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Measurements of Boundary Layer Wind Profiles with Scanning Doppler Lidar

스캐닝 도플러 라이다를 이용한 대기경계층 내 바람 특성 관측 연구

2017년 2월

서울대학교 대학원 지구환경과학부 박 수 진
ABSTRACT

Understanding characteristics of the planetary boundary layer (PBL) is important since winds and PBL height have a strong influence on the dispersion of pollutants and its precursors that are emitted from the surface and, therefore is closely related with human health. Lack of observations of parameters that influence and are influenced by PBL dynamics, such as wind and aerosol distribution, has made it difficult to define the characteristics of PBL solely on numerical model and parameterization schemes. With remote sensing techniques, continuous observation of winds and aerosols within the PBL is possible. In this study, the evolution of planetary boundary layer winds and aerosol characteristics was investigated using co-located lidar observations. Measurement of winds within the PBL was done with a wind Doppler lidar (WDL) at Seoul National University and WISE Jungnang station. Assessment of the WDL wind results was carried out by comparing observations with radiosonde soundings. In retrieving wind data from WDL radial velocity, it was concluded that using singular value decomposition (SVD) on the mean radial velocities of 15 minutes showed the best agreement with radiosonde measurements with a bias of 0.66 m s\(^{-1}\) and root mean square error of 2.38 m s\(^{-1}\). In determining PBL height, the gradient method on aerosol backscatter signal profiles from Mie-scattering lidar and the threshold method on vertical wind velocity variance were used on observation data from 25\(^{\text{th}}\) to 31\(^{\text{st}}\) May 2016. PBL height determined by each method showed reasonable diurnal variation,
although PBL heights were irretrievable for some points due to operational shortcomings of WDL. Thermally induced winds were detected for a few days during the observation period with strong winds in the afternoon and weak at night. For those days when surface heating was a major driving force of winds, the diurnal variation of wind direction showed the characteristics of mountain and valley winds. In the case of wind observations at WISE Jungnang site, wind direction was more influenced by the synoptic weather pattern.

**Keyword:** wind Doppler lidar, Mie lidar, planetary boundary layer, winds

**Student number:** 2015-20465
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CHAPTER 1. INTRODUCTION

1.1 Background

Understanding planetary boundary layer (PBL) dynamics is important for accurate modelling of air quality, numerical weather prediction and conversion of satellite measurements to near-surface air quality information (Davies et al., 2007; Emeis et al., 2008; Pearson et al., 2010). This is due to the fact that winds within the PBL and their temporal variation influence the dispersion and transport of aerosols and their precursors that are emitted near the surface. The dynamics within the PBL is complex due to its numerous driving forces; incoming solar radiation, surface temperature, potential temperature, surface roughness, vertical wind shear, etc. However the complex structure and evolution of PBL in urban environment is yet unclear due to lack of observation (Barlow et al., 2010). Rather, the characteristics are inferred from meteorological parameters such as wind, temperature and radiation from parameterization schemes or from numerical models (Seibert et al., 2000).

PBL height is also an important meteorological parameter that affects near-surface air pollutant concentrations in urban areas since it determines the volume of air into which pollutants and their precursors are emitted (Seibert et al., 2000; Kim et al., 2007). Methods in determining the PBL height from in-situ measurements and surface-based remote sensing have been studied since as early as 1964 and continuous development has taken place, especially with the
technical development of remote sensing (Seibert et al., 2000; Emeis et al., 2008). The definition of PBL height varies with the observation data used, and each method has its advantages and shortcomings. Combining various methods and data would be a way to overcome the shortcomings and produce more accurate knowledge about the PBL. An overview of methods to define the PBL height with various observation data was given by Seibert et al. (2000) and an updated review was given by Emeis et al. (2008). They also emphasize the importance of knowing the characteristics of the PBL and its height.

In measuring winds within the PBL, wind Doppler lidar is effective due to its capability of continuous, automatic operation. Numerous studies on boundary layer characteristics using Doppler lidar in various environments have been done, from tropical rain forest boundary layer in Pearson et al. (2010) to urban boundary layer in Barlow et al. (2011). Deriving PBL heights from wind Doppler lidar measurements has several advantages. Compared to radiosonde soundings, continuous wind Doppler lidar data is retrievable PBL height may be over-estimated when using aerosol backscatter signals since aerosol distribution is not influenced by boundary layer turbulence alone, but also by other factors such as long range transport, synoptic weather patterns, emission, etc. However, wind Doppler lidars can be a direct way of measuring mixing within the PBL.
1.2 Objectives

The evolution of PBL is influenced by various factors such as surface temperature, surface heating, radiation, surface roughness etc. Therefore the PBL height, aerosol concentration and wind structure within the PBL have complex patterns which are still unclear. The objectives of this study were to estimate the height and structure of PBL using lidar systems and to investigate the characteristics of PBL that may affect near-surface aerosol concentration. To achieve these objectives, performance evaluation of the recently deployed wind Doppler lidar at Seoul National University was done and an algorithm to improve results was developed. This study adopted some methods that defined PBL height from preceding studies using the observation data within Seoul urban environments. The specific objectives of this study are as follows:

(1) Develop an algorithm to retrieve winds from wind Doppler lidar and quantify its uncertainties.

(2) Determine the PBL height with co-located lidar measurements.

(3) Investigate the diurnal variation of PBL height and characteristics of winds and aerosols within the PBL.
CHAPTER 2. METHODOLOGY

2.1 Instrumentation

This study uses the measurements of two lidar systems deployed at Seoul National University and three lidar systems operated at Jungnang WISE (Weather Information Service Engine) observation station. Lidar (Light Detection and Ranging) is an optical remote sensing instrument that makes range-resolved measurements of backscattered laser light to provide vertical profiles of atmospheric constituents (Fernald, 1984). A wind Doppler lidar and Mie lidar made observations from a container laboratory on the roof of Bldg. 501, Seoul National University. At WISE Jungnang observation station a Mie lidar and wind Doppler lidar were deployed and the wind Doppler lidar from Seoul National University was relocated to the WISE Jungnang observation station for direct comparison between the two wind Doppler lidar systems. Given in Table 1 and Table 2 are summaries of the technical data of each instrument.

The principle and technical specifications of the wind Doppler lidar and Mie lidar at Seoul National University are as follows.

2.1.1. Wind Doppler lidar

The wind Doppler lidar (referred to as WDL) utilizes the Doppler frequency shifts of photons when they are scattered by moving molecules. If the difference
Table 1. Technical specifications of lidar systems operated at Seoul National University.

<table>
<thead>
<tr>
<th></th>
<th>Wind Doppler Lidar</th>
<th>Mie Lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>1.55 μm</td>
<td>532 nm, 1064 nm</td>
</tr>
<tr>
<td><strong>Average Power</strong></td>
<td>10 W (@ 30 m res.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 W (@ 75 m res.)</td>
<td>20 mJ</td>
</tr>
<tr>
<td></td>
<td>5 W (@ 150 m res.)</td>
<td></td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>16 kHz</td>
<td>10 Hz</td>
</tr>
<tr>
<td><strong>Pulse length</strong></td>
<td>200 ns (@ 30 m res.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 nm (@ 75 m res.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000 ns (@ 150 m res.)</td>
<td></td>
</tr>
<tr>
<td><strong>Range resolution</strong></td>
<td>30 m, 75 m, 150 m</td>
<td>6 m</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Automated, Continuous (not waterproof)</td>
<td>Automated, Continuous</td>
</tr>
</tbody>
</table>

Table 2. Technical specifications of lidar systems operated at WISE Jungnang station.

<table>
<thead>
<tr>
<th></th>
<th>Wind Doppler Lidar</th>
<th>Aerosol Lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>1.54 μm</td>
<td>532 nm, 1064 nm</td>
</tr>
<tr>
<td><strong>Average Power</strong></td>
<td>370 W</td>
<td>-</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>10 kHz</td>
<td>20 Hz</td>
</tr>
<tr>
<td><strong>Range resolution</strong></td>
<td>50 m</td>
<td>3.75 m</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Automated, Continuous</td>
<td>Automated, Continuous</td>
</tr>
</tbody>
</table>
between the frequency of the emitted light and the observed light is measured, the relative speed of the source with respect to the receiver can be determined. A Doppler lidar system that emits light of wavelength $\lambda_0$ has a frequency of $f_0 = \frac{c}{\lambda_0}$. Due to the Doppler effect, backscattered light by a moving particle would have a frequency of

$$f = f_0 \left(1 + \frac{2v}{c}\right)$$

where $v$ (line of sight velocity or radial velocity) is the velocity component parallel to the direction of light emitted by the lidar. To retrieve the correct velocity vector of the particle, the wind vector, the lidar system needs measurements of the line of sight velocity from at least three different directions. As depicted in Figure 1(a), the WDL retrieves line of sight velocity from the scanning circle and plots a sine wave of the line of sight velocity (Figure 1(b)). Assuming that wind velocity is horizontally homogeneous at each altitude, the lidar system can calculate the horizontal wind speed and its direction from this sine curve.

The WDL used in this study is the LR-S1D2GA Short Range lidar System manufactured by Mitsubishi Electric Corporation. The emitted light has a wavelength of 1.55 μm and the user can choose from a range resolution of 30 m, 75 m and 150 m when making observations. The system has 20 range bins and the first range bin starts at 60 m, which makes the measurement ranges 660 m, 1560 m and 3060 m according to the range resolution. The WDL makes continuous, automated observations but is not waterproof so measurements were only made for non-rainy days.
2.1.2. Mie-scattering lidar

The Mie-scattering lidar (referred to as Mie lidar) employs the following lidar equation.

\[
(R) = \frac{E_0 \eta_L}{R^2} O(R) \beta(R) \exp\left[-2 \int_0^R \alpha(r) \, dr\right] \tag{2}
\]

The backscattered signal by Rayleigh and particle scattering at range \( R \) received by the lidar transmitter is \( P(R) \), \( E_0 \) is the energy of the pulse emitter, \( \eta_L \), the lidar parameters having to do with lidar efficiencies of the optical and detection units, \( O(R) \), the overlap
between the outgoing laser and receiver field of view, $\beta(R)$, the backscatter coefficient and $\alpha(r)$, the extinction coefficient. Both backscatter and extinction are caused by aerosols and molecules and the lidar equation can be summarized to

$$S(R) = E_0 \eta_L [\beta_{aer}(R) + \beta_{mol}(R)]O(R) \exp[-2 \int_0^R (\alpha_{aer}(r) + \alpha_{mol}(r))dr] \quad (3)$$

Here $S(R) = R^2 P(R)$ is the range corrected signal. The molecular scattering properties ($\beta_{mol}(R)$, $\alpha_{mol}(R)$) can be determined from temperature and pressure profiles. However, the aerosol backscatter and extinction coefficient are yet to be determined. To solve the lidar equation, the ratio of particle extinction to particle backscatter coefficient (lidar ratio) is introduced. The lidar ratio,

$$L_{aer}(R) = \frac{\alpha_{aer}(R)}{\beta_{aer}(R)} \quad (4)$$

is dependent on particle size distribution, shape and chemical composition. Solutions of the lidar equation using various assumptions of the lidar ratio are given in Klett et al. (1981) and Sasano et al. (1985).

The Mie lidar emits laser beams of two wavelengths (532 and 1064 nm) with a depolarization ratio measurement channel at 532 nm. It is vertically fixed with measurement range from 0 to 18 km above surface and a range resolution of 6 m. The temporal resolution is 15 minutes, and it measures backscattering intensity in 532 nm and 1064 nm and depolarization ratio at 532 nm. The Mie lidar system is automated and continuous observations were made. This study used range corrected attenuated
backscatter coefficient in determining the PBL height.

2.2 Measurements

The LR-S1D2GA WDL (hereafter referred to the SNU WDL) made measurements for non-rainy days only, making the longest continuous observation of 13 days from 25 May 2016 to 6 June 2016. The SNU WDL was operated on the roof of Bldg. 501, Seoul National University during the study period, except for a few days during which it made observations at the WISE (Weather Information Service Engine) Jungnang station for direct comparison and evaluation from October 4th to October 7th 2016. A map of the location of each site is given in Figure 2. It should be noted that Seoul National University is located in a valley of Mount Gwanak while the Jungnang station is situated considerably far from any mountains. Parameter settings of the instrument during the observation period are given in Table 3.

During the study period, regular radiosonde soundings were made from Jungnang station at 0 UTC, 6 UTC, 12 UTC and 18 UTC. Apart from radiosonde measurements, a Leosphere WINDCUBE 200 (hereafter referred to the WISE WDL) and a LB210-D200 aerosol lidar manufactured by Raymetrics were operated at Jungnang station. Both data during the period of co-located measurement were used in this study.
Table 3. Operational parameter settings of the SNU WDL during the study period.

<table>
<thead>
<tr>
<th>Observation mode</th>
<th>PPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation angle</td>
<td>80 °</td>
</tr>
<tr>
<td>Azimuth angle</td>
<td>-90 ° ~ 90 °</td>
</tr>
<tr>
<td>Scanning speed</td>
<td>1 deg s⁻¹</td>
</tr>
<tr>
<td>Resolution range</td>
<td>75 m</td>
</tr>
<tr>
<td>Minimum range</td>
<td>60 m</td>
</tr>
<tr>
<td>Pulse hits</td>
<td>16000</td>
</tr>
</tbody>
</table>

Figure 2. Location of Seoul National University and Jungnang station.
2.3 Wind data retrieval processes

For wind data to be retrieved from a WDL, the line of sight velocity (radial velocity) must be converted to the wind vector \( \mathbf{U}(u, v, w) \). The WDL assumes that wind is horizontally homogeneous. Under this assumption, the line of sight velocity can be decomposed into the \( u, v \) and \( w \) components as:

\[
v_r = -usin\theta cos\varphi - vcos\theta cos\varphi - wsin\varphi
\]  \hspace{1cm} (5)

Where \( \theta \) is the azimuth angle and \( \varphi \) the elevation angle.

The SNU WDL system originally applies the sine-fitting method in which it makes a sine curve fitting of radial velocities according to the azimuth angle. The function of the fitted sine curve will be in the form of

\[
v_r = a + bcos(\theta - \theta_{max}),
\]  \hspace{1cm} (6)

where \( a \) is the offset, \( b \), the amplitude and \( \theta_{max} \) the phase shift. From this function the three-dimensional wind vector \( \mathbf{U} \) can be reconstructed as follows.

\[
\mathbf{U} = (u, v, w) = \left(-\frac{b \sin\theta_{max}}{cos\varphi}, -\frac{b \cos\theta_{max}}{cos\varphi}, -\frac{a}{sin\varphi}\right)
\]  \hspace{1cm} (7)

However this method has a shortcoming in that the retrieved wind vector is the result of the average of a fixed time period and so in reconstructing wind data, the user has a restriction in the time length of averaging data. Also, noise may be included in the fitted sine function, resulting in inaccurate wind data retrieval.
Since the wind data retrieved by the SNU WDL system has these shortcomings, this study also used radial velocity data to directly retrieve wind data. Retrieval of winds from radial velocity was done by using the method introduced in Päschke et al. (2015). This method, hereafter referred to the SVD method, solves the system of equations using the method of least squares. The wind vector components u, v and w are obtained by solving the overdetermined linear system; \( AU = V_r \). Here, \( A \) is a matrix comprised of rows of the unit vectors along each pointing direction and \( V_r \) is the mean of radial velocities measured at each azimuth angle during a specific period of time as follows:

\[
U = \begin{pmatrix} u \\ v \\ w \end{pmatrix}, V_r = \begin{pmatrix} v_{r1} \\ v_{r2} \\ \vdots \\ v_{rn} \end{pmatrix}, A = \begin{pmatrix} -\sin \theta_1 \cos \varphi & -\cos \theta_1 \cos \varphi & -\sin \varphi \\ -\sin \theta_2 \cos \varphi & -\cos \theta_2 \cos \varphi & -\sin \varphi \\ \vdots & \vdots & \vdots \\ -\sin \theta_n \cos \varphi & -\cos \theta_n \cos \varphi & -\sin \varphi \end{pmatrix}
\tag{8}
\]

where \( \theta_n \) is the azimuth angle at the \( n^{th} \) point direction and \( \varphi \) is the elevation angle.

In solving the linear system, singular value decomposition (SVD) method is used. With this method, the data user can choose the averaging time used in creating one wind vector. Also, it is possible to filter out noise before calculating wind vectors.
2.4 Determination of planetary boundary layer height

The PBL can be defined as the lowest part of the troposphere that is directly influenced by the ground and whose changes are shown in less than 1 hour (Stull, 2012). Since the atmospheric boundary layer typically has a much higher concentration of aerosols than the free troposphere above, it thus provides a stronger backscatter signal of lidar pulses. Although it is difficult to say that aerosol profiles accurately depict the extent of the PBL, due to the complexity of aerosol mixing within the PBL and/or possible layers above the PBL (Sicard et al., 2006), it is possible to find a relationship between the sudden drop in aerosol concentration and PBL height. Due to this relationship, the negative derivative of range-corrected lidar profile, $-\frac{ds(z)}{dz}$, is calculated. The height where this value peaks, within a reasonable height range that changes with time and season, is detected and shown in this study as the “apparent PBL height determined by the gradient method”.

Another possible definition of the PBL height uses the variance of vertical wind velocity. Since thermally induced winds are the key source of mixing within the PBL and thus defines the PBL, the 15 minute averaged vertical wind velocity variance was used as a parameter of defining the PBL height. Following the threshold given in Pearson et al. (2010), the lowest height where velocity variance did not exceed $0.3 \text{ m}^2 \text{ s}^{-2}$ was defined as the “apparent PBL height determined by vertical wind speed variance”.

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CHAPTER 3. RESULTS AND DISCUSSION

3.1 Comparison of wind retrieval processes: sine-fitting method vs. SVD method

Evaluation of the sine-fitting method and the SVD method was done by comparing results with 14 co-located radiosonde flight observations done at Seoul National University and Jungnang station. Comparison of wind speed and wind direction obtained from radiosonde and both methods from the SNU WDL are shown in Figure 3. Here, the averaging time period in retrieving a wind vector with the SVD method was the same as with the sine-fitting method; 3 minutes. The radiosonde took around 15 minutes to reach 1,500 m (the maximum observation range of the SNU WDL), so the mean of 5 wind vectors from the start of the radiosonde flight was compared. Overall, the SVD method showed much better results than the sine fitting method with a bias of 1.65 m s\(^{-1}\) and root mean square error (RMSE) of 2.62 m s\(^{-1}\), while those of the sine method were 1.73 m s\(^{-1}\) and 3.35 m s\(^{-1}\), respectively. Both methods had a tendency to overestimate the wind speed, especially for points near the surface. This is thought to be due to the turbulent winds induced by surface friction. Even though signals from higher points had a tendency to have smaller signal to noise ratio compared to those of lower points, this did not affect the accuracy of wind observation.
Figure 3. Scatter plots of wind data retrieved from SNU WDL against radiosonde soundings. (Top) Wind data from the SNU WDL retrieved using the sine-fitting method. (Bottom) Wind data from the SNU WDL retrieved using the SVD method.

Figure 4 are examples of wind profiles from the SNU WDL compared to radiosonde soundings. Wind data observed at 14 KST on 4 May 2016 and at 21 KST on 5 October 2016 with the SNU WDL showed bad agreement with radiosonde measurements. Wind speed and wind direction retrieved using both methods showed a noisy profile and unrealistic wind speeds such as 20 m s$^{-1}$ at
500 m above ground level. For further evaluation of these cases, radial velocity-azimuth plots are given in Figure 5. The colored crosses are radial velocities measured during 15 minutes of the beginning of the radiosonde flight. A different color is used for each minute. The black stars are the mean of the radial velocities at each azimuth angle. For the cases where wind speed profiles were noisy (May 4th and October 5th) the colored radial velocities show a very dispersive distribution which led to dispersive wind speeds in a short period of time. On the other hand the radial velocities from October 4th showed a fairly consistent velocity-azimuth plot. This difference in velocity-azimuth plots may be due to inhomogeneity in horizontal winds or instrumental shortcomings.

Assuming that noisy radial velocities were the reason for the unreliable wind profiles, winds were retrieved by changing the averaging time period of radial velocity from a range of 1 to 15 minutes. Mean wind profiles of winds retrieved during the 15 minutes of radiosonde flights retrieved using different averaging time periods for the cases in Figure 4 are given in Figure 6. Overall, wind profiles retrieved from shorter averaging time periods were noisy. Since noise from radial velocities were cancelled for longer averaging time periods, winds retrieved from radial velocities averaged over longer time periods showed smaller differences in wind speed and wind direction by height. However, despite this improvement, the wind speed from SNU WDL still showed bad agreement with radiosonde data. It is thought that further improvement can be made by adding a few tests for quality check, such as test of horizontal
homogeneity and collinearity diagnostics, as was done in Päschke et al. (2015). On the other hand, large improvements were made on wind direction profiles with results from 15 minute averaged radial velocities almost perfectly matching the radiosonde measurements.

**Figure 4.** Wind profiles from SNU WDL using the sine-fitting method (blue) and the SVD method (red) compared with radiosonde soundings (black) on 4 May, 5 October and 4 October 2016. (Top) Wind speed profiles. (Bottom) Wind direction profiles.
Figure 5. Radial velocities observed during the radiosonde flights of 4 May 2016 (14 KST), 5 October 2016 (21 KST) and 4 October 2016 (21 KST). Colored crosses are raw radial velocity and black crosses are 15 minute averaged radial velocities of each azimuth angle.
Figure 6. Wind profiles from SNU WDL using the sine-fitting method (grey) and using the SVD method (colored) compared with radiosonde sounding data (black). (Top) Wind speed profiles. (Bottom) Wind direction profiles.

In Figure 7, the number of data points, bias (SNU WDL – radiosonde) and RMSE are plotted according to the averaging time period of radial velocity. It can be seen that wind data retrieved from short averaging time periods show low reliability when compared to radiosonde measurements. Overall, using the
SVD method showed better agreement with radiosonde data than wind data from the sine-fitting method. Scatterplots of wind data measured by the SNU WDL against wind data measured by radiosonde are given in Figure 8. Both wind speed and wind direction retrieved using the SVD method on 15 minute averaged radial velocity data showed better agreement with radiosonde measurements than wind data retrieved using the sine-fitting method. Although wind speed was still overestimated by the SNU WDL, the overestimation of weak, near surface winds was reduced. Wind direction measurement showed a more dramatic improvement when increasing the averaging time period of radial velocity. This can be lead to the thought that wind direction in urban boundary layer has a tendency to be more consistent with time than wind speed. Since wind data retrieved using the SVD method with 15 minute averaged radial velocity showed the best agreement with radiosonde measurements, all upcoming wind data in this study measured by the SNU WDL will be retrieved using the SVD method with 15 minute averaged radial velocities.
Figure 7. Number of points, bias and RMSE of wind data retrieved using the SVD method when compared to radiosonde soundings.
3.2 Comparison of winds from two wind Doppler lidar systems

To compare the performance of the SNU WDL with another WDL, we compared the observation results with the WISE WDL during the period when

Figure 8. Scatter plots of wind data retrieved from SNU WDL against radiosonde soundings. (Top) Wind data from the SNU WDL retrieved using the sine-fitting method. (Bottom) Wind data from the SNU WDL retrieved using the SVD method with 15 minute averaged radial velocity data.
the SNU WDL was deployed at Jungnang station. Examples of both WDL wind profiles with radiosonde data are shown in Figure 9. Both WDLs had difficulty in observing accurate wind speeds and wind direction in the lower points which can again be thought to be due to surface friction. It could be seen that the WISE WDL made observations up to higher heights than the SNU WDL for all profiles. Under the same atmospheric conditions, the WISE WDL is able to make accurate observations up to higher heights due to its stronger laser power.

Figure 10 are scatter plots of WDL observations of wind at Jungnang station against radiosonde soundings. Due to the stronger laser power of the WISE WDL, it has a larger number of data points than the SNU WDL, showing that the detection range of the WISE WDL is larger than that of SNU WDL. However, even with the strong laser power of the WISE WDL, the highest height of WISE WDL observations was around 3,600 m, even though its observation range is 6,000 m. This indicates that wind Doppler lidars are sensitive to the atmospheric background. The WISE WDL had surprisingly good agreement with radiosonde data with a bias of -0.02 m s\(^{-1}\) and RMSE of 1.09 m s\(^{-1}\). This accuracy is very impressive compared to the SNU WDL’s bias of 0.53 m s\(^{-1}\) and RMSE of 2.15 m s\(^{-1}\). The difference in accuracy may be due to the high power of the WISE WDL or the algorithm used in retrieving wind data.
Figure 9. Wind profiles from SNU WDL using the SVD method (red), from WISE WDL (green) compared with radiosonde sounding data (black) on 7 October 2016 (03 KST) and (09 KST). (Top) Wind speed profiles. (Bottom) Wind direction profiles.
Figure 10. Scatter plots of wind data retrieved from SNU WDL and WISE WDL against radiosonde soundings. (Top) Wind data from the SNU WDL. (Bottom) Wind data from the WISE WDL.

3.3 Evolution of planetary boundary layer height

Time series of Mie lidar attenuated backscatter signal and the derived PBL height using the gradient method (black crosses) from 15 KST May 25th to 15
KST May 31st are shown in the top plot of Figure 11. A diurnal variation of PBL height can be observed with the PBL height at its highest around 14 KST and lowest around 5 KST. However, the apparent PBL height derived from Mie lidar attenuated backscatter signal is not completely continuous and there are kinks in its growth and decline. This is thought to be due to the complexity of mixing or long-range transported aerosols above the PBL.

The bottom plot of Figure 11 are time series of 15 minute averaged vertical velocity variance profiles with PBL heights derived from vertical velocity variance indicated by pink crosses. Here, the threshold of vertical velocity variance indicating mixing within the PBL was bought from Pearson et al. (2010), with a value of 0.3 m$^2$ s$^{-2}$. The apparent PBL height derived from vertical velocity variance also shows a similar diurnal variation. However cases where the PBL height derived from vertical wind velocity are not idealistic is thought to be due to the noise of the instrument itself.

Because of its low laser power, the performance of the SNU WDL is highly sensitive to atmospheric conditions. Under clear sky conditions, the SNU WDL is not able to detect Doppler shifts because of the weak return signal. On the other hand, too much aerosol and light-scattering materials in the air may also affect the observation range of the SNU WDL, because it would attenuate the entire laser light within just a few range bins. The latter case is thought to be the reason for the underestimated PBL heights.
Figure 11. (Top) Time series of vertical profiles from Mie lidar with apparent PBL height determined using the gradient method (black cross) and vertical velocity variance (pink cross) from May 25th 15 KST to May 31st 15 KST 2016. (Bottom) Time series of 15 minute averaged vertical velocity variance profiles with apparent PBL heights.

3.4 Characteristics of aerosol backscatter and wind distribution in planetary boundary layer

Continuous wind Doppler lidar observations made from May 25th to May 31st and from October 5th to October 7th were analyzed to investigate the temporal variation of winds within the PBL. The topmost plot in Figure 12 is time series of Mie attenuated backscatter signal profiles. Plotted above are the wind speed indicated by vectors measured with SNU WDL. The lower plots in Figure 12
are time series of the vertical profiles of SNU WDL signal to noise ratio, horizontal wind speed, horizontal wind direction and vertical wind speed.

Figure 12 (a), shows that wind measurements by the SNU WDL were only available up to heights with high backscattering signals. This is because of low signal to noise ratio for signals backscattered by air columns with low aerosol density. The SNU WDL does not measure radial velocity for signals with signal to noise ratio less than 7 dB. The points where signal to noise ratio is 7 dB is colored in white in the signal to noise ratio plot (Figure 12 (b)) and comparing this with the other time series plots, it can be seen that SNU WDL wind data is only retrieved within this range.

Thermally induced winds are weaker in the morning and become strongest in the afternoon. This is true for all cases except the results from May 26th when there was high PM$_{10}$ mass concentration of over 100 $\mu$g m$^{-3}$ (http://www.airkorea.or.kr) and the wind speed is almost 10 m s$^{-1}$. Most of the time westerly winds were observed. In the morning however, Easterly winds were detected on May 27th and May 28th and this diurnal pattern may be due to the mountainous surroundings of Seoul National University.

Winds and aerosols within the PBL at Jungnang station from October 4th to October 7th 2016 are plotted in Figure 13. Comparing the wind results from the SNU WDL (left panel) with the results from the WISE WDL (right panel), the difference in observation range is clearly noticeable. The topmost plots are the
aerosol backscatter profile time series of the Jungnang aerosol lidar with horizontal wind speeds from each WDL indicated in vectors. However, the short time period of observation is not sufficient to determine any long-term characteristics of PBL winds. It can be said that during the time of measurement at Jungnang, wind speed was not necessarily weaker in the morning and evenings and stronger during the day. Also no clear diurnal variation in wind direction could be found during the short period of data available. However, the wind direction change from westerlies to easterlies may indicate that winds within the PBL at Jungnang station were influenced by synoptic weather patterns.
Figure 12. Time series of vertical profiles from Mie lidar and SNU WDL measurements at Seoul National University from May 25th to May 31st 2016.
**Figure 13.** (Left) Time series of vertical profiles from Mie lidar and SNU WDL measurements at Jungnang station from October 4th to October 7th 2016. (Right) Time series of Mie lidar profiles and WISE WDL measurements.
CHAPTER 4. SUMMARY

Evaluation of WDL wind measurements was performed by comparison with radiosonde wind profiles. Comparison between two methods in retrieving wind vectors from radial velocities showed that simple solving of the linear equation using singular value decomposition showed more accurate results. Increasing the time period of averaging radial velocities in retrieving wind data improved wind profiles when compared to radiosonde soundings.

Results from side-by-side observation with the WISE WDL showed that the SNU WDL measured relatively accurate winds, although the detection limit was not as good. The accuracy of WDL was found to be not directly influenced by the altitude of the observation point but had more to do with the atmospheric conditions itself.

The apparent PBL height using gradient method was determined by finding the maxima of the negative gradient of aerosol backscatter signals. The lowest point where 15 minute averaged vertical velocity variance is less than $0.3 \text{ m}^2 \text{s}^{-2}$ was defined as the apparent PBL height using wind data. All PBL heights derived by aerosol profiles and vertical wind profiles showed reasonable diurnal variations. However, the high sensitivity of the WDL performance on atmospheric conditions and noise from the instrument itself resulted in loss of PBL height data.
In this study, characteristics of winds and aerosol profiles within the PBL were investigated. The diurnal variations in aerosol profiles indicated the growth and decay of the PBL with time. Both horizontal and vertical winds were stronger in the afternoon. At Seoul National University winds blew mostly from the west.

Although wind results from the SNU WDL were improved by using the SVD method, additional horizontal homogeneity test and collinearity diagnostics following the footsteps of Päschke et al. (2015) may be ways to further improve collinearity with radiosonde data. In investigating characteristics of winds and aerosols within the PBL, longer and continuous observation is needed for a more reliable characterization of wind and PBL height variation.
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국문 초록

스캐닝 도플러 라이다를 이용한
대기경계층 내 바람 특성 관측 연구

박 수 진

지구환경과학부
서울대학교 대학원

대기경계층 내에서의 에어로졸과 에어로졸의 전구 물질의 분포, 혼합 및 수송은 대기경계층 내의 바람에 의해 이루어진다고 (Pearson et al., 2010). 따라서 지형이 복잡한 도심 지역의 대기경계층 내 에어로졸 농도에 대한 정확한 예보를 위해서는 대기경계층 내 바람의 특성과 변화(일변화)를 아는 것이 중요하다. 본 연구에서는 서울대학교에서 측정한 윈드 도플러 라이다와 에어로졸 라이다 관측 자료를 이용하여 도심대기경계층 내에서의 바람 특성과 에어로졸의 수직 분포 특성을 살펴보았다. 사용된 자료는 서울대학교 501동 옥상과 차세대도시농림융합기상사업단 (WISE) 중량 관측소에서 관측한 에어로졸 연직 분포와 바람의 연직 분포이었다. 같은 장소에서 띄운 라디오 존재 결과와의 분석을 통해 윈드 도플러
라이다의 관측 결과를 확인해 보았다. 윈드 도플러 라이다의 원시 관측 자료로부터 바람 자료를 산출하는데 있어서 사용된 방법들 중, 15분 동안 평균한 원시자료를 특이값분해 (Singular value decomposition, SVD) 하여 구한 결과가 가장 라디오 존데와 잘 맞았으며, 이때 편차는 0.66 m s\(^{-1}\), 평균 제곱근 편차는 2.38 m s\(^{-1}\) 이었다. 대기경계층 고도는 미-라이다의 후방산란강도가 높이에 대해 가장 크게 감소하는 고도를 구하는 방법과 수직 방향 바람의 분산이 0.3 m\(^2\) s\(^{-2}\)보다 작은 고도를 찾는 방법을 사용하여 산정하였다. 위와 같은 방법을 사용한 2016년 5월 25일부터 31일까지의 자료에 대해서 대기경계층 고도는 밤에는 낮고 낮에는 높은 일변화를 보였다. 서울대학교에서 지표면 가열에 의한 바람의 일변화가 두렷하게 관찰되는 사례가 있었으며, 그 특징으로는 낮에는 강한 바람, 밤에는 약한 바람 그리고 해가 끝 후 극풍이 불었다. 반면에 중랑 관측소에서는 두렷한 바람의 일변화는 찾기 어려웠으며, 풍향은 지표면 가열과 같은 국지적인 요소보다 종관 기상장의 영향을 받은 것으로 보였다.

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