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Measurement of above-canopy meteorological profiles using unmanned aerial systems

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1 | INTRODUCTION

Unmanned aerial systems (UASs) are becoming valuable environmental data collection tools, allowing the user freedom to attach sensors and to launch at a moment's notice while also collecting spatially precise data all at a relatively low cost (Simic Milas et al., 2018; Nowak, Dzión, & Bogawski, 2019; Dunbabin & Marques, 2012; Manfreda et al., 2018). Atmospheric data, such as air temperature and relative humidity, can be collected by UASs as a vertical profile above forest canopies to study canopy boundary layer processes and associated trace gas fluxes. Traditionally, vertical atmospheric profiles are collected by using drop sondes, tethered blimps, weather balloons, or weather towers (Russell & Uthe, 1978; Seibert et al., 2000). These methods are limited because they are expensive, difficult to control, and/or require detailed logistics and careful planning (Beyrich, 1997; Hill, Konrad, Meyer, & Rowland, 1970).

The objective of the study was to test the ability of a UAS to characterize the canopy boundary layer and lower atmosphere stability. The canopy boundary layer, also known as the roughness sublayer, can be defined as a layer that has been formed due to vegetative influence on the production of eddies due to roughness, transfer of heat, water vapour, and CO_2 (Arnqvist, Segalini, Dellwik, & Bergström, 2015; Raupach, Finnigan, & Brunet, 1996). In this video, the UAS's data collection ability is demonstrated by visualizing the rapid changes in temperature and relative humidity during UAS ascents and descents in a variety of outdoor environments. As shown in the video, minute differences in atmospheric vertical profiles over small scales of space and time occur because of the complexity of hydrological and atmospheric processes that govern our planet.

Three distinct landscapes were surveyed using this method: farmland, transitional tropical forest, and mountainous temperate forests. In College Station, Texas, USA, flights were conducted at the Texas A&M Experimental Farm, a research site associated with the Texas Water Observatory (http://two.tamu.edu, 30°32′04.2″N 96°25′53.3″W). Vertical profiles were collected over cotton and corn fields located near the Brazos River. Flights in San Isidro, Costa Rica, were launched from the Texas A&M Soltis Center for Research and Education (http://soltiscentercostarica.tamu.edu/, 10°22′59.7″N 84°37′03.5″W). Vertical profiles were taken over transitional premontane rainforest. Flights in Morganton, Georgia, USA, were conducted in the Blue Ridge Mountains, a subsection of the Appalachian Mountains, near the Chattahoochee National Forest. Vertical profiles were collected over deciduous forest (34°49′45.1″N 84°10′30.2″W).

The UAS consists of three components: a small multi-rotor unmanned aerial vehicle (UAV), a Kestrel DROP D3FW Fire Weather Monitor (Kestrel Meters, Boothwyn, PA, USA), and a simple tether connecting these elements. Two different UAV models were used for the study: the Autel Robotics X-Star Premium (Autel Robotics, Bothell, WA, USA) in Costa Rica and the DJI Phantom 4 Pro V2.0 (DJI, Shenzhen, China) in Texas and Georgia. To record the meteorological data, the Kestrel DROP was tethered to the UAV landing gear using 7.5 m of monofilament. This configuration allowed the sensors to experience undisturbed air and remain unaffected by the turbulence produced by the propellers (Machado, 2015).

Before each flight, the sensor was preset to begin data collection 5 min before the UAV was launched and then record relative humidity and air temperature data every 5 s. While the UAV was taking off, the sensors and monofilament were held taut and slowly released as the

UAV rose to prevent the monofilament from being tangled in the propellers. The UAV was flown vertically upwards from the launch site to a maximum altitude and then lowered down to collect the descent profile. In Georgia, maximum altitude was 187 m above the launch point, which was within the Federal Aviation Administration (FAA) regulation of 122 m above adjacent ground due to the steep, mountainous terrain. In Texas, the maximum altitude for the flights was 122 m due to the FAA regulation. In Costa Rica, the maximum altitude was 154 m above the launch point. For the Costa Rica and Georgia flights, the UAV was launched, rose to maximum altitude of that flight and flown to several sampling locations where it was lowered as close to the forest canopy as possible and rose back up to maximum altitude. All ascents and descents were conducted at approximately 1 m/s, which gave a vertical spatial resolution of 2 m for all data and minimized any potential for effects of UAV propeller downdraft. Flight time varied from 10 to 20 min and were manually controlled by the pilot. Once all profiles were collected, the UAV was then flown back over the launch site and lowered down. As the UAV was lowering, the sensor was then caught by the visual observer and the monofilament was respooled.

In the visualization, we highlight three common weather occurrences that our system can detect. The profile from the Texas A&M Experimental Farm shows a distinct increase in dew point when comparing the ascent versus the descent, demonstrating a rapid change in humidity in the underlying air mass, which was confirmed by ground station data. The profile collected in Morganton, Georgia, captured a temperature inversion and associated low cloud cover, which can be attributed to the surrounding topography. From both the profiles collected at the Texas A&M Experimental Farm and Morganton, Georgia, changes in relative humidity were observed over very short periods of time. Multiple profiles were taken during the Costa Rica flight. When launching and landing at the Texas A&M Soltis Center parking lot, there was a distinct jump in air temperature and dew point across a small altitude change, which illustrates a pronounced boundary layer effect due to the elevated ground heat flux over asphalt. In contrast, profiles collected over pristine forest were consistent over the spatial extent of the flights, approximately 500 m.

The main limitations of this methodology can be attributed to the equipment configuration and to U.S. FAA regulations regarding the use of UASs. The UAV cannot be operated in rainy conditions or in wind speeds greater than about 15 m/s (34 mi/hr). FAA regulations prohibit flight above 122 m above ground level without a waiver and include controlled airspace restrictions around airports (typically 8 km [5 mi]; Federal Aviation Administration, 2016). These restrictions limit the method especially in urban and metropolitan areas and in situations where rapid deployments are necessary. Also, due to internal protocols, some public sector personnel may not be able to deploy a UAS rapidly. For flights that are not conducted in the United States, each country may have their own set of laws and regulations that should be abided by (Jones, 2017). In addition, UAV battery life can be another limitation; one charge typically provides for approximately 20 to 25 min of flight time, less under windy conditions. The relative humidity sensor used was a thin-film polymer capacitive sensor. These sensors are the most common type deployed aboard small UASs and have been widely used in meteorological radiosondes for nearly 40 years (Elston et al., 2015; Smit, Kivi, Vömel, & Paukkunen, 2013). Discussion of thin-filmed polymer capacitive sensor limitations has shown that the polymer can become chemically contaminated, thus inducing a dry bias or decreasing its sensitivity (Kämpfer, 2012). Additional issues with the sensor are hysteresis, which can occur at low temperatures, and increased response under non-isothermal, transient conditions (Dooley & O'Neal, 2008; Miloshevich, Vömel, & Paukkunen, 2001). Two errors that could have occurred at the Costa Rica site were the deposition of water onto the sensor due to high humidity and sensor reading drift due to moist bias from extreme humid conditions (Miloshevich et al., 2001; Zhang & Chou, 1999). The sensor was stored in a desiccant chamber between flights to reduce saturation effects. However, even with these limitations, the use of a UAS gives new insight to potential relationships between the land surface and near-surface atmosphere thanks to a spatial and temporal resolution that other techniques struggle to achieve.

Our system, a UAV coupled with an atmospheric sensor, is affordable ($935 to $1635 strongly depending on UAV cost), requires little set-up, and produces high resolution data sets in space and time. This method also allows the user to quickly decide when and where data collection will occur in addition to allowing repeated data collection at remote locations. The data visualization exemplifies the effectiveness of the UAS set-up and the effects of land development on the near-surface atmosphere, temperature and vapour influx with mere second accuracy, and meteorological changes due to the topography.

In recent years, numerous atmospheric UAS data collection studies have been published, including air pollution (Šmídl & Hofman, 2013; Malaver Rojas et al., 2012), wild fire detection (Wegener et al., 2004), collection of meteorological measurements at sea (Machado, 2015), facilitation in climate control for crop monitoring (Roldán, Joossen, Sanz, del Cerro, & Barrientos, 2015), and many other applications (Villa, Gonzalez, Miljievic, Ristovski, & Morawska, 2016). There have also been a number of studies published on atmospheric boundary layer monitoring using fixed wing UASs (Elston et al., 2015) and multi-rotor UASs (Chilson et al., 2019), all with sensors attached directly to the aircraft. The UAS configuration for this study allows for undisturbed air to be accessed by the sensor. As shown in the data visualization video, the proposed method proves to be successful in collecting atmospheric parameters from undisturbed air space. From these UAS atmospheric developments, it can be seen that UASs could potentially replace traditional boundary layer sampling techniques. The next step is to apply these methodologies to hydrology, specifically land surface-atmosphere interactions over various land cover, natural or human made. This could better the understanding of local evapotranspiration response to a changing climate and how much humans are locally influencing the radiative budget and acceleration of the hydrologic cycle. In summary, UAS methods provide powerful tools that can be applied to near surface environmental data collection while consistently providing data that is temporally and spatially rich in accuracy.

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REFERENCES

Arnqvist, J., Segalini, A., Dellwik, E., & Bergström, H. (2015). Wind statistics from a forested landscape. *Boundary-Layer Meteorology*, *156*(1), 53–71.

Beyrich, F. (1997). Mixing height estimation from sodar data—A critical discussion. *Atmospheric Environment*, *31*(23), 3941–3953.

Chilson, P. B., Bell, T. M., Brewster, K. A., de Azevedo, G. B. H., Carr, F. H., Carson, K., … Grimsley, J. L. (2019). Moving towards a network of autonomous UAS atmospheric profiling stations for observations in the Earth's lower atmosphere: The 3D Mesonet Concept. *Sensors*, *19*(12), 2720.

Dooley, J. B., & O'Neal, D. L. (2008). The transient response of capacitive thin-film polymer humidity sensors. *HVAC&R Research*, *14*(5), 663–682.

Dunbabin, M., & Marques, L. (2012). Robots for environmental monitoring. *IEEE Robotics Automation Magazine*, *19*(1), 24–39.

Elston, J., Argrow, B., Stachura, M., Weibel, D., Lawrence, D., & Pope, D. (2015). Overview of small fixed-wing unmanned aircraft for meteorological sampling. *Journal of Atmospheric and Oceanic Technology*, *32*(1), 97–115.

Federal Aviation Administration (2016). Code of Federal Regulations (14 CFR) part 107. In *In, edited by United States Department of Transportation*. FAA Washington: DC.

Hill, ML, Konrad, TG, Meyer, JH, and Rowland, JR. 1970. "*A small, radio-controlled aircraft as a platform for meteorological sensors*."

Jones, Therese. 2017. "International commercial drone regulation and drone delivery services." In.: RAND.

Kämpfer, Niklaus. 2012. *Monitoring atmospheric water vapour: Ground-based remote sensing and in-situ methods.* Vol. 10: Springer.

Machado, Christopher R. 2015. "*An analysis of meteorological measurements using a miniature quad-rotor unmanned aerial system*." In.: NAVAL POSTGRADUATE SCHOOL MONTEREY CA.

Manfreda, S., McCabe, M., Miller, P., Lucas, R., Madrigal, V. P., Mallinis, G., … Ciraolo, G. (2018). On the use of unmanned aerial systems for environmental monitoring. *Remote Sensing*, *10*(4), 641.

Milas, Simic, Anita, Joaquim João Sousa, Warner, Timothy A, Teodoro, Ana Cláudia, Peres, Emanuel, Gonçalves, José Alberto, Garcia, Jorge Delgado, Bento, Ricardo, Phinn, Stuart, and Woodget, Amy. 2018. "*Unmanned aerial systems (UAS) for environmental applications special issue preface*." In.: Taylor & Francis.

Miloshevich, L. M., Vömel, H., & Paukkunen, A. (2001). Characterization and correction of relative humidity measurements from Vaisala RS80-A radiosondes at cold temperatures. *Andrew J Heymsfield, and Samuel J Oltmans, Journal of Atmospheric Oceanic Technolog*, *18*(2), 135–156.

Nowak, M. M., Dzióbek, K., & Bogawski, P. (2019). Unmanned aerial vehicles (UAVs) in environmental biology: A review. *European Journal of Ecology*, *4*(2), 56–74.

Raupach, MR, Finnigan JJ, and Brunet Y. 1996. "Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy." In *Boundary-layer meteorology 25th anniversary volume, 1970–1995*, Dordrecht, Netherlands:Springer-Science+Business Media, 351-382.

Rojas, Malaver, Alexander, Jairo, Motta, N, Gonzalez, Luis F, Corke, Peter, and Depari, Alessandro. 2012. "Towards the development of a gas sensor system for monitoring pollutant gases in the low troposphere using small unmanned aerial vehicles."

Roldán, J., Joossen, G., Sanz, D., del Cerro, J., & Barrientos, A. (2015). Mini-UAV based sensory system for measuring environmental variables in greenhouses. *Sensors*, *15*(2), 3334–3350. https://doi.org/10.3390/s150203334

Russell, P. B., & Uthe, E. E. (1978). Regional patterns of mixing depth and stability: Sodar network measurements for input to air quality models. *Bulletin of the American Meteorological Society*, *59*(10), 1275–1287.

Seibert, P., Beyrich, F., Gryning, S. E., Joffre, S., Rasmussen, A., Tercier, P., & J Atmospheric environment Tercier (2000). Review and intercomparison of operational methods for the determination of the mixing height. *34*(7), 1001–1027.

Šmídl, V., & Hofman, R. (2013). Tracking of atmospheric release of pollution using unmanned aerial vehicles. *Atmospheric Environment*, *67*, 425–436.

Smit, H, Kivi R, Vömel H, and Paukkunen A. 2013. "Thin film capacitive sensors." In *Monitoring atmospheric water vapour: Ground-based remote sensing and in-situ methods*. ed N. Kämpfer. New York:Springer Science & Business Media.

Villa, T., Gonzalez, F., Miljievic, B., Ristovski, Z., & Morawska, L. (2016). An overview of small unmanned aerial vehicles for air quality measurements: Present applications and future prospectives. *Sensors*, *16*(7), 1072.

Wegener, S., Schoenung, S., Totah, J., Sullivan, D., Frank, J., Enomoto, F., … Theodore, C. (2004). UAV autonomous operations for airborne science missions. In *Paper presented at the AIAA 3rd "Unmanned Unlimited" Technical Conference*. Workshop and Exhibit.

Zhang, C., & Chou, M.-D. (1999). Variability of water vapor, infrared radiative cooling, and atmospheric instability for deep convection in the equatorial western Pacific. *Journal of the Atmospheric Sciences*, Boston, Massachusetts, USA:American Meteorological Society, *56*(5), 711–723.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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