Investigating the Role of Meteorological Factors in the Vertical Variation in PM_{2.5} by Unmanned Aerial Vehicle Measurement

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ABSTRACT

Clarifying the effects of meteorology on the vertical variation in PM_{2.5} is critical to understanding the formation of haze. We investigated the PM_{2.5} and synchronous meteorological variations in a three-dimensional space by measuring them with a lightweight unmanned aerial vehicle (UAV) equipped with portable monitors. Our field campaign was conducted on 5 separate days selected between August 2014 and February 2015 at altitudes ≤ 1000 m above a 4×4 km² area in Lin'an, China. The UAV measurement was performed 4 times on each of the selected days, and every flight followed a designed spiral route from ground level up to an altitude of 1000 m. The PM_{2.5} mass concentration and meteorological factors, viz., the air temperature, relative humidity, dew point temperature and air pressure, were sampled at three-dimensional spatial locations during each flight. The measurements indicate that the PM_{2.5} distribution is more homogeneous horizontally than vertically. The PM_{2.5} concentration also decreases as the height increases; furthermore, it exhibits obvious stratification in the morning but more homogeneity in the afternoon. The concentrations above 500 m slightly rise in the afternoon, especially on days that display more stratification. The vertical gradient of the concentrations shows a decrease from the morning to the afternoon, which is smaller during winter than summer and autumn. Meteorologically induced changes in the planetary boundary layer height and inversion layer also significantly affect the PM_{2.5} variation in the lower troposphere. Our results serve as a reference for analyzing and forecasting PM_{2.5} pollution and provide a basis for smarter and more targeted air pollution management and governance.

Keywords: PM_{2.5}; Spatio-temporal variation; Vertical distribution; Meteorology; UAV.

INTRODUCTION

Ambient air pollution is a primary environmental problem in industrial and developing countries, and China is not spared (Ouyang *et al.*, 2013). Fine particulate matter (PM_{2.5}) holds the key to some of the greatest mysteries of climate science (Davidson *et al.*, 2005; Booth *et al.*, 2012; Stevens *et al.*, 2012). The complex interactions between aerosol particles and climate have been reported that different components of particulate matter have either warming or cooling effects on the climate (U.S. EPA, 2007). In addition, PM_{2.5} can threaten human health, especially

the cardio-respiratory system (Pope *et al.*, 2002; Dominici *et al.*, 2006; Pope *et al.*, 2009). Hence, it is urgent to understand the formation and dispersion mechanisms of PM_{2.5}, particularly to investigate vertical profiles of PM_{2.5} concentrations and its relationship with meteorological factors, which is also of great importance for air pollution forecasting and prevention (Syu *et al.*, 2016).

Fine particles make up the dominant fraction of particulate matter in the troposphere (Wang *et al.*, 2008). Generally, PM_{2.5} concentrations logarithmically decrease with increasing altitude and the vertical distributions are classified into two patterns: gradual decline pattern and rapid decline pattern (Ding *et al.*, 2005; Yang *et al.*, 2005). However, the distributions of PM_{2.5} concentrations could be affected by multiple factors, e.g., meteorological factors and planetary boundary layer structure (Strawbridge *et al.*, 2004; Wang *et al.*, 2008; Sun *et al.*, 2013). PM_{2.5} tends to

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be well mixed vertically during daytime (Maletto *et al.*, 2003), while $\text{PM}_{2.5}$ are discovered having layered feature in nocturnal settings of wintertime (Mckendry *et al.*, 2004). The reverse distribution of relative humidity might explain the “higher-top and lower-bottom” pattern of the $\text{PM}_{2.5}$ distribution, considering the moisture absorption (Sun *et al.*, 2013). Except the above limited literature, most of the previous studies focused mainly on the characteristics of $\text{PM}_{2.5}$ at surface level. Ground-based observations are insufficient for a correct understanding of the trans-boundary transport of pollutants and the influence of atmospheric microcirculation (e.g., sea-land breeze, urban heat island effect) on pollutant distribution in urban areas (Strawbridge *et al.*, 2004; Ding *et al.*, 2009). Besides, current climate models are usually based on simplifications that ignore the complexity of the small scale physical processes. It is thus necessary to calibrate climate models with detailed and parameterized measurement data (Boy *et al.*, 2006; Ding *et al.*, 2009; Stevens *et al.*, 2012).

Typically, meteorological towers, tethered balloons, LiDAR, and manned aerial vehicles are routinely utilized in measuring vertical profile of particulate matter in the troposphere and PBL (Wang *et al.*, 2015a). Meteorological tower can be used for long-term and continuous observations, but it is limited in terms of elevation (no more than 350 m) and mobility (Ding *et al.*, 2005; Yang *et al.*, 2005). Compared with meteorological tower, tethered balloon is able to monitor pollutant and meteorology in troposphere with a high spatial resolution (Li *et al.*, 2015; Bisht *et al.*, 2016; Renard *et al.*, 2016). Nevertheless, it is usually restricted to a horizontal monitoring range. LiDAR can easily measure the aerosol vertical distribution, but the limitations of LiDAR method are expensive instrumentations and the lack of data within the 200 m height (Li *et al.*, 2015; Wang *et al.*, 2015a). Manned aerial vehicles are easy to undertake a large range of measurements but cannot be used extensively due to high costs of operation (Wang *et al.*, 2008; Axisa *et al.*, 2016).

In later decades, unmanned aerial vehicles (UAVs), including fixed-wing and multi-rotor, have been developed as a new environmental measurement tool because its operating cost and maneuverability are superior to manned aircrafts (Ramana *et al.*, 2007; Ramanathan *et al.*, 2007; Villa *et al.*, 2016a). With the flourish of newly developed, highly sensitive sensors (Li and Biswas, 2017; Johnson *et al.*, 2018; Ly *et al.*, 2018), UAV equipped by lightweight sensors becomes flexible for measuring meteorology (Van den Kroonenberg *et al.*, 2008; Wildmann *et al.*, 2013; Wildmann *et al.*, 2014a; Altstädter *et al.*, 2015), atmosphere structure (Thomas *et al.*, 2012; Wildmann *et al.*, 2013, 2014b) and atmospheric particulate matter (Clarke *et al.*, 2002; Harnisch *et al.*, 2009; Bates *et al.*, 2013; Altstädter *et al.*, 2015; Peng *et al.*, 2015; Brady *et al.*, 2016; Villa *et al.*, 2016b, 2017; Li *et al.*, 2018). For example, Harnisch *et al.* (2009) used UAV for an aerosol observation and discovered an asymmetry in the aerosol distribution in the cross-valley direction, which was explained by differences in orientation and albedo of the two valley slopes. Based on UAV measurements, Bates *et al.* (2013) revealed that

frequent aerosol layers were aloft with high particulate number concentrations and enhanced aerosol light absorption; Altstädter *et al.* (2015) also observed a particle burst event during the boundary layer development in the morning; Wang *et al.* (2008) found that PM_{10} and $\text{PM}_{2.5}$ were influenced by similar sources over Yangtze River Delta, China, and the average ratio of $\text{PM}_{2.5}$ to PM_{10} mass concentration was 0.84. In summary, there have been studies focusing on the vertical distributions of particulate matter concentrations, but few studies describe the local three-dimensional variation of $\text{PM}_{2.5}$ and resolve the impacts of multiple meteorological factors, and hardly analyze the generation and disappearance process of a haze event based on both UAV and ground observations.

In this paper, the UAV technology was adopted to investigate the three-dimensional variation of $\text{PM}_{2.5}$ concentrations and to explore its relationship with synchronous meteorology. A total of 20 monitoring flights were carried out over the suburban area of Lin'an, China. To be specific, Section 2 details the field experiments and methods. Section 3 presents the observational results and discusses the $\text{PM}_{2.5}$ accumulation and dispersion events due to meteorological factors. Finally, a conclusion is provided in Section 4.

FIELD EXPERIMENTS AND METHODS

Experimental Site

Field campaigns were conducted in a $4 \times 4 \text{ km}^2$ suburban area in the northern part of Lin'an, China ($29^\circ 56' - 30^\circ 23' \text{N}$, $118^\circ 51' - 119^\circ 52' \text{E}$) (see Fig. 1). Lin'an is located in a subtropical monsoon climate zone with four distinct seasons. Northeastern winds prevail in winter, whilst southerly winds reign in summer (Meng *et al.*, 2012). The experimental site is approximately 13 km distant from downtown Hangzhou, China. A highway runs west to east across the experimental site. A high-tech development zone located on the southern side of the highway is under construction. Thirteen machinery manufacturing plants are operated in the high-tech zone. Some residential areas are located on the north side of the highway. No direct pollution sources are within or close to the experimental site. Less than 10% of the experimental area is residential land that is surrounded by hills on the southeast and northwest of the area. Nearly half of the area is covered by trees, and one third of the area is bare land.

Observation Campaigns

Observation experiments were performed using a fixed-wing UAV equipped with fast-response and miniaturized monitors for measuring three-dimensional $\text{PM}_{2.5}$ mass concentrations and synchronous meteorological factors including air temperature, relative humidity, dew point temperature and air pressure in the lower troposphere. Detailed performance parameters of the UAV are shown in Table 1 and the platform arrangement is described in Fig. 2. In this experiment, the UAV was controlled by an operator when it took off and landed. When it reached 300 meters high, the operator switched over to autopilot. In the lower

Fig. 1. Experimental site in the northern suburban area of Lin'an, China.

Table 1. Performance parameters of the UAV.

Project	Parameter
Wingspan	2.4 m
Maximum take-off weight	15 kg
Maximum payload	5 kg
Cruising speed	30–35 m s ⁻¹
Flight endurance	1 h
Powered by	Gasoline engine with a maximum output power of 2800 kW

Fig. 2. Instrument arrangement on the UAV platform: 1) UAV engine; 2) the customized cabin with the AM510 monitor inside; 3) Columbus V-900 GPS receiver; 4) HOB0 Temp/RH Data Logger U12-011; 5) inlet of the sampling tube of the AM510 monitor.

troposphere, the UAV climbed from 300 m to more than 1000 m altitude along the designed spiral route at a cruising speed (see Fig. 3).

The onboard portable instruments include the PM_{2.5} monitor, the meteorology monitor and the trajectory recorder. A SidePak Personal Aerosol Monitor AM510 (TSI Inc., USA) based on light scattering principle was used to

measure three-dimensional PM_{2.5} mass concentrations with a logging interval of 2 seconds. Air temperature, relative humidity and dew point temperature were measured by using a HOB0 Temperature/Relative Humidity Data Logger U12-011 at a 2-sec resolution, which was fixed outside the fuselage. As shown in Fig. S1, HOB0 sensor mounted on UAV agreed well with the balloon with a

Fig. 3. The UAV platform and its flight route.

commonly used Rotronic sensor in the synchronous measurements of air temperature and relative humidity within the 1000 m lower atmosphere. This demonstrates the reliable meteorological measurement by UAV mounted with a HOBO sensor. It is noted that air pressure was recorded every 10 seconds based on a portable ozone monitor with a built-in air pressure sensor. The trajectory data including latitude, longitude and height information were recorded by a Columbus V-900 GPS receiver at a 1-sec interval. Prior to each UAV flight, the logging time of all onboard instruments was strictly synchronized according to the Beijing Standard Time. Detailed parameters of airborne equipment are summarized in Table 2.

As shown in Table 3, field observations were taken for 5 days including Aug. 21, Oct. 11, Nov. 14 and Dec. 12 in 2014, and Feb. 5 in 2015 that covered varied seasons and time periods of a day. Each experimental day included 4 flights, which were separately performed at sunrise, at noon, in afternoon and near dusk (here named as Flight-1, Flight-2, Flight-3 and Flight-4). Considering time resolution of the measurements, each flight lasted for more than 30 minutes to collect enough data for mapping the spatial distribution of $PM_{2.5}$. Finally, samples of 25–30 minutes were available for each flight. It is noted that no measurements on dew point temperature were recorded during Flight-2, -3 and -4 on Aug. 21, 2014, due to equipment failures. Table 3 also summarizes weather conditions at the ground level, the data of which was obtained from the Air Quality On-line Monitoring and Analysis Platform of China (AQMAC, 2016) corresponding to Lin'an regional background station (30°18'N, 119°44'E).

Quality Guarantee and Data Processing

A routine factory calibration of the SidePak aerosol monitors was done relative to the respirable fraction of standard ISO 12103-1, A1 Test Dust every year. We have

also tested the reliability of the SidePak monitors against U.S. Federal Reference Methods (FRMs) of different principles for $PM_{1.0}$, $PM_{2.5}$ and PM_{10} mass measurements with 37 days of samples at 4 outdoor environmental stations in Shanghai (Wang *et al.*, 2015b, c, 2017, 2018a, b). We found that the SidePak monitor was strongly correlated with FRMs, but the SidePak overestimated all FRMs by a factor of 2 or so. Relative humidity (RH) was shown to be a key factor that distorted the measurement of the SidePak monitor, which is consistent with previous studies (Mamouri *et al.*, 2013). Therefore, before all the UAV measurements of this study, we conducted a field calibration with a consideration of RH adjustment against a standard instrument. The SidePak $PM_{2.5}$ readings with a RH compensation proposed by Ramachandran *et al.* (2003) were compared with the Thermo 1405-F instrument with the principle of tapered element oscillating microbalance (TEOM) at an urban station supported by the Shanghai Environment Monitoring Center. The $PM_{2.5}$ measurements were compared on 1-min averages in a total 18-h time period, during which the ambient RH varied between 40% and 70%. As described in Fig. 4, the SidePak monitor has a good linear relationship with the standard instrument ($y = 0.56x + 13.9$, $R^2 = 0.96$).

The $PM_{2.5}$ monitor was wrapped with foam buffers to filter vibration and noise. A 40-cm-long Tygon® sample tube was used to link the outside air with the $PM_{2.5}$ monitor, and air samples can be measured by the onboard monitor with the aid of its built-in air pump. The intake vent of the tube was fixed on the belly side of the UAV, about 15 cm away from the UAV bottom and 50 cm after the UAV nose. As reported by Zhang *et al.* (2017), the layout of the intake vent of the UAV similar to ours was testified to be optimal to avoid the turbulence. Because the exhaust port of the UAV engine was installed 15 cm above the UAV nose, the exhaust gas can hardly pollute the air

Table 2. Summary of airborne equipment.

Parameter	Instrument	Weight (g)	Measurement range	Minimum resolution	Accuracy	Logging interval
PM _{2.5}	TSI SidePak™ AM510	540	1–20,000 µg m ⁻³	1 µg m ⁻³	/	1 s–1 h
AT	HOBO Logger U12-011	46	–20 to 70°C	0.03°C	±0.35°C	1 s–18 h
RH			5–95%	0.03%	±2.5%	
DT			–76 to 54°C	0.03%	+1.5°C	
AP	2B Tech POM™	340	0–1013 mbar	0.1 mbar	/	10 s
Geographic trajectory	Columbus V-900	55	/	0.1° (direction) & 0.1 m (height)	0.1 µs & < 3 m	1 s

Note: AT, RH, DT and AP represent abbreviations of air temperature, relative humidity, dew point temperature and air pressure, respectively. For AP, the original unit “mbar” equates to “hPa,” and in the following Fig. 7 and Table 4, AP is unified to the unit “hPa.”

near the intake vent, especially considering the quite high UAV cruising speed ($\sim 35 \text{ m s}^{-1}$). The length of the inlet tube from the manifold to the monitor was minimized to reduce particle loss due to sorption. In our recent study, we have also carried out a wind tunnel experiment to assess the impacts of wind speed and wind direction on the SidePak PM_{2.5} measurement (Li *et al.*, 2019). Although there are absolute errors caused by the change of the wind field, we ignored this error here because it has limited impact on our measurement results. We are also more concerned with the relative variation trend of the PM_{2.5} concentration in the air, which is more important than the true measurement value. Additionally, the sampling mouth of the PM_{2.5} monitor was always kept opposed to the UAV flying direct. With these considerations, the UAV platform was further compared with a tethered balloon platform that was deployed with the standard instrument for PM_{2.5} measurement (Li *et al.*, 2018). In general, the acceptable measurement consistency between two platforms proves the reliability of UAV for air pollution measurement.

Before each take-off, the status of instruments, e.g., remaining battery and storage space, were carefully checked. The logging time was synchronized and a visual inspection was conducted to prevent the possible extrusion of inlets. The monitors for measuring PM_{2.5} and meteorological factors were warmed up for at least 20 minutes before each flight. When air temperature was less than 10°C, the warm-up time would be extended to 35–40 minutes to ensure stable readings. After the SidePak monitor warmed up, the PM_{2.5} readings were routinely zeroed by a zero filter against the zero baseline drift for a more accurate measurement, particularly for low aerosol levels (Padró-Martínez *et al.*, 2012; Wang *et al.*, 2018a).

After each UAV flight, the PM_{2.5}, meteorology and GPS data were exported immediately. Then, measurements associated with instrument errors were removed. For example, the PM_{2.5} data during the taking-off and descending periods were removed because of the possible contamination caused by the UAV's exhaust. Besides, the outliers were excluded according to the 3-sigma principle. Accordingly, the three-dimensional PM_{2.5} concentrations gathered by the UAV platform were rectified using this linear fitting equation shown in Fig. 4. After the data cleaning and calibrating, the processed data with different time resolutions was averaged to a 10-sec interval in order to eliminate noise and facilitate data interpretation.

RESULTS AND DISCUSSION

Three-dimensional Variations of PM_{2.5} Concentrations

Three-dimensional distributions of PM_{2.5} concentrations for 20 UAV flights were mapped in Fig. 5. Obviously, there is a stratification feature in the vertical distribution of PM_{2.5}, especially in the morning. However, the difference of PM_{2.5} horizontal distribution is not obvious in this $4 \times 4 \text{ km}^2$ area, implying there is no prominent impact of local pollution sources around the field site. Fig. 6 further presents the vertical profiles of PM_{2.5} concentrations based on samples averaged for each 100 m within 300–1000 m

altitude ($\text{PM}_{2.5}$ averages at ground was shown as well). In general, $\text{PM}_{2.5}$ value decreases with increasing altitude, which is consistent with previous studies using other

observation means (Šmidl *et al.*, 2013; Liao *et al.*, 2014). The vertical gradients of $\text{PM}_{2.5}$ concentrations in morning flights (Flight-1 and Flight-2) are about 2–13 times larger

Table 3. Surface $\text{PM}_{2.5}$ concentrations and weather conditions during each UAV flight.

Date	Flight time	Weather conditions ^a	$\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$) ^a	Air temperature ($^{\circ}\text{C}$) ^a	Relative humidity (%) ^a	Wind direction/ Wind speed ^a
2014/08/21	06:26–07:00	Cloudy	25	20	99	SW/2
	10:17–10:52	Cloudy	23	25	78	SE/1
	14:11–14:46	Cloudy	15	30	60	NE/2
	16:22–16:57	Cloudy	16	30	58	E/2
2014/10/11	07:32–08:09	Cloudy	46	21	86	E/2
	10:02–10:39	Cloudy	28	23	63	NE/3
	14:00–14:35	Cloudy	23	26	52	E/3
	15:47–16:22	Cloudy	27	24	57	NE/3
2014/11/14	07:28–08:01	Cloudy	46	3	89	SW/1
	10:02–10:37	Cloudy	48	12	53	SE/1
	14:02–14:37	Cloudy	44	16	34	NE/3
	15:33–16:07	Cloudy	51	15	34	NE/3
2014/12/12	08:08–08:46	Sunny	104	2	87	SE/1
	10:35–11:17	Sunny	95	5	41	N/1
	14:22–15:02	Sunny	37	9	26	W/3
	15:32–16:13	Sunny	33	8	27	W/3
2015/02/05	08:08–08:45	Cloudy	151	0	89	NE/1
	10:44–11:21	Sunny	190	5	51	E/1
	14:14–14:50	Sunny	36	8	31	N/3
	15:25–15:59	Sunny	28	7	31	E/3

Note: Wind direction was divided into 8 categories, i.e., north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW); wind speed was indicated as grades, where 1, 2 and 3 correspond to $0.3\text{--}1.5\text{ m s}^{-1}$, $1.6\text{--}3.3\text{ m s}^{-1}$ and $3.4\text{--}5.4\text{ m s}^{-1}$, respectively.

^a Surface $\text{PM}_{2.5}$ concentrations and meteorological data were obtained from the Air Quality On-line Monitoring and Analysis Platform of China, the openair project website of <http://www.openair-project.org>.

Fig. 4. Comparison between the SidePak $\text{PM}_{2.5}$ monitor and the standard instrument.

Fig. 5. Three-dimensional distribution of $\text{PM}_{2.5}$ concentrations.

than those in afternoon flights (Flight-3 and Flight-4). This can be mainly attributed to the diurnal variation of the PBL height (Li *et al.*, 2018). The PBL height is usually low during nighttime and early morning, which prevents upward

transport of surface $\text{PM}_{2.5}$. As PBL height increases in the late morning, atmosphere convection will strengthen to facilitate $\text{PM}_{2.5}$ upward. In the afternoon, the well mixed-up $\text{PM}_{2.5}$ tends to be homogeneous within the lower troposphere.

Fig. 6. Vertical profiles of $PM_{2.5}$ concentrations.

The averaged $PM_{2.5}$ concentration within the 1000 m altitude is obviously higher in the afternoon than in the morning in summer and autumn days (i.e., Aug. 21, Oct. 11 and Nov. 14, 2014). This reflects the contribution of atmospheric turbulence to increase $PM_{2.5}$ concentration in the afternoon (Ding *et al.*, 2005). The transport of pollutants from remote regions may also enhance the local $PM_{2.5}$ level with the meteorological enhancement in the afternoon. The $PM_{2.5}$ vertical gradient decreases from Flight-1 to Flight-4, which is relatively weaker in winter (i.e., Dec. 12, 2014, and Feb. 5, 2015) than in summer and autumn. Intuitively, the morning polluted level determine the vertical $PM_{2.5}$ pattern of winter days. For example, a serious morning pollution event occurred below 400 m in Dec. 12, 2014, and within the 1000 m lower troposphere in Feb. 5, 2015. These $PM_{2.5}$ vertical features imply the important roles of meteorological factors in the day.

The Impacts of Meteorological Factors on Vertical Variations of $PM_{2.5}$ Concentrations

Fig. 7 illustrates the vertical profiles of air temperature (AT), dew point temperature (DT), relative humidity (RH), and air pressure (AP) measured by UAV within 1000 m altitude. We can see that the UAV measured data well characterize the vertical variation of meteorological factors. From Flight-2 to Flight-4 for all days, AT generally decreases as height increases within 1000 m altitude. However, during Flight-1, AT is lower at ground than around 300 m with the exception on Oct. 11, 2014. This demonstrates the thermal inversion layer which is likely caused by the heterogeneity of terrain and underlying surface as well as meteorological conditions. The thermal inversion layer is bound to produce dynamic and thermodynamic effects on airflow movements. The cloudy weather accompanied with a weak wind in early morning easily leads to air sinking movement and subsidence inversion at ground (Table 3), which also suppresses turbulence and obstructs the vertical dispersion of surface air pollutants. Therefore, the thermal inversion layer is responsible for the inversion of $PM_{2.5}$ concentrations around 300–400 m altitude on Aug. 21 and Nov. 14, 2014 (see Fig. 5). We further calculated the Pearson correlation coefficients on the basis of mean value of each 100-m-high layer within 300–1000 m altitude as shown in Table 4. We

find that the vertical $PM_{2.5}$ concentration has significant positive correlation with AT at the 99% confidence level in summer and autumn days, but almost no correlation exists in winter days. The vertical variation of AT reflects the stability of atmospheric structure, which affects the strength of turbulence activity and governs the spread of air pollution, especially in summer and autumn.

RH generally increases as height increases, which presents a trend nearly opposite to AT. As an exception in Flight-1, RH decreases as height increases due to high humidity at ground (Table 3). A larger correlation between $PM_{2.5}$ and RH was found on Oct. 11 and Dec. 12, 2014, than in the other days (see Table 4). However, the correlation is negative on Oct. 11, 2014, but positive on Dec. 12, 2014. From early morning to late afternoon on Oct. 11, 2014, the mean value of the vertical RH for each flight gradually decreases (Fig. 7), while the corresponding mean value for $PM_{2.5}$ increases (Fig. 5). In contrast, the mean value for RH or $PM_{2.5}$ has little difference from morning to late afternoon on Dec. 12, 2014. Only a big difference for both RH and $PM_{2.5}$ occurs below and above 500 m altitude during the early morning flight (Flight-1) on Dec. 12, 2014, which likely determines the positive correlation between RH and $PM_{2.5}$ in the day. This agrees with previous studies that a higher air humidity was more favorable for aerosol particle formation due to its strong hygroscopicity (Ding *et al.*, 2005; Quan *et al.*, 2011; Booth *et al.*, 2012; Stevens *et al.*, 2012; Bates *et al.*, 2013; He *et al.*, 2016). In summary, Oct. 11, 2014, indicates a pollution accumulation event, but Dec. 12, 2014, represents a pollutant diffusion event. These 2 days also have stronger positive correlation between DT and $PM_{2.5}$. This suggests that an increase in the water vapor condensation temperature brings out high humidity in the air, which can promote the formation of new particles and increase concentrations of $PM_{2.5}$ (Wang *et al.*, 2017). The joint impact of RH and DT well explains the vertical evolution of $PM_{2.5}$ with more stratification in these 2 days compared to the other days as well.

Compared with other 4 days, there is very weak correlation between vertical $PM_{2.5}$ variation and each meteorological parameter on Feb. 5, 2015 (see Table 4). It is clearly seen from Table 3 and Figs. 5 and 6 that the unfavorable ground meteorology caused a serious haze event within 1000 m lower troposphere in the morning. As weather becomes

Fig. 7. Vertical profiles of AT, DT, RH and AP measured by the UAV.

sunny and surface wind increases in the afternoon, the $\text{PM}_{2.5}$ level drops rapidly within the lower troposphere. This is a typical winter haze event that we will focus on analysis of its process in the following section. With the exception on Feb. 5, 2015, AP has significant positive correlation with vertical $\text{PM}_{2.5}$ variation. As a whole, AT itself or together with AP affects the diurnal activity of airflow within the lower troposphere, and has the most important effect on the vertical variation of $\text{PM}_{2.5}$ concentration. As discussed above, RH also significantly influences the vertical profile

of $\text{PM}_{2.5}$ concentrations. AT and RH have more significant impacts on the vertical pattern of $\text{PM}_{2.5}$ concentrations in the morning than in the afternoon. Especially, if considering thermal inversion layer, AT and RH are more important.

Explanations of Meteorology Acting on the Evolution of Typical Haze Events

According to the discussion in above sections, we identified Aug. 21 (a summer day) and Oct. 11 (an early autumn day), 2014, as an identical category in the vertical

Table 4. Pearson correlations among PM_{2.5} and meteorological parameters at a vertical scale.

		PM _{2.5}	AT	RH	DT	AP
2014/8/21	PM _{2.5}	1	0.313**	−0.142**	0.032	0.750**
	AT		1	−0.800**	−0.852**	0.140**
	RH			1	0.632**	−0.018
	DT				1	0.223
	AP					1
2014/10/11	PM _{2.5}	1	0.761**	−0.666**	0.857**	0.583**
	AT		1	−0.916**	0.742**	0.477**
	RH			1	−0.531**	−0.259**
	DT				1	0.797**
	AP					1
2014/11/14	PM _{2.5}	1	0.447**	0.319**	0.690**	0.497**
	AT		1	−0.338**	0.664**	0.467**
	RH			1	0.477**	0.037
	DT				1	0.614**
	AP					1
2014/12/12	PM _{2.5}	1	−0.011	0.854**	0.764**	0.502**
	AT		1	−0.364**	0.528**	0.686**
	RH			1	0.591**	0.147**
	DT				1	0.710
	AP					1
2015/2/5	PM _{2.5}	1	0.010	−0.001	0.068*	0.034
	AT		1	−0.840**	0.005	0.833**
	RH			1	0.532**	−0.423**
	DT				1	0.513**
	AP					1

Note: AT, RH, DT and AP represent abbreviations of air temperature, relative humidity, dew point temperature and air pressure, respectively. ** Correlation is significant at the 0.01 level (one-tailed). * Correlation is significant at the 0.05 level (one-tailed).

variation of PM_{2.5}. These 2 days prove that under a low background level, local surface pollutants transport upwards and downwards over day and form a lightly polluted event due to the local meteorological parameters especially the air temperature and relative humidity. In this section, we focused on discussing the meteorology influence to the evolution of typical haze events in middle autumn (Nov. 14, 2014) and winter (Dec. 12, 2014, and Feb. 5, 2015) days when the high pollution often breaks out.

(1) Formation of a Light Haze in a Middle Autumn Day (Nov. 14, 2014)

Fig. 8 shows the time series of hourly averaged surface PM_{2.5} concentrations, relative humidity as well as wind speed and direction at Lin'an ground station from Nov. 12 to 16, 2014. We can see that a light haze near ground occurred between Nov. 12 and Nov. 13, and dissipated quickly under a larger wind from the east after the noon on Nov. 13. Since then, a low PM_{2.5} level was maintained till 14:00 on Nov. 14, and then PM_{2.5} began to accumulate and climbed to a peak of approximately 113 $\mu\text{g m}^{-3}$ at 19:00 of that day. In the next 2 days, such a light haze went on with a little fluctuation. Thus, Nov. 14 was a beginning of the haze that is likely due to the occurrence of static weather within 1000 m lower atmosphere. Wind speed at 0–1500 m altitude was less than 2.6 m s^{-1} over the day (see Fig. S2). Air temperature and relative humidity changed little within

the lower atmosphere during our 4 UAV flights (see Fig. 7). All of these are unfavorable for horizontal and vertical dispersion of air pollutants. As discussed before and illustrated in Fig. 7, both relative humidity and dew point temperature suddenly increased at 300–400 m and 600–800 m altitude compared to each former height in Flight-1 (07:28–08:01) of this day. There forms two shallow thermal inversion layers causing the steady atmospheric stratification and plenty of moisture, which can restrain the dispersion of surface PM_{2.5} and promotes the formation of new aerosol particles (Platis *et al.*, 2016). On the whole, thermal inversion layers accompanied with high moisture in early morning determine the generation of such a haze if the whole day maintains unfavorable local weather.

(2) Dissipation of the Typical Haze Events in Winter Days (Dec. 12, 2014, and Feb. 5, 2015)

Fig. 9 shows a typical regional haze pollution generating on Dec. 11 and dissipating from Dec. 12, 2014. The pollution was attributed to long-distance transport from north and northwest China according to 48-h backward trajectories in our previous study (Li *et al.*, 2018). This transport was mainly driven by the increased surface wind from morning to afternoon on Dec. 11, and then the pollution maintained a high level under a low wind speed till to the morning of Dec. 12. At about 09:00 on Dec. 12, particles began to quickly dilute under the increasing

Fig. 8. PM_{2.5} concentration, relative humidity, wind speed and wind direction measured by ground station at Lin'an (30°18'N, 119°44'E) on Nov. 12–16, 2014. The UAV experiment period is marked by the grey box line.

Fig. 9. PM_{2.5} concentration, relative humidity, wind speed and wind direction measured by ground station at Lin'an (30°18'N, 119°44'E) on Dec. 10–14, 2014. The UAV experiment period is marked by the grey box line.

northwest wind (Fig. 9). We clearly see from Fig. S2 that northwest wind with a speed larger than 10 m s^{-1} dominates the lower atmosphere (especially above 600 m) on Dec. 12. At noon, wind speed even increased to 20 m s^{-1} above 1000 m altitude. These demonstrate the sweeping effect of north or northwest wind within the lower atmosphere. As a result, $\text{PM}_{2.5}$ concentrations dropped to the minimum of approximately $30 \mu\text{g m}^{-3}$ at 15:00 in the day. As discussed in the former section, in early morning, there also existed a thermal inversion layer at about 300 m, and high relative humidity and dew point temperature happened below 500 m altitude (see Fig. 7). Although the joint impact of the special local meteorology has caused a $\text{PM}_{2.5}$ stratification that obstructs the pollution dispersion, a strong external wind determines the quick dissipation of the haze. Therefore, Dec. 12 presented a typical dispersion of a regional haze under the driving force of external air mass.

A dissipation process of $\text{PM}_{2.5}$ was also recorded on Feb. 5, 2015 (Fig. 10). Surface $\text{PM}_{2.5}$ began to accumulate at 06:00 on Feb. 4 and remained at a relatively high concentration level of $70\text{--}100 \mu\text{g m}^{-3}$. After that, $\text{PM}_{2.5}$ started to enhance at 00:00 and gradually climbed to a peak value of about $190 \mu\text{g m}^{-3}$ at 10:00 on Feb. 5. In the process, the surface wind always remained $1\text{--}2 \text{ m s}^{-1}$. 5 hours later, $\text{PM}_{2.5}$ concentration decreased sharply from $190 \mu\text{g m}^{-3}$ to $26 \mu\text{g m}^{-3}$. The pollution was diluted due to the clean air from southeast (surface wind speed increased to 3 m s^{-1}). Before the haze dissipation on Feb. 5, there existed a gradual accumulation process of particles due to

the local unfavorable meteorology, which is completely different from Dec. 12, 2014, when a long-distance transport brought out the haze before the $\text{PM}_{2.5}$ dissipation. Compared with 00:00 on Feb. 5, wind speed generally decreased from $5\text{--}15 \text{ m s}^{-1}$ to about 5 m s^{-1} within lower atmosphere at noon of this day (see Fig. S2), the wind of which is far weaker than that on Dec. 12, 2014. The sweeping effect of wind in lower atmosphere seems not obvious in the day, while the increased surface wind strongly decreases high humidity in the morning, and weather changes from cloudy to sunny in Flight-2, -3 and -4 (see Figs. 5–7). Such a haze dissipation indicates that surface wind plays a key role in urgently improving the haze if the dispersion conditions within lower atmosphere are not enhanced at that time.

CONCLUSIONS

This study developed a flexible UAV platform equipped with portable monitors for measuring the $\text{PM}_{2.5}$ mass concentrations and meteorological parameters above a $4 \times 4 \text{ km}^2$ area in eastern China. Data collected from 20 UAV flights was used to map three-dimensional distributions of the $\text{PM}_{2.5}$ in high spatial resolution. The vertical profiles of the $\text{PM}_{2.5}$ concentrations from ground level to an altitude of 1000 m were also characterized to help explain the accumulation and dispersion of haze. The major findings of our experiment are as follows: The $\text{PM}_{2.5}$ does not display any obvious horizontal variation, but the concentration decreases as the height increases and exhibits

Fig. 10. $\text{PM}_{2.5}$ concentration, relative humidity, wind speed and wind direction measured by ground station at Lin'an ($30^{\circ}18'N$, $119^{\circ}44'E$) on Feb. 3–7, 2015. The UAV experiment period is marked by the grey box line.

clear stratification in the morning. Greater homogeneity is observed in the afternoon, although the concentration still slightly rises above 500 m, particularly on days that display more stratification. The vertical gradient of the concentrations shows a decrease from the morning to the afternoon, which is smaller during winter than summer and autumn. Daily changes in the planetary boundary layer height and inversion layer are caused by the vertical pattern of the air temperature, which, in addition to relative humidity, affect the vertical variation in the $PM_{2.5}$ concentration, especially in the morning. Local meteorology, particularly the two factors mentioned above, thus plays a key role in determining diurnal changes in the $PM_{2.5}$ concentration in the lower troposphere during summer and autumn. However, a third factor, transported air masses, typically influences the formation and dissipation of haze during winter.

We successfully used a lightweight UAV to measure the vertical variation in the $PM_{2.5}$ concentration and meteorological factors up to an altitude of 1000 m, but our experiment was still bound by several limitations. For example, monitoring the evolution of the atmospheric structure and the aerosol composition in detail over a long period of time was unfeasible due to the small selection of monitors on board as well as the payload and battery life of the UAV. Therefore, future research should strive to improve this platform.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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