monitoring stations have already been used for decades to monitor atmospheric pollution from gases and aerosols. Equipped with high quality and expensive measuring equipment, these stations have high power consumption, maintenance, and operating costs. They also have some limitations when used to assess actual human exposure to ultrafine particles and other traffic-related air pollutants, due to the large spatial variability of these pollutants in urban environments [7].

Aside from its low-cost advantage, UAV technology is a new approach that has gained popularity in recent years in air quality applications due to its ease of use, high maneuverability, and ability to sample in inaccessible areas. Monitoring the vertical profile of pollutant distribution is crucial, given the potential for pollutants to be found in different layers of the atmosphere. These small and light UAVs can provide high-resolution atmospheric data in both horizontal and vertical dimensions, in any complex topography

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such as urban or rural areas, in the lower troposphere [6], [8], [9].

UAVs equipped with sensors to measure carbon dioxide, ozone, particulate matter and other pollutants for air quality monitoring have been used in many previous studies in cities, greenhouses, mines and other dangerous or hard-to-reach places [7], [10]–[12]. Several studies identified the opportunities and challenges of using gas sensors (electrochemical and semiconductors) and dust sensors (optical sensors) coupled to mini, micro and nano UAVs [9], [13]–[17]. Yu et al., (2017) used a UAV with multiple sensors to collect pollutant and atmospheric (temperature and relative humidity) data from atmospheric vertical profiles and found a high correlation between particle size concentrations ($PM_{2.5}$ and PM_{10}) and atmospheric parameters [14]. Babaan et al., (2018) obtained $PM_{2.5}$ mass concentration data using UAV integrated with mobile monitoring sensors. They stated that as the altitude increases, the $PM_{2.5}$ concentration generally decreases and the vertical profile of the $PM_{2.5}$ concentration is affected by meteorological parameters. According to the results of the correlation analysis, it was determined that $PM_{2.5}$ concentration has a positive relationship with temperature, and a negative relationship with relative humidity and wind speed [7]. In another study conducted by Pochwała et al. (2020), it was found that the distribution of pollutants is variable with altitude and the PM concentration can increase with altitude from 0 to 100 m in the range of 30% to 50% of the measured value [18].

In this study, a UAV equipped with low-cost sensors was used to investigate the vertical distribution of $PM_{2.5}$ and PM_{10} concentrations and meteorological parameters (temperature, relative humidity, pressure) in an urban area of Istanbul, Turkey.

II. Materials And Methods

A. Measurement Module

We used a measurement module that consists of the Nova SDS011 particle sensor (Inovafit), the Grove HM3301 particle sensor (Huaman Electronics), BME280 meteorological parameter sensor (Robert Bosch GmbH; Gerlingen City, Germany), Raspberry Pi 4, and a rechargeable battery. The total weight of the measurement module was 367 g.

In this study, two low-cost sensors were used for vertical particle concentration measurements. Technical parameters of the Nova SDS011 and the Grove HM3301 particle sensors are given in Table I. The NOVA SDS011 PM sensor is 71x70x23 mm (LxWxH) in size with 50 g weight while the Grove HM3301 PM sensor is 80x40x18 mm (LxWxH) in size with 45 g weight. They are low-power PM monitoring sensors based on laser light scattering technology. NOVA SDS011 laser sensor can identify particles on a planar dimension between 0.3 and 10 μm in diameter and detect particles between 0.0–999.9 μg/m^3 concentration ranges. Although Grove HM3301 laser sensor can provide PM concentrations for PM_1, $PM_{2.5}$, and PM_{10}, this study is limited to $PM_{2.5}$ and PM_{10} measurement results due to data comparability. The sensors have a digital output and a built-in fan that driven air through a detection chamber. They can monitor particle density distributions in the air then report the results after converting them into $PM_{2.5}$ and PM_{10} particle mass concentration using an algorithm. The measurement results of meteorological factors such as pressure, temperature, and humidity were also acquired using the combined ambient sensor BME280. Each sensor's data (particle matter, pressure, temperature, and humidity) is relayed to a ground station via a Wi-Fi wireless connection for monitoring and recording, as well as being recorded on a micro SD card. The PM system was set to a reaction time of one second. GPS time stamp was used for time synchronization of each reading.

TABLE I
TECHNICAL PARAMETERS OF THE PARTICLE SENSORS

	Nova SDS011	**Grove HM3301**
Parameters	$PM_{2.5}$ and PM_{10}	PM_1, $PM_{2.5}$ and PM_{10}
Size (LxWxH)	71x70x23 mm	80x40x18mm
Weight	50 g	45 g
Detection range	0.0–999.9 μg/m^3	1-1000 μg/m^3
Operating Temperature	-10 ~ 50 °C	−10 ~ 60 °C
Operating Humidity	Max %70	10% ~ 90%
Operating voltage	5V	3.3V / 5V

The DJI Mavic2 drone was chosen for the field experiments. It is a quadrotor drone with 570 g weight. The UAV has a flying time of up to 30 minutes on average and may be utilized in temperatures ranging from 0 to 40^0 C with a maximum wind speed of 10 m/s. The simulation results of the airflow surrounding the drone rotors by Yang et al., (2018) and Wu et al., (2019) reported that the downwash effects of the rotor bottom were greater than the effects at the top [19], [20]. Therefore, we mounted the measurement module at the top of the UAV to minimize the downwash effect of the rotors as presented in Fig. 1.

Fig. 1. UAV

B. Study Site and Data Collection

Data was collected at Yildiz Technical University Davutpaşa campus, in an urban area of Istanbul, Turkey (Fig. 2). Data was collected at every 10 meters on a vertical extent, with a 30-second hover time, ranging in height from ground level to 100 m and the results were averaged for each altitude. Measurements were taken by flying once a week under favorable weather conditions.

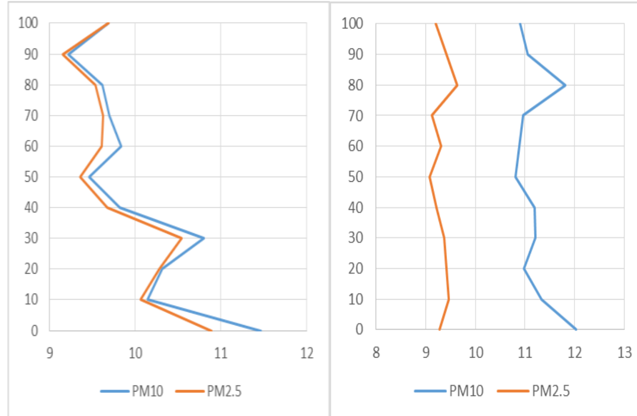
Fig. 2. Study site

III. Limitations

Although the UAV equipped with low-cost sensors has the great ability to collect atmospheric data, several limitations should be recognized. One is the restrictions imposed by governments that allow the use of UAVs with license and permissions. Another is that the study is limited to days when there is no significant change in environmental conditions, which is one of the drawbacks of working in an outdoor environments. The current UAV was not waterproof and did not allow flight on rainy days. We also did not fly on windy days as little is known about the effect of wind on sensor performance. According to field experiments, it can be concluded that the onboard devices have a negative impact on the UAVs power consumption and flying time.

IV. Results And Discussion

In this study, we aimed to investigate the vertical distribution of PM and meteorological parameters up to 100 m height using a measurement module mounted on a UAV. For this purpose, three field experiments were conducted on August 20, August 25, and September 3, 2021. Experimental flight results were recorded with altitude increase of 10 m in intervals with a hovering of 30 secs. Fig. 3 shows the PM_{10} and $PM_{2.5}$ vertical averaged concentrations during three field experiments measured by GROOVE HM3301 and NOVA SDS011 sensors.



(a) (b)

Fig. 3. PM_{10} and $PM_{2.5}$ vertical averaged concentrations ($\mu g/m^3$) during three field experiments measured by GROOVE HM3301 (a) and NOVA SDS011 (b) sensors

According to the GROVE HM3301 and NOVA SDS011 measurement results at 100 m, PM_{10} concentrations decreased by about 15.5% and 9.4%, while $PM_{2.5}$ concentrations decreased by about 11.1% and 0.8%, respectively. The GROVE HM3301 PM_{10} and $PM_{2.5}$ measurement concentrations were found to be closer to each other, and the NOVA SDS011 particle sensor provided more sensitive measurement results. All the peak $PM_{2.5}$ and PM_{10} concentrations were found at the ground level except for the NOVA SDS011 $PM_{2.5}$ measurement results, where the maximum $PM_{2.5}$ concentration was observed at 80 m altitude. It was observed that the $PM_{2.5}$ and PM_{10} concentrations measured during the three flight experiment was less than 16 $\mu g/m^3$ and 18 $\mu g/m^3$, respectively. Similar to our study, a 20% reduction in particle concentrations at 100m was reported in an experiment conducted by Liu et al. (2018) [21]. In another study that investigated vertical particle distribution a decreasing trend found in particle concentrations [22].

The vertical distributions of the meteorological parameters including temperature, relative humidity and pressure were shown in Fig. 4. Temperature, pressure and humidity were generally decreasing with the increase in altitude. A study conducted by Yu et al. (2017), the vertical distribution of meteorological parameters changed the most in pressure, while temperature and pressure were slightly changed [14]. In another study Babaan et al., (2018) indicated that temperature and pressure generally decreased with an increase in altitude, while Zheng et al., (2021) reported a slight decrease in temperature and a slight increase in pressure [7], [23].

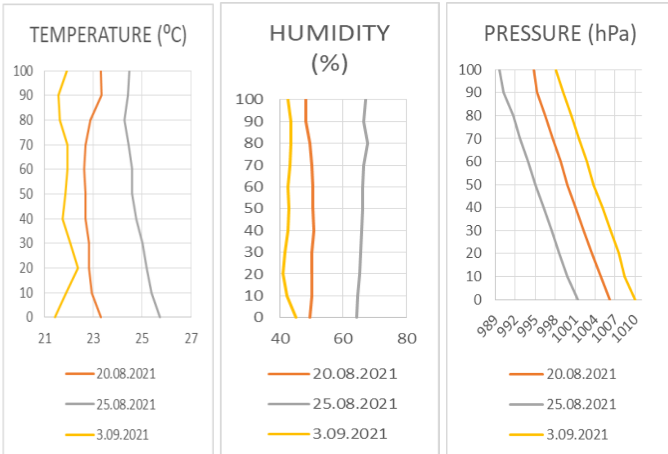


Fig. 4. Vertical distribution of the meteorological parameters including temperature (^{0} C), pressure (Pa), humidity (%)

V. Conclusion

In this study, the UAV equipped with low-cost sensors was used to investigate the vertical distribution of PM and meteorological parameters up to 100 m height in an urban area of Istanbul, Turkey. Three field experiments were conducted on August 20, August 25, and September 3, 2021. According to the field experiment results, $PM_{2.5}$ and PM_{10} concentrations generally presented a decreasing trend as the altitude increases. Also a negative trend was found between height and meteorological parameters.

However, this study investigated the vertical profiles of PM and meteorological parameters with limited data, future work will include increasing the number of days to obtain more representative results and Pearson correlation analysis to determine the relationship between the vertical distribution of PM and meteorological conditions. The vertical distribution of pollutants remains a large gap for current air quality models, so we suggest the use of the vertical measurement results of the meteorological parameters and PM for the evaluation of a numerical model performance.

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