Ground-based remote sensing measurements of aerosol and ozone in an urban area: A case study of mixing height evolution and its effect on ground-level ozone concentrations

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Abstract

We have estimated the mixing height (MH) and investigated the relationship between vertical mixing and ground-level ozone concentrations in Seoul, Korea, by using three ground-based active remote sensing instruments operating side by side: micro-pulse lidar (MPL), differential absorption lidar (DIAL), and differential optical absorption spectroscopy (DOAS). The MH is estimated from MPL measurements of aerosol extinction profiles by the gradient method under convective conditions. Comparisons of the MHs estimated from MPL and radiosonde measurements show a good agreement ($r^2 = 0.99$). Continuous MPL measurements with high temporal and vertical resolution reveal the diurnal variations of the MH under convective conditions and the presence of a residual layer during the nighttime. Comprehensive measurements of ozone and aerosol by MPL, DIAL and DOAS during an high ozone episode (24–26 May 2000) in Seoul, Korea, reveal that (1) photochemical ozone production and advection from upwind regions (the western part of Seoul) contribute two peaks of ozone concentrations at the ground around 14:00 and 18:00 local time on 25 May 2000, respectively, and (2) the entrainment and the fumigation processes of ozone aloft in the nighttime residual layer into the ground is a major contributor of high concentrations of ground-level ozone observed on the following day (26 May 2000).

Keywords: Mixing height (MH); Ground-level ozone; Micro-pulse lidar (MPL); Differential absorption lidar (DIAL); Differential optical absorption spectroscopy (DOAS)

1. Introduction

Mixed layer height is 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 (Russell et al., 1974; Coulter, 1979; Menut et al., 1999; Seibert et al., 2000; Sanchez et al., 2007). For example, ground-level ozone is a secondary pollutant formed by a photochemical reaction between volatile organic compounds (VOCs) and oxides of nitrogen (NOx) in the presence of heat and sunlight (Seinfeld and Pandis, 1998). In addition to the amounts of

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photochemical ozone production, the temporal evolution of ground-level ozone concentration is strongly controlled by the diurnal evolution of the mixing height (MH) in an urban area. Ozone formed near the ground can be mixed into the upper levels of the MH during the day, or ozone trapped aloft in the residual layer during the night, inversely, can be entrained downward into the ground level on the following day. Ground-level ozone concentrations can be rapidly enhanced by the vertical mixing process.

The objectives of this study are to estimate the MH in an urban area and to document the relationship between vertical mixing and high concentrations of ground-level ozone. To address these goals, we analyze data collected by three ground-based active remote sensing methods operating side by side: micro-pulse lidar (MPL) for the vertical profile of aerosol extinction, differential absorption lidar (DIAL) for the both horizontal and vertical profiles of ozone concentrations, and differential optical absorption spectroscopy (DOAS) for ground-level ozone concentrations. Since these techniques permit continuous monitoring of aerosols and ozone, they offer clear pictures of the temporal evolution and spatial distribution of aerosol extinctions and ozone concentrations in the lower troposphere, giving a major advantage over other commonly used methods, such as radiosounding and conventional fixed ultraviolet (UV) ozone spectrometry.

In this study, we present estimates of the MH using data acquired from MPL measurements in the greater Seoul area, Korea. The estimated MHs are also compared with those evaluated from co-located radiosonde observations. Comprehensive field measurements of aerosol extinction and ozone concentrations at Olympic park (127°07′38.004″E, 37°31′10.805″N), Seoul, Korea during a high-level ozone episode on 24–26 May 2000 are analyzed to investigate the relationship between diurnal MH evolution and the temporal variation of ground-level ozone concentrations, especially focusing on the entrainment of high ozone plume in the nighttime residual layer into the ground level. Section 2 gives brief descriptions of the instruments used in this study. Section 3 shows the evaluation and validation of the MH from MPL measurements. A case study of the effects of temporal variations in MH on high-level surface ozone concentrations during a ground-level ozone event is presented in Section 4.

2. Measurements

2.1. Micro-pulse lidar (MPL)

Continuous measurements of the vertical profile of the ambient aerosol extinction coefficient (σ) were taken by a MPL (Kim et al., 2005, 2007; Yoon et al., 2006) to describe aerosol vertical distribution and the variations in height of the urban mixed layer, and to help understand the process by which a high-level ozone plume is entrained to the ground level in urban areas (e.g., Russell et al., 1974; Coulter, 1979; Baxter, 1991; Vukovich and Scarborough, 2005). The MPL used in this study is manufactured by SES Inc., USA and emits a laser pulse at a wavelength of 523.5 nm. The vertical resolution was adjusted to 30 m, and the MPL was set to average and analyze the backscattered signals every 10 min. The aerosol extinction coefficient profiles were retrieved from the lidar return signals using the method of Fernald (1984). Complete descriptions of the MPL system and data retrieval process can be found in the works of Welton et al. (2000) and Yoon et al. (2006).

2.2. Differential absorption lidar (DIAL)

Range-resolved remote sensing measurements of the horizontal and vertical distribution of ozone concentrations were taken by a mobile scanning DIAL (Godin et al., 1999; Choi et al., 2004; Sanchez et al., 2007). In the DIAL system, developed by the Korea Atomic Energy Research Institute, measurements of the horizontal and vertical concentration profiles of ozone are derived from the ratio of the signals at the wavelengths 266 (one of major absorption line of ozone) and 299.5 nm (outside of the main ozone absorption region) with a 50-m spatial resolution and a 2-min temporal resolution. Detailed information on the DIAL system and the retrieval process of ozone concentrations deployed in this study can be found in Choi et al. (2001, 2004).

2.3. Differential optical absorption spectroscopy (DOAS)

Extensive measurements of ground-level ozone concentrations using a commercial DOAS (Thermo Environ. Ins., USA) were conducted (Axelsson et al., 1990; Kim et al., 2001). Ozone concentrations along a single horizontal light beam between a
telescope (the emitter and receiver) and a retro-reflector, which was set to 144 m (i.e., total path length 288 m) during the field experiment, were measured around the 283 nm wavelength, because an identified absorber in the 280–290 nm wavelength region is not an artifact of the analysis of ozone concentrations with the DOAS technique (e.g., Reisinger, 2000), and showed a good comparison with the conventional fixed point UV sampler (e.g., Stevens and Drago, 1993; Kim et al., 2001). The DOAS was set to average and analyze the backscattered signals every 1 min. Detailed background information and the DOAS data retrieval processes used in this study are given in Kim et al. (2001).

2.4. Radiosoundings

Balloon-borne measurements of the vertical profiles of meteorological parameters, i.e., pressure, temperature and relative humidity, are the most common source of data for operational determination of the MH (Seibert et al., 2000). In this study, we carried out radiosonde observations and MPL measurements simultaneously at the same location to establish the correctness and reliability of the estimated MH from the MPL measurements.

2.5. Conventional fixed point samplings of pollution gas concentrations

Ground-level concentrations of criteria gas-phase pollutants such as ozone, nitrogen dioxide and carbon monoxide were routinely measured by the conventional fixed-point methods at Bang-I conventional air quality monitoring station of the Korean Ministry of Environment, which is located in the center of Olympic Park. Hourly mean ozone and nitrogen dioxide concentrations were used in this study.

3. Determination of the mixing height

3.1. Method for estimating the mixing height from aerosol lidar measurements

Remotely sensed vertical profiles of ambient aerosol extinction by ground-based lidar can provide direct estimations of the MH (Russell et al., 1974; Coulter, 1979; Baxter, 1991; Seibert et al., 2000) under stable and cloud-free or fog-free conditions. The MH separates two regions with different properties, the well-mixed boundary layer and the stable free troposphere. The transition zone between both layers is characterized by a large variability in aerosol concentration as well as ambient temperature and humidity. Therefore, the MH can be determined from the strongest gradients in the retrieved aerosol extinction coefficients, because the returned backscatter signals originate directly from the atmospheric particulate matters (hereafter, called “the gradient method”).

Fig. 1 shows idealized profiles of the aerosol extinction coefficient ($\sigma$) retrieved from MPL measurements and the potential temperature ($\theta$) obtained from radiosonde measurements. The potential temperature profile obtained by radiosoundings is the most common operational method to determine the MH. The MH is identified with the base of an elevated inversion layer or as the height ($h$) of a significant change of potential temperature. Typically, in a well-mixed boundary layer, the potential temperature is nearly constant with height. At the top of the boundary layer, in the inversion layer, the potential temperature increases sharply with height. In the free troposphere above the boundary layer, the potential temperature usually increases with altitude, i.e. the atmosphere is stably stratified. Similar to the basic concept of radiosoundings, the MH can be determined from aerosol lidar measurements. The lidar measurement of the MH is based on detecting the gradient in the returned lidar backscattering intensity associated with a decrease in aerosol backscatter often found in the transition zone from the mixed layer to the overlying free troposphere. As shown in Fig. 1, the maximum gradient height of the aerosol extinction coefficient is determined to be the MH.

In this study, ground-based MPL measurements for the estimation of the MH were made in Seoul and its suburban areas (Shi-hwa and Yongin), Korea. Coincident measurements of the vertical profiles of temperature, humidity and pressure were also carried out for the validation of the MH. Fig. 2 is an example of coincident measurements of the vertical profiles of the aerosol extinction coefficient and the potential temperature and its gradients at Seoul National University campus (Seoul) and Shi-hwa, 30 km southwest of Seoul. To compare the MHs determined from lidar and radiosonde measurements, the lidar-derived MHs are averaged to 30 min due to having to factor in the launch time of the balloon-borne radiosonde, i.e. radiosounding provides a “snapshot” of the state of the atmosphere as they ascend, but lidar makes multi-shots
of aerosol profiles during radiosonde flight. In the
gradient method deployed in this study, a maximum
(minimum) of the first derivative of the potential
temperature profile $d\theta/dh$ (the aerosol extinction
coefficient profile $d\sigma/dh$) is chosen as the MH
(Seibert et al., 2000). In Fig. 2, estimated MHs from
lidar and radiosonde measurements by the gradient
method used in this study show a good agreement.

The estimated MH from lidar and radiosonde
measurements is 930 m (860 m) and 850 m (800 m)
at Seoul National University campus (Shi-hwa, in
parentheses), respectively. Further results of the
comparison are given in Section 3.2.

### 3.2. Comparison of the mixing heights estimated by aerosol lidar and radiosoundings

In contrast to the radiosonde, which routinely
ascends for only 2–4 soundings per day at fixed
times, even during field campaigns the closest
interval is 1.5–3 h, continuous high-resolution mea-
surements of the backscatter signals with ground-
based lidar allow us to determine the diurnal
variation of the MH by the gradient method,
because aerosols and gas-phase pollutants in the
urban atmosphere are usually well-mixed within the
MH under convective conditions. Fig. 3 shows
diurnal variations in the aerosol extinction coeffi-
cient (unit: km$^{-1}$) and the MH determined from
MPL return signals (dashed line) on (a) 3 September
1999 at Shi-hwa, Korea and (b) 14 October 1999 at
Seoul, Korea. The estimated MH, both in Figs. 3a
and b, under clear conditions exhibits not only the
typical diurnal variation pattern of the MH, but
also pollutants or any constituents emitted from
urban surfaces well confined within the MH. In the
morning, as the sun starts to heat up the ground,
convective thermals initiate at the surface, forcing
the growth of the boundary. The MH peaks in the
afternoon with a few hours time lag after the peak
of solar insolation near local noon. As the sun goes
down, radiative cooling results in the formation of a
stable nocturnal boundary layer, corresponding to a
radiation inversion. This strong diurnal variation of
the MH also appears in Fig. 6 (see Section 4).

To compare the lidar-derived MH, we added the
MHs determined by radiosonde (crosshair),
which were made at the same locations during the
MPL operations. The comparison of MHs deter-
mined by radiosonde and coincident lidar back-
scatter for the two cases shown in Fig. 3 show
visually a good agreement. The MHs estimated
from simultaneous MPL and radiosonde measure-
ments for six intercomparison experiments are well
shown in Fig. 4. Under convective conditions, the
MH determined by the MPL correlates well with the

Fig. 2. Profiles of radiosonde-derived potential temperature and Lidar-measured aerosol extinction (solid line) and their gradients (dashed line) (a) at Seoul National University campus on 14 October 1999 (14:30–15:00 LST) and (b) at Shi-hwa industrialized area on 3 September 1999 (11:00–11:30 LST). Horizontal line represents estimated MH by the gradient method.
MH determined from radiosoundings by the gradient method \( (r^2 = 0.996) \). This result suggests that the lidar-derived MH can be considered reliable. It is, however, worth mentioning that the MH estimation from lidar measurements may be of limited use when low-level cloud or a dense aerosol layer is present or the contrast in aerosol backscatter signals between the MH and the free troposphere is not very pronounced.

However, as explained above, a typical rise in the MH on a day with strong convection in the afternoon, as well as the residual layer above the MH during the night and early morning, can be well illustrated from the lidar measurements (e.g., Fig. 3a). In particular, pollutants emitted from the surface are well-mixed within the MH during the daytime, but are trapped above the MH and form a separate layer due to the formation of a stable nocturnal boundary layer by strong radiative cooling after sunset. This residual layer usually does not mix during the night with either the inversion boundary layer below or the free troposphere above. The effects of the entrainment of these pollutants, from the residual layers to the boundary layer, on the concentrations of pollutants near the surface are discussed in Section 4.

### 4. Relationship between vertical mixing and ground-level ozone concentrations: A case study

Extensive experimental measurements of both aerosol and ozone by ground-based remote sensing
techniques were performed at Olympic Park, Seoul, Korea, on 24–26 May 2000. The experimental site, the Olympic park where the Olympic games were held in 1988, is located in the eastern part (downwind region) of Seoul, and is frequently affected by the advection of pollutants from the western part of the city due to the prevailing westerly wind. During the experiment, synoptic analyses of weather maps showed that a slowly migrating anti-cyclone overlay the Korean Peninsula and possibly caused a build-up of pollutants in the region, providing favorable conditions for photochemical ozone production and the thermally induced development of the boundary layer. The surface weather maps at 09:00 LST (00:00 UTC) and 21:00 LST (12:00 UTC) on 25 May 2000 were shown in Fig. 5.

4.1. Temporal evolution of the mixing height and the presence of the residual layer

Fig. 6 depicts the evolution of the aerosol extinction coefficient (unit: km$^{-1}$) measured by MPL at the Olympic Park in Seoul, Korea during the experiment, plotted together with the MH derived from MPL measurements. Unfortunately, radiosonde data at the site were not available during the experiment. From an examination of Fig. 6, the typical well-established evolution of the MH under convective situations can be inferred: the MH at its lowest during the night and at its highest in the afternoon. Though an elevated aerosol layer appeared at between 1 and 2 km, the aerosol loading near the surface was very low on 24 May. After sunrise on 25 May, the MH gradually developed by thermal buoyancy due to increased solar insolation, and reached an apex at 17:00–18:30 local standard time (LST) at around 1300 m height. The MH, however, rapidly dropped to near 850 m at 19:00 LST and to 600 m near 21:00 LST. The MH below 500 m continued till 08:00 LST on 26 May, before the start of the new diurnal cycle.

During the daytime on 25 May, pollutants emitted from urban surface were well confined within the MH and the thick aerosol layer was elevated to the upper part of the MH, with an aerosol extinction coefficient of 0.3–0.5 km$^{-1}$. It should be noted that lidar returned signals from below several hundred meters may have relatively large observational uncertainties due to the geometrical form factor, mainly concerning the overlap of the area of laser irradiation with the field of view of the receiver optics (Yoon et al., 2006). After sunset on 25 May, pollutants emitted from the surface during the daytime were trapped above the MH and formed the residual layer during the night, with an aerosol extinction coefficient of 0.1–0.2 km$^{-1}$, because a stable nocturnal boundary layer is formed due to radiative cooling. The pollution aerosols in the upper region of the MH led to a significant net heating of the pollution plume, which contributes to maintaining a warmer layer and increasing static stability (i.e., buoyancy), and ultimately may help maintaining the residual layer structure during the night (e.g., Kim et al., 2004; Won et al., 2004). This effect is more dominant in an urban area, because the urban atmosphere usually contains lots of sunlight-absorbing aerosols (e.g., black carbon emitted from vehicles). An increase in the aerosol extinction coefficient around 08:00 LST on 26 May may be related to the rush hour which usually reaches a peak between 07:00 and 09:00 LST in Seoul.

4.2. Temporal variation of ground-level ozone concentrations

Fig. 7 shows variations in the hourly averages of ozone and nitrogen dioxide (NO$_2$) concentrations, and meteorological parameters during the high-level ozone episode. Here, ground-level meteorological parameters, including temperature, wind direction and wind speed were continuously measured by an automatic weather station (AWS), maintained by the Korea Meteorological Administration (KMA). Examination of Fig. 7 yields the following conclusions:

(a) On 25 May, two peaks of ozone concentration appeared, near 14:00 and 18:00 LST, respectively. The first ozone peak was induced by photochemical ozone production in the local area, as indicated by the positive correlation between ozone (Fig. 7a) and nitrogen dioxide (Fig. 7b) and high temperature ($> 30^\circ$C). Unfortunately, solar radiation data were not available at this site during the experiment. However, the advection of high ozone concentrations, which had formed over the western region of Seoul, into the eastern area of Seoul by the prevailing westerly wind of moderate wind speed (see Fig. 7d), are also likely to have contributed to the secondary peak of ozone concentration at the site near 18:00 LST, as indicated by Ghim et al. (2001). High ozone...
Concentrations (>70 ppb) were reported at the conventional ground monitoring stations, maintained by the Korean Ministry of Environment, in the western part of Seoul between around 14:00–16:00 LST, i.e., 2–4 h before the ozone peak (18:00 LST) at the site. For example, the ozone concentrations at 15:00 LST and 16:00 LST on 25 May 2000 reported 93 and 98 ppb at Guro (126°53'52.655''E, 37°28'44.894''N), 108 and 79 ppb at Shiheung (126°54'43.663''E, 37°27'01.129''N), and 72 and 104 ppb at Gwanak (126°57'25.765''E, 37°27'13.775''N).

Fig. 5. Weather maps on the surface (a) at 09:00 LST (00:00 UTC) and (b) 21:00 LST (12:00 UTC) on 25 May 2000.
monitoring stations, respectively. In addition, the topography of Seoul is like a basin, surrounded by mountains to the east, north and south, which causes a build-up of pollutants (e.g., ozone) over the eastern part of Seoul, including at this experimental site (Ghim et al., 2001).

(b) After sunset on 25 May, an increase in nitrogen oxide (NO) emissions derived from traffic, which usually reaches a peak between 18:00 and 20:00 LST in the evening, contributed to a clear decrease of ambient ozone concentrations below 10 ppb and an increase of nitrogen dioxide, with a peak of about 80 ppb. These
low-level ozone concentrations continued until 09:00 LST on 26 May.

(c) On 26 May, the ozone concentration showed a rapid rate of increase, about 20–30 ppb h\(^{-1}\), after the peak of NO\(_2\) concentration at 11:00 LST, and reached up to 80 ppb at 13:00 LST and 90 ppb at 14:00 LST. These levels of ozone concentration are about 20 ppb higher than those measured at 13:00–14:00 LST on 25 May.

On the other hand, as shown in Fig. 7a, ozone concentrations derived from different measurement techniques—conventional fixed UV spectrometer, DOAS and DIAL—showed a good agreement. The comparative results for the three instruments are summarized in Table 1. Over the comparison periods, the conventional fixed point UV spectrometer and DOAS (DIAL) are in agreement to within the bias 4.1 (4.8) ppb. The mean difference between DOAS and DIAL is an estimated 1.6 ppb. The difference between conventional fixed point UV spectrometer and DOAS (DIAL) can be explained quantitatively from the spatial inhomogeneity of ozone concentrations as well as different observational principles, i.e., the conventional UV spectrometer measures ozone concentrations at a certain point by an intake of ambient air through an inlet, whereas ozone concentrations by DOAS and DIAL systems are made along a single light beam in an open environment. In this study, the distance between the telescope (the emitter and receiver) and the retro-reflector of a DOAS system is 144 m (i.e., total path length 288 m). DIAL-derived ground-level ozone concentrations are the averages of the measured horizontal profiles of ozone concentrations between 450 and 1200 m distances.

4.3. The role of vertical mixing in the temporal evolution of ground-level ozone concentrations

Based on the good performance of DOAS and DIAL measurements of ozone concentrations (see Fig. 7a and Table 1), as well as MH estimated from MPL measurements (see Section 3), the role of vertical mixing in the temporal evolution of ground-level ozone concentrations is investigated and discussed in this section. Fig. 8 represents the vertical profiles of ozone concentrations between 450 and 1000 m altitude measured by the DIAL system and ground-level ozone concentrations by DOAS. The horizontal line represents the estimated MH from MPL measurements. Before sunset on 25 May, the vertical distributions of ozone concentrations measured by DIAL were well in agreement with DOAS-derived ground-level ozone concentrations below the MH, as shown in Figs. 8a–d, i.e., a very concentrated ozone plume extended from the surface to the top of the boundary layer during the day. These ozone profiles also suggest that the photochemical production of ozone in the daytime is important for ozone accumulation at the ground level. As we explained in regard to Fig. 7a, two peaks of ozone concentrations at 14:00 and 18:00 LST can be clearly distinguished. For example, the range-resolved DIAL ozone profile obtained at 16:45 LST on 25 May shows that ozone concentrations both at the ground and within the boundary layer reached up to 90 ppb. The vertical profiles of ozone measured at 20:11 LST (Fig. 8e) and 23:30 LST (Fig. 8f) show that ozone concentrations are sharply divided by the MH, which is independently estimated from MPL measurements. Ozone concentrations below the MH are low, whereas

| Table 1 | Statistical comparisons of ozone concentrations (ppb) measured by three different techniques: UV spectrometer, DOAS and DIAL* |
|---|---|---|---|
| x, UV spectrometer | y, DOAS | x, UV spectrometer | y, DIAL | x, DOAS | y, DIAL |
| BD | -4.07 | -4.79 | -1.62 |
| RMSD | 5.7 | 7.26 | 6.64 |
| Slope | 1.06 | 0.89 | 0.9 |
| Intercept | 2.67 | 8.85 | 5.03 |
| N\(^b\) | 41 | 11 | 10 |

*The instrument \(x\) was chosen as the reference instrument. Bias difference (BD, unit: ppb), root mean square difference (RMSD, unit: ppb) are \(\frac{1}{N}\sum_{i=1}^{N} (y_i - x_i)\) and \(\sqrt{\frac{1}{N}\sum_{i=1}^{N} (y_i - x_i)^2}\), respectively. The slope and intercept (unit: ppb) are calculated as \(y = \text{slope} \times x + \text{intercept}\).

\(^b\)Hourly mean ozone concentration data (\(N = 44\)) were used for comparison between UV spectrometer and DOAS, whereas comparisons between UV spectrometer and DIAL (\(N = 11\)) as well as DOAS and DIAL (\(N = 10\)) were made for instantaneous measurement data points, because the DIAL made only 11 horizontal shots for ground-level ozone concentration measurements.
High-level ozone concentrations are > 70 ppb, which level is in good agreement with that measured during the day. This situation is consistently observed during the night. Although the lidar-derived MH was not available at 02:56 LST on 26 May (Fig. 8g), we can analogize the same situations. The ozone profile at 05:43 LST on 26 May (Fig. 8h) reveals the presence of elevated ozone concentrations of about 70 ppb in the nighttime residual layer, but the MH remained very shallow throughout the morning. This result corresponds to the presence of the residual layer identified from MPL measurements, as discussed in Section 3. Another possible reason for high-level ozone concentration in the residual layer during the night is that there are no significant ozone sinks. After sunrise on 26 May, the discrepancy of ozone concentrations between ground and lower troposphere decreased due to the development of the MH. At 13:42 LST (Fig. 8j), ozone was well mixed below the MH, with an ozone concentration of about 90 ppb. This level of ozone concentration at a given local time may exceed that from photochemical production. In addition to the ozone production by photochemical reaction and advections from upwind regions, we conclude that ozone aloft in the nighttime residual layer is an important contributor to the ground-level peak ozone concentration observed on the following day by the entrainment and fumigation processes.

5. Summary and conclusions

We have estimated the mixing height (MH) and investigated the relationship between vertical mixing and ground-level high ozone concentrations in the greater Seoul area, Korea, by using three ground-based active remote sensing instruments operating side by side: micro-pulse lidar (MPL), differential absorption lidar (DIAL), and differential optical absorption spectroscopy (DOAS). The principal findings of our analysis are summarized below:

1. Based on the remotely sensed vertical profiles of ambient aerosol extinction by ground-based MPL, we have successfully estimated the MH by the gradient method.
2. Estimated MHs from lidar and radiosonde measurements by the gradient method show a good agreement ($r^2 = 0.996$) under convective conditions.
3. Continuous high-resolution measurements of the backscatter signals with ground-based lidar reveal the diurnal variations of the MH in an urban area and the presence of a residual layer.
during the night. Pollutants emitted from the surface are well-mixed within the MH during the daytime, but are trapped above the MH and form a separate layer, with an aerosol extinction coefficient of 0.1–0.2 km⁻¹, during the night due to the formation of a stable nocturnal boundary layer by strong radiative cooling after sunset.

4. Ozone concentrations measured by different measurement techniques—conventional fixed point UV spectrometer, DOAS and DIAL—show a good agreement. Over the comparison period, the conventional fixed point UV spectrometer and DOAS (DIAL) are in agreement within the bias 4.1 (4.8) ppb. The difference between DOAS and DIAL is an estimated 1.6 ppb.

5. Diurnal patterns of ground-level ozone concentrations and some selected ozone profiles suggest that photochemical ozone production and advection from upwind regions (in the western part of Seoul) contribute a large portion of the ozone concentrations at the ground, as indicated by two peaks of ozone concentrations at 14:00 LST and 18:00 LST on 25 May, 2000.

6. Measurements of diurnal patterns between ground-level ozone concentrations and the vertical profiles of ozone concentrations constitute observational evidence that the entrainment and fumigation processes of ozone aloft in the nighttime residual layer into the ground is an important contributor to the peak of ground-level ozone concentrations observed on the following day.

Results of this study are consistent with previous modeling studies (e.g., Zhang and Rao, 1999) on vertical mixing and ground-level ozone concentrations, and will help us gain a better understanding of ozone characteristics at the ground and its life cycle in an urban atmosphere.

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