Environmental Pollution 224 (2017) 107–116

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

# Three-dimensional investigation of ozone pollution in the lower troposphere using an unmanned aerial vehicle platform☆

Xiao-Bing Li [a], Dong-Sheng Wang [a], Qing-Chang Lu [a, **], Zhong-Ren Peng [a, b, c, *], Si-Jia Lu [a], Bai Li [a], Chao Li [a]

[a] *Center for Intelligent Transportation Systems and Unmanned Aerial Systems Applications Research, State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[b] *China Institute for Urban Governance, Shanghai Jiao Tong University, Shanghai 200240, China*
[c] *Department of Urban and Regional Planning, University of Florida, PO Box 115706, Gainesville, FL 32611-5706, USA*

## ARTICLE INFO

*Article history:*
Received 6 November 2016
Received in revised form
15 January 2017
Accepted 24 January 2017
Available online 12 February 2017

*Keywords:*
Drone
Tropospheric ozone
Vertical profiling
Ozone horizontal variation

## ABSTRACT

Potential utilities of instrumented lightweight unmanned aerial vehicles (UAVs) to quickly characterize tropospheric ozone pollution and meteorological factors including air temperature and relative humidity at three-dimensional scales are highlighted in this study. Both vertical and horizontal variations of ozone within the 1000 m lower troposphere at a local area of 4 × 4 $km^2$ are investigated during summer and autumn times. Results from field measurements show that the UAV platform has a sufficient reliability and precision in capturing spatiotemporal variations of ozone and meteorological factors. The results also reveal that ozone vertical variation is mainly linked to the vertical distribution patterns of air temperature and the horizontal transport of air masses from other regions. In addition, significant horizontal variations of ozone are also observed at different levels. Without major exhaust sources, ozone horizontal variation has a strong correlation with the vertical convection intensity of air masses within the lower troposphere. Higher air temperatures are usually related to lower ozone horizontal variations at the localized area, whereas underlying surface diversity has a week influence. Three-dimensional ozone maps are obtained using an interpolation method based on UAV collected samples, which are capable of clearly demonstrating the diurnal evolution processes of ozone within the 1000 m lower troposphere.

## 1. Introduction

In recent decades, tropospheric ozone pollution has become one of the severest environmental problems in China (Zhang et al., 2008). Generally, tropospheric ozone is neither emitted directly by natural nor anthropogenic processes. Instead, it is mainly formed by many precursors such as volatile organic compounds (VOCs) and nitric oxides ($NO_X$) through complicated photochemical reactions, and it accounts for nearly 10% of the total atmospheric ozone (Blanchard, 2000; Wang et al., 2001; Gao, 2007). Ozone is one of the most important atmospheric trace gases due to its special roles in regulating many photochemical processes (Illingworth et al., 2014). However, it is also a serious air pollutant, and high ozone concentrations have significant detrimental effects on human health, air quality, plant development, and climate change (McKee, 1994; Ding et al., 2008). With the rapid development of society and economy in China, large amounts of ozone precursors are emitted into the atmosphere due to intensive human activities in many metropolitans such as Beijing and Shanghai. Ozone and its precursors could accumulate in the planet boundary layer (PBL) under unfavorable synoptic weather conditions, leading to severe air pollution events. Therefore, detailed investigations for a better understanding to ozone spatiotemporal evolution patterns within the PBL are extremely important. Meanwhile, efficient observation approaches that are capable of capturing three-dimensional (3D) characteristics are necessary premises.

Typically, most of the atmospheric composition measurements in the troposphere are made using routine ground-based methods with satisfied temporal, while poor spatial, resolutions (Brady et al.,

---

☆ This paper has been recommended for acceptance by Dr. Hageman Kimberly Jill.

* Corresponding author. Center for Intelligent Transportation Systems and Unmanned Aerial Systems Applications Research, State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.

** Corresponding author.

*E-mail addresses:* qclu@sjtu.edu.cn (Q.-C. Lu), zrpeng@sjtu.edu.cn (Z.-R. Peng).

http://dx.doi.org/10.1016/j.envpol.2017.01.064
0269-7491/

2016). However, accuracy loss often occurred when ground observations are used to represent a large 3D scale. In the past decades, vertical profiling was widely used to improve the universality and reliability of in situ measurements within the troposphere. Most of the vertical profiles, in terms of atmospheric chemistry and physics, are usually obtained by advanced approaches such as LiDAR (ground and aircraft based), nadir, balloon, kite, and tower, whereas many of which are always operated at fixed locations or heights to represent a regional scale (Pelon and Megie, 1982; Megie et al., 1985; Knapp et al., 1998; Aneja et al., 2000; Coheur et al., 2005; Meng et al., 2008; Ma et al., 2011; Li et al., 2015). Apparently, these approaches have either limited spatial resolutions (kite, tower, and balloon) or limited accuracies (LiDAR and nadir), and their representativeness at a regional scale were barely assessed. To capture the spatiotemporal variations of atmospheric compositions at 3D scales, aircraft research and special-equipped commercial aircraft are sometimes used (Doran et al., 2003; Emmons et al., 2004; Ding et al., 2008; Geng et al., 2009; Aruffo et al., 2014). In addition to the MOZAIC program that is conducted to achieve routine observations based on commercial aircrafts with predefined lines (Ding et al., 2008), most of the other large aircraft applications were mainly conducted for special studies instead of being used as routine observations due to their high use-cost (Kleinman and Daum, 1991; Castelluccio et al., 2007; Chen et al., 2013). As alternatives, lightweight unmanned aerial vehicles (UAVs), which have a maximum take-off mass of less than 150 kg and a cruising speed of lower than 130 km $h^{-1}$ (Haddon and Whittaker, 2004), can be used in air quality measurements.

Lightweight UAVs are more flexible and cost efficient than conventional large aircrafts, and great efforts have been devoted to exploring their potential applications in air quality measurements (Ramanathan et al., 2007; Ramana et al., 2007; Corrigan et al., 2007; Neumann et al., 2012; Bates et al., 2013; Merlaud et al., 2013; Haas et al., 2014; Illingworth et al., 2014; Peng et al., 2015; Brady et al., 2016). In comparison to ground-based methods, lightweight UAVs equipped with miniaturized sensors not only can collect data at different altitudes, but also can obtain corresponding vertical profiles with much higher spatial resolutions, especially within complex terrains (Rossi and Brunelli, 2015; Brady et al., 2016). In addition, detailed 3D maps of air pollutants and meteorological factors at local scales can be quickly obtained using the UAV sampling platform (Peng et al., 2015; Luo et al., 2015). UAV platforms are also capable of performing routine observation tasks to provide in situ validations for air quality models and satellite products (Illingworth et al., 2014; Harrison et al., 2015). Nevertheless, there are still many challenging problems that are urgent to be solved before a wider application of the UAV platforms in air quality measurement. For example, the miniaturized sensors attached on the UAVs should be quick-response and less affected by air turbulence to guarantee satisfactory measurement accuracies. In addition, mounting positions of the miniaturized sensors and related sample tubes on the UAVs also require more professional evaluations. What's more, appropriate flight schemes should be carefully designed and assessed for different UAV application scenes. In this regard, we attempted to use and assess a lightweight fixed-wing UAV, attached with a miniaturized ozone monitor, to investigate the spatiotemporal distribution characteristics of ozone within the PBL.

The objective of this study is to investigate the ozone spatiotemporal variations within the 1000 m lower troposphere using a lightweight fixed-wing UAV sampling platform at a localized area in Lin'an County, Zhejiang Province, China. Integrated vertical profiles of ozone and meteorological factors including air temperature and relative humidity (RH) are analyzed. Subsequently, horizontal and 3D variations of ozone, as well as their relationships with meteorological factors and the underlying surface diversity, are presented.

## 2. Materials and methods

### 2.1. UAV platform and instrumentation

Ozone mixing ratio, RH, and air temperature were measured using a lightweight fixed-wing UAV (Fig. 1(a)) equipped with a fast-response miniaturized ozone monitor (POM™, 2B Tech) and a temperature&RH (Temp/RH) sensor (HOBO logger, Model: U12-011). Detailed information about the model, resolution, and accuracy for each sensor are presented in Table S1. The UAV has a total wingspan of 2.4 m and a maximum payload of 3.5 kg. It is powered by a gasoline engine (two-cylinder and two-stroke) with two exhaust vents installed on the nose position. The fuselage is mainly constituted of three cabins: the front cabin, close to the engine, is designed to hold two built-in fuel tanks (the main and auxiliary), the median cabin is used to hold instrument payloads, and the last cabin is used to hold UAV control-related instruments (Fig. 1(a)). As illustrated in Fig. 1(b), the UAV performs flight missions according to preplanned waypoints that are planned by a ground control station.

The ozone monitor is fixed in the median cabin lined with vibration-absorptive material (shock-absorbing sponge) to alleviate vibration impacts during flight operations. The ozone monitor makes measurements based on the attenuation of light at 254 nm and has a temporal resolution of 10 s. A section of FEP-lined Tygon® tube, about 0.4 m in length, is used to import air samples with the aid of an inbuilt air pump. The intake vent of this sample tube is fixed on the belly side of the fuselage in order to alleviate air turbulence impacts induced by UAV operations (Peng et al., 2015). In addition, the ozone monitor is also originally designed to ensure reliable measurements when used in an aircraft environment (Section S1). Moreover, it also has a built-in Nafion® tube to eliminate water vapor interference, which is of great importance for aircraft measurements (Wilson and Birks, 2006; http://www.twobtech.com/dewline.htm). In application, the ozone monitor requires a warmup time of 10–20 min before obtaining reliable readings. The Temp/RH sensor is fixed on the belly side of the fuselage with a temporal resolution of 1 s. UAV waypoints, characterized by latitudes, longitudes, and altitudes, during each flight are recorded using a Multifunction GPS receiver (Model: Columbus V-900) fixed on the backside of the fuselage. The UAV waypoints are recorded every 1 s with a horizontal resolution of approximately 33 m. All the environmental sensors were strictly calibrated by the Shanghai Environmental Monitoring Center before and after each field campaign (Section S1).

### 2.2. Description of field campaigns

A rural area (118°51′-119°52′ E, 29°56′-30°23′ N, belonging to Lin'an county, Hangzhou city, Zhejiang Province, China) that is roughly 50 km southwest of Shanghai, 10 km northeast of downtown Lin'an, and 35 km northwest of downtown Hangzhou is selected as the experimental site (Fig. S5). This site covers a total area of $4 \times 4$ $km^2$ (the bottom cruising level, Fig. S6), and is surrounded by less developed mountainous regions with the exception of the east side that is a suburban area of Hangzhou. Nearly half of the underlying surface in this area is covered by vegetation and the remaining area is bare land. No major exhaust emission sources are found in and around this area (Fig. S7).

In this study, the total weight (15.9 kg) and the maximum flight height (1000 m) of the UAV platform have exceeded the upper limits (7 kg and 120 m, respectively) of registration-free flights in