Daytime Evolution of Lower Atmospheric Boundary Layer Structure: Comparative Observations between a 307-m Meteorological Tower and a Rotary-Wing UAV

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Abstract: A 307-m tall meteorological tower was used to evaluate meteorological observation data obtained using a rotary-wing unmanned aerial vehicle (UAV). A comparative study between the tower and UAV observations was conducted during the daytime (06:00 to 19:00 local time (LT)) in the summer of 2017 (16–18th August). Hourly vertical profiles of air temperature, relative humidity, black carbon (BC), and ozone (O3) concentrations were obtained for up to 300 m height. Statistical metrics for evaluating the accuracy of UAV observations against the tower observation showed positive (potential temperature) and negative (relative humidity) biases, which were within acceptable ranges. The daytime evolution of the lower atmospheric boundary layer (ABL) was successfully captured by the hourly UAV observations. During the early morning, a large vertical slope of potential temperature was observed between 100 and 140 m, corresponding to the stable ABL height. The large vertical slope coincided with the large differences in BC and O3 concentrations between altitudes below and above the height. The transition from stable to convective ABL was observed at 10–11 LT, indicated by the ABL height higher than 300 m in the convective ABL. Finally, we provide several recommendations to reduce uncertainties of UAV observation.

Keywords: atmospheric boundary layer; daytime evolution; vertical profile; meteorological observation tower; rotary-wing UAV

1. Introduction

Vertical structure of the lower atmospheric boundary layer (ABL) plays a crucial role in determining the evolution of near-surface wind and thermal environments as well as local air quality. The surface layer of the ABL, defined as the lower 10% of the total ABL, exhibits large gradients of atmospheric momentum and heat [1–5]. Nocturnal low-level jet and temperature inversion are well-known examples of wind and thermal phenomena, respectively, which occur in the lower ABL [6,7]. In addition, air pollutants frequently accumulate within the lower ABL close to emission sources when the atmosphere is stable [8,9]. The variations in the vertical structure of lower ABL are predominantly attributed to the heating of the earth’s surface due to solar insolation, topography, land cover types,
vegetation, anthropogenic heat, surface obstacles, etc. [10]. As the atmospheric vertical structure is site-specific, in situ observations of atmospheric variables in the lower ABL are required for understanding the local wind and thermal environments at the site of interest.

Various methods for in situ observations have been developed and employed toward examining the vertical profiles of the atmospheric boundary layer. For decades, radiosondes have been widely used for tracking meteorological variables, such as air pressure, air temperature, relative humidity, and wind speed and direction, directly from the instruments mounted on-board. The ABL height can then be accurately estimated, based on the vertical profiles of virtual potential temperature, water-vapor mixing ratio, and relative humidity [11]. However, telemetry instruments mounted onto a balloon are prone to observational errors due to wind-driven displacement of the drifting balloon, and these instruments and balloons are quite expensive considering they are of single-use. A tethersonde, which is mounted onto a tethered balloon, is an alternative instrument that overcomes the limitations of the radiosonde. A repeatedly ascending and descending tethersonde produces measurement data for determining the vertical profiles of atmospheric variables; however, this experiment can only be carried out during calm/weak wind conditions [12–14]. A meteorological observation tower provides a representative way to continuously measure vertical profiles of atmospheric variables at the site of interest for a long period. Several tall meteorological towers with heights of a few hundred meters have been installed in Boulder, USA [15], Tsukuba, Japan [16], Beijing, China [17], Boseong, South Korea [18], and Shenzhen, China [19], and have been used to observe the temporal evolution of the vertical profiles of various meteorological variables in the lower ABL. A meteorological observation tower is the most accurate in situ arrangement for obtaining meteorological data at various altitudes. However, it has practical limitations on arranging observational sites.

In recent years, there have been increasing attempts to employ unmanned aerial vehicles (UAVs) for meteorological observations in an effort to overcome the disadvantages of the observation methods discussed above [20]. Owing to the rapid developments in measurement technologies using UAVs, in situ observations using UAVs become feasible, especially in cases of high impact weather events, remote sites, and intensive observations [21]. Among the observations using fixed-wing and rotary-wing UAVs, vertical profile observations using rotary-wing UAVs have become popular as a rotary-wing UAV can hover at an altitude for a certain time [22]. In previous studies using rotary-wing UAV observations, large daytime variations in the vertical profiles of the lower ABL and its impacts on near-surface atmospheric environments have been clearly discussed [8,23–25].

In preliminary studies using fixed-wing UAVs, the temporally-varying vertical profiles captured by the UAV were compared with radiosonde and tethersonde observations and showed the good agreement with the traditional observations [26–28]. On the contrary, the vertical profiles of the lower ABL observed using a rotary-wing UAV still have some uncertainties owing to observational errors in the light-weight observation sensors [29]. Specifically, the uncertainties in observation using a rotary-wing UAV can be mainly attributed to the displacement of air temperature and humidity sensors [30,31], the effect of downdraft produced by the rotors [32], and the inlet position of particulate matter instrument [33]. Therefore, a comparison between a rotary-wing UAV observation and a conventional observation, such as those obtained from a tall meteorological observation tower, is required for assessing the reliability of the data obtained using a UAV. In a couple of previous studies, a 307-m tall meteorological observation tower at Boseong, South Korea was regarded as a reference site. Atmospheric profiles of air temperature, relative humidity, wind components, and estimated sensible heat flux observed using a rotary-wing UAV were compared to those observed at the reference tower [34,35].

In this study, we evaluated the applicability of the UAV-based observations of air temperature and relative humidity, as well as airborne black carbon (BC) and ozone (O\textsubscript{3}) concentrations, by comparing hourly atmospheric profiles observed using a rotary-wing UAV to those observed at a tall meteorological observation tower from sunrise to sunset in the summer of 2017 (16–18th August). Using the comparative observation data, the daytime evolution of vertical profiles within the lower ABL was then analyzed.
2. Methods

2.1. Study Site and Period

The study site is located at the Boseong global standard meteorological observatory (34°45′48″ N, 127°12′46″ E) in Boseong-gun, Jeollanam-do, South Korea (Figure 1). A 307-m tall meteorological observation tower was installed at the Boseong observatory in 2013, which is surrounded by rice fields on a flat terrain up to a radius of 1.5 km. The area is free from any major emission sources of air pollutants. Due to the location of the sea-shore to the south and low-rise mountains to the north and west, the site is characterized by strong diurnal variations in land-sea breeze circulations [36]. The Boseong meteorological observation tower has been operated by the Korea Meteorological Administration. The comparative observations using the meteorological tower and a UAV were conducted for 3 consecutive days (16–18 August 2017). The UAV observation was conducted over a region covered by grassland approximately 50 m away from the meteorological observation tower for the sake of flight safety at every hour from 06:00 (immediately after the sunrise) to 19:00 (immediately before the sunset) local time (LT).

Figure 1. (a) Map showing the location of Boseong global standard meteorological observatory (source: Google Earth); images of (b) rotary-wing UAV (unmanned aerial vehicle) and (c) 307-m tall meteorological observation tower.

2.2. Tower and UAV Observations

At the Boseong meteorological observation tower, air temperature (5628 PRT, Fluke, Everett, WA, USA), relative humidity (HMP155, Vaisala, Helsinki, Finland), and 2-D wind components (UA-2D, Thies Clima, Göttingen, Germany) were observed simultaneously at 11 different altitudes (i.e., 10, 20, 40, 60, 80, 100, 140, 180, 220, 260, and 300 m) with a 1-min interval. Quality assurance (QA)/quality control (QC) data were provided following the procedure described in the NIMR (National Institute of Meteorological Research) report [18].

The rotary-wing UAV used for the observation was an octocopter UAV with a total width of 1050 mm, a height of 500 mm, and a maximum carrying capacity of 2 kg (Kpro System, Seoul, Korea) [9]. The maximum flight time of the fully equipped UAV is 12 min. During each 10 min flight, the UAV ascends for 5 min from the ground at a constant speed of 1 m s⁻¹, hovers for 1 min
at approximately 300 m altitude, and descends at a constant speed of 1.5 m s\(^{-1}\), similar to the flight schedule of the rotary-wing UAV in Zhu et al. [24] and Lee et al. [37]. Meteorological observation sensors manufactured for a radiosonde, consisting of 10K3A1 Thermistor (Betatherm, Galway, Ireland) for air temperature measurement, SHT15 (SENSIRION, Stäfa, Switzerland) for relative humidity measurement, and bmp085 (BOSCH, Reutlingen, Germany) for atmospheric pressure measurement, were mounted underneath the main frame of the UAV for protection from solar radiation (Table 1). In order to stabilize the meteorological observation sensors, the UAV equipped with the sensors was kept in stand by for 3 min before takeoff and after landing. The UAV was also equipped with AE51 microaethalometer (Aethlabs, San Francisco, CA, USA) for BC concentration measurement and aeroqual series 500 (Aeroqual, Auckland, New Zealand) for \(O_3\) concentration measurement. The flow rate of AE51 microaethalometer was set to 150 mL min\(^{-1}\). In order to minimize the interference of the revolving blades, the BC and \(O_3\) sensors were placed in the loading box located at the bottom of the UAV [38]. The data collection intervals for the meteorological sensors, microaethalometer, and \(O_3\) sensor were set to 1 s, 10 s, and 1 min, respectively. We used the UAV observation data recorded only during the ascending flight times except for BC (both ascending and descending flight times) for data analysis [26].

### Table 1. Specifications of instruments used for UAV observation.

| Variable     | Model and Manufacturer | Measurement Resolution | Accuracy | Time Interval |
|--------------|------------------------|------------------------|----------|---------------|
| Air temperature Relative humidity | bmp085, BOSCH | 0.01 °C | ±0.5% ± 4.5% | 1 s |
| BC | AE51, Aethlab | 0.001 µg m\(^{-3}\) | ±0.1 µg m\(^{-3}\) | 10 s |
| \(O_3\) | Aeroqual 500, Aeroqual | 0.001 ppm | ±0.008 ppm | 1 min |

2.3. Data Processing of UAV Observation

The time delay for each UAV instrument was corrected by adjusting 30 s, 10 s, and 1 min to the recorded meteorological variables, BC concentration, and \(O_3\) concentration data, respectively. The BC concentration data was used after smoothing by means of the local polynomial regression algorithm provided by the manufacturer (Aethlabs) in order to minimize the random noise in the raw data. Given the different data collection intervals of the observed variables, the meteorological observation data, and \(O_3\) and BC concentration data were averaged for every vertical interval of 10 m and 50 m, respectively.

The air temperature and relative humidity observed using the UAV were corrected against the observation data at the ground automatic weather station (AWS) located close to the observation tower to minimize the biases in UAV observation data. Overall, compared to the AWS observations, the UAV sensors tended to overestimate (underestimate) the air temperature (relative humidity) at the ground before takeoff. The largest biases in air temperature and relative humidity from the UAV observations against the ground AWS observations were 1.96 °C (12–15 LT) and −8.1% (06–07 LT), respectively. For the correction process, the biases were independently set to zero at each time zone (i.e., 06–07, 08–09, 10–11, 12–15, and 16–19 LT). The corrected UAV observation data were used for analysis. While the number of hourly UAV meteorological observations was 14 per day, the frequencies of UAV observation data available at 300 m height were 12, 11, and 10 for 16, 17, and 18 August, respectively, due to the insufficient capacity of the UAV battery.
3. Results and Discussion

3.1. Overview of Meteorological Conditions

The 2-m air temperature, relative humidity, 10-m wind speed, and wind direction observed at the ground AWS during the observation period are shown in Figure 2. During 16–18 August 2017, typical summertime weather was observed, with little clouds, high daytime air temperature, and weak-to-moderate winds during the course of the day. The lowest daily minimum and the highest daily maximum air temperatures were reported on 17 August (21.8 °C at 04 LT) and 18 August (32.4 °C at 13 LT), respectively. Wind speeds were occasionally high in the early afternoon and relatively low in the morning and night. Due to the sea-breeze circulation during the daytime, southerly winds were predominant in the early afternoon, especially on 17 and 18 August. Based on the meteorological conditions, the daytime evolution of vertical profiles in the lower ABL is obviously expected, which shows calm and neutral atmosphere in the morning and windy and unstable atmosphere in the early afternoon.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Time series of hourly (a) 2-m air temperature, relative humidity, (b) 10-m wind speed, and wind direction observed at the ground AWS during the observation period from 00:00 LT (local time) on August 16 to 23:00 LT on August 18, 2017.

3.2. Comparisons between Tower and UAV Observations

To evaluate the validity of the UAV-based meteorological observations, the UAV observation data of potential temperature and relative humidity were compared to the tower observation data for five different periods (i.e., 06–07, 08–09, 10–11, 12–15, and 16–19 LT). In Figure 3, the potential temperature and relative humidity from UAV observations exhibit good linear correlations with those from tower observations. Correlation coefficients (R) of potential temperature and relative humidity are the highest for 06–07 LT (R = 0.95, p-value < 0.01) and 12–15 LT (R = 0.76, p-value < 0.01), respectively (Table 2). In the early morning, large vertical gradients of potential temperature in the highly stratified atmosphere than in the afternoon are attributed to the strong correlations. Although atmospheric instabilities have reduced the vertical measurement ranges of the temperature and humidity sensors of UAV during the late morning and early afternoon on a couple of days, the majority of temperature and humidity biases remained less than 2 °C and 10%, respectively.
Figure 3. Scatter plots of (a) potential temperature and (b) relative humidity between tower and UAV observations at 06–07 (blue triangle), 08–09 (red cross), 10–11 (green diamond), 12–15 (yellow square), and 16–19 LT (black circle).

Table 2. Correlation coefficients (R) of potential temperature and relative humidity between tower and UAV observations at 06–07, 08–09, 10–11, 12–15, and 16–19 LT.

|                  | 06–07 LT | 08–09 LT | 10–11 LT | 12–15 LT | 16–19 LT |
|------------------|----------|----------|----------|----------|----------|
| Potential Temperature | 0.95     | 0.83     | 0.73     | 0.55     | 0.72     |
| Relative Humidity | 0.60     | 0.66     | 0.42     | 0.76     | 0.73     |

For evaluating the UAV observations against the tower observations, vertical profiles of statistical metrics such as R, RMSE (root mean square error), and MB (mean bias) for potential temperature and relative humidity for each day are presented in Figure 4. Note that the UAV observation data at the 300-m altitude was excluded from evaluation due to an insufficient number of UAV observations. As the UAV observation data were corrected against the ground AWS observation data for each period, the correlations between tower and UAV observations for potential temperature and relative humidity were the strongest near the ground. The R for potential temperature and relative humidity were higher than 0.9 below 40 and 140 m, respectively. The RMSE for potential temperature and relative humidity were 0.77–1.93 K and 3.1–7.8%. The accuracy of UAV observations, estimated based on R and RMSE values, was inferred to be higher near the ground than at the highest altitude corresponding to the meteorological observation tower. The magnitudes of MB for potential temperature and relative humidity were less than 1.51 K and 5.1%, respectively, which were also within the acceptable ranges, and they generally exhibited positive and negative biases, respectively [29]. Note that the large systematic errors and biases for relative humidity at 60 m height were caused by inaccurate humidity sensors deployed at the meteorological tower. The RMSE and MB were consistently large on August 18, corresponding to the day of clear sea-breeze wind in the early afternoon. The day-to-day variations in RMSE and MB would be minimized when the correction of the UAV observation data is carried out at every hour of each day. Thus, the UAV meteorological observation data are acceptable in terms of R, RMSE, and MB for examining the daytime atmospheric profiles and its evolution in the lower ABL.
Figure 4. Vertical profiles of (a,d) R, (b,e) RMSE, and (c,f) MB for potential temperature (upper panels) and relative humidity (lower panels) observed using the UAV on August 16 (blue triangle), 17 (red square), and 18 (black circle).

3.3. Daytime Evolution of Atmospheric Vertical Profiles

The vertical profiles of potential temperature and relative humidity observed hourly using the UAV from 06:00 to 19:00 LT for 3 days were averaged over five different periods (i.e., 06–07, 08–09, 10–11, 12–15, and 16–19 LT) to examine the daytime evolution of lower ABL (Figure 5). Immediately after sunrise (06–07 LT), relatively stable atmosphere was observed, with the largest vertical gradient of potential temperature (+3.3 K) between 10 and 300 m. The slope is the largest between 100 and 140 m (+1.6 K per 100 m), implying that the ABL height is approximately 120 m in the early morning. The humid air with higher relative humidity (>90%) is clearly separated from the relatively drier air with lower relative humidity (<90%) above the stable ABL. As the solar heating on ground intensifies, the potential temperatures at all observation altitudes increase. The increasing rates of potential temperature and the decreasing rates of relative humidity with time were larger at lower observation altitudes than at higher altitudes. This reduced the degrees of slopes of potential temperature and relative humidity due to the development of convective ABL. The ABL height became >300 m after 10–11 LT, exhibiting almost uniform vertical profiles of potential temperature and relative humidity from the ground to at least 300 m. The vertical profile of potential temperature at 16–19 LT is similar to that at 12–15 LT, which revealed that the convective ABL maintained its thermal structure until 19:00 LT (i.e., immediately before sunset). In the afternoon, relatively moist air flowed into the lower ABL following the sea-breeze from the south, resulting in a slight negative slope of relative humidity with height again.

The evolution of ABL at the developing stage from relatively stable to convective layers was further investigated using the hourly vertical profiles of BC and O₃ concentrations from 06:00 LT to 09:00 LT (Figure 6) averaged over the 3 observation days. Note that the average altitude intervals of BC and O₃ concentrations were not identical to those of potential temperature and relative humidity due to longer data record intervals of BC and O₃ data (10 s and 1 min, respectively) during the continuously ascending flight (O₃) and ascending and descending flight (BC). Although the observation site is located
far from villages and other places of anthropogenic activities, higher BC and lower O3 concentrations near the ground were clearly observed under the stratified atmosphere in the morning, possibly due to agriculture-related pollutant emission sources such as diesel-engine machines. The highest BC concentrations were observed at 40 m (07 and 09 LT) and 80 m (06 and 08 LT), whereas the lowest BC concentrations (<0.6 µg m\(^{-3}\)) were observed above 200 m. In contrast to the BC concentration, the lowest O3 concentrations appeared at 50 m (07, 08, and 09 LT) and 100 m (06 LT), whereas the highest O3 concentrations (>48 ppbv) appeared above 250 m. Although the hourly variations in the vertical profiles of BC and O3 concentrations are not monotonic, it is notable that the vertical differences of BC and O3 concentrations between altitudes below and above the ABL height are quite substantial in the morning. The typical distribution in the lower ABL has been well known especially in a densely populated urban area at the morning rush hours [39]. This provides solid evidence for ABL height assumed to be between 80 and 200 m above the ground in the morning, which agrees with the ABL height determined from potential temperature and relative humidity profiles.

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**Figure 5.** Vertical profiles of (a) potential temperature and (b) relative humidity observed using the UAV at 06–07 (black triangle), 08–09 (blue inverse triangle), 10–11 (green diamond), 12–15 (purple square), and 16–19 LT (red circle).

**Figure 6.** Vertical profiles of (a) BC and (b) O3 concentrations observed using the UAV at 06 (black triangle), 07 (blue inverse triangle), 08 (green diamond), and 09 LT (red circle).
4. Summary and Concluding Remarks

A comparative observation study using a 307-m tall meteorological tower and a UAV was conducted during the daytime for 3 consecutive days in summer. The comparisons between tower and UAV observations showed the applicability of UAV observation on the daytime evolution of lower ABL after bias correction of air temperature and relative humidity. Using statistical metrics such as R, RMSE, and MB, the characteristics of the UAV observations were explained. The accuracy of UAV observations was the highest near the ground, in the early morning, and under weak interference from solar radiation. The vertical profiles of potential temperature and relative humidity exhibited the daytime transition of ABL from stable to convective layers at 10–11 LT. In addition to meteorological profiles, the vertical profiles of BC and O$_3$ concentrations exhibited their large differences between altitudes below and above the ABL heights (80–200 m) in stratified atmosphere in the morning.

We found some uncertainties in the UAV observations after evaluation against the observations from the 307-m tall meteorological tower. Reducing the uncertainties is further required following the recommendations. First, to ensure the reproducibility of UAV observation data, a sufficient hovering time at a specific observation height for collecting multiple data is required instead of constantly ascending or descending flight during the data collection. Second, a sufficiently rapid response time of on-board sensors would be beneficial for capturing instantaneous variations. Third, careful placement of the meteorological sensor on the UAV is required to avoid interference due to solar heating on the frame and heat generation from the UAV rotor and the main body. Fourth, bias correction of UAV observation data for each flight should be performed against the ground AWS observation data as the UAV meteorological sensors are influenced by many environmental factors. We believe that the recommendations provided in this paper serve as a guide toward more reliable UAV observations.

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