Comparison of tethered balloon vertical profiles of particulate matter size distributions with lidar ceilometer backscatter in the nocturnal urban boundary layer

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Abstract: A novel ceilometer validation is presented for a nocturnal elevated PM layer observed over Vancouver, British Columbia. The boundary-layer structure was confirmed by both meteorological and PM vertical profiles. This result is especially significant due to the low PM concentrations present during the observational period (a mean PM_{10} concentration of 10.6 μg m^{-3} was recorded) and suggests that ceilometers are able to resolve boundary-layer structure more subtle than that normally present during periods of poor air-quality. A direct relation between backscatter intensity and PM concentration suggests that not only may these relatively cheap, robust ceilometers be used to elucidate boundary-layer structure, but they represent a promising quantitative alternative to the measurement of PM concentrations that complements existing surface-based instrumentation. This study extends and confirms the growing body of evidence supporting the utility of ceilometers for making detailed, cost-effective measurements of the boundary-layer.

Keywords: urban boundary layer; remote sensing; lidar; ceilometer; particulate matter.

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Biographical notes: Derek van der Kamp is a graduate student with an undergraduate degree in Physics from the University of Victoria, Canada. The objective of his research is to develop algorithms to diagnose urban boundary-layer characteristics from ceilometer data.

Ian G. McKendry has research interests focused on air pollution meteorology. He has published extensively on the mesoscale air pollution meteorology of the Lower Fraser Valley, British Columbia, and most recently has written on the trans-Pacific transport of dust and pollutants. Much of his work has a strong observational basis and includes the development of tethered balloon approaches for profiling in the planetary boundary-layer.

1 Introduction

Developments in lidar (light detection and ranging) technology have resulted in affordable, robust, low-maintenance ceilometers that provide not only reliable measurements of cloud height, but also high resolution optical backscatter measurements of boundary-layer structure. The *Vaisala CL31* (and its predecessor, the *CT25K*), with its novel single lens design, shows considerable promise with respect to identifying boundary-layer structures, and has been demonstrated to be a valuable tool for diagnosing boundary-layer heights (Emeis et al., 2004; Eresmaa et al., 2006; Münkel et al., 2007) and for elucidating the air pollution meteorology in regions of complex terrain (Zéphoris et al., 2005). Furthermore, the *CL31* has been shown to be a potentially viable substitute for ground-based Particulate Matter (PM) sensors, with the added advantage of providing vertical information (Münkel et al., 2007).

Although confirmation of ceilometer performance in the diagnosis of mixed-layer depths and boundary-layer structure has been achieved by simultaneous comparisons with other remote sensing instruments (Emeis et al., 2004) and with vertical meteorological soundings (Zéphoris et al., 2005; Eresmaa et al., 2006; Münkel et al., 2007), few studies have attempted to compare optical backscatter profiles with direct vertical measurements of PM concentrations. Münkel et al. (2007) consider the latter to be an important test of the ability of such instruments to obtain vertical aerosol concentration profiles.

In this study, aerosol backscatter measurements from the *CL31* are compared with size-segregated vertical profiles of PM obtained from an optical particle counter (*GRIMM 1.108*) deployed on a tethered balloon in the summertime nocturnal urban boundary layer in Vancouver, British Columbia. As such, it represents a novel attempt to examine the efficacy of the *CL31* for remote sensing of vertical aerosol structure, and attempts to address the call by Münkel et al. (2007) for more validation studies. Furthermore, the case examined is one in which $PM_{2.5}$ concentrations were low (~5 μg m^{-3}), and consequently the study represents a rigorous test of the ability of the *CL31* to diagnose, with good signal-to-noise ratio, Stable Boundary Layer (SBL) heights as well as PM layers, for the cases where the SBL height is greater than the minimum lidar range gate.

2 Background

Vancouver (49.5°N, 123°W), is a coastal city comprising part of a larger metropolitan area with a population of close to two million inhabitants. It is located at the western edge of the triangle-shaped Lower Fraser Valley and is bounded on the western side by the Strait of Georgia, which separates the mainland from Vancouver Island. Winds in the region are strongly influenced by thermo-topographic effects and include significant channelling of flow as well as the presence of thermally induced circulations, such as sea and land breezes and slope and valley winds. Extensive field studies during summer (e.g. McKendry, 1994; Banta et al., 1997; McKendry et al., 1997; McKendry et al., 1998) have demonstrated the presence of complex wind patterns driven by land–water contrasts and mountain effects. This complexity has been notoriously difficult to reproduce in model simulations (e.g. Steyn and McKendry, 1988; Cai and Steyn, 2000; van der Kamp et al., 2008) and is known to be responsible for the creation and advection of elevated pollutant layers (McKendry and Lundgren, 2000).

With a west coast location, few industrial or solid-fuel home heating sources, and abundant winter rainfall, PM concentrations are relatively low compared with those of many industrialised mid-latitude cities. Mean annual PM_{10} concentrations are ~15 μg m^{-3}, with maximum hourly values reaching ~50 μg m^{-3} during periods of reduced dispersion, primarily during occasional summer photochemical smog events (McKendry, 2000).

3 Methods

A tethered balloon and ceilometer were co-located at an urban cemetery in central Vancouver (49.24°N, 123.09°W), ~5.2 km south-west of the central business district and 6–8 km from the nearest coastline (to the north-west). The area is relatively flat and unobstructed, and is surrounded by single-storey residential dwellings arranged in a gridded street pattern. Ground-level $PM_{2.5}$ concentrations observed at an air-quality monitoring station located 8.3 km from the field site were also used in the analysis. The observations were taken to be representative of the field site, as $PM_{2.5}$ concentrations are relatively homogeneous throughout urban areas (McKendry, 2000; Wilson et al., 2005).

3.1 Ceilometer

The *Vaisala CL31 Ceilometer* is described in detail in Münkel et al. (2007). Briefly, the eye-safe instrument has a 5–10 m resolution and a 0–7500 m range, and it produces a light source of wavelength 910 nm from a laser diode. The *CL31* uses a novel lens design in which the common lens is used for collimating the outgoing laser beam, while the outer part of the lens is used for focusing the backscattered light onto the receiver. For this study, the ceilometer was run at the maximum vertical resolution of 5 m with a sampling rate of 15 s. This temporal resolution was deemed sufficient for analysing the development of BL structure. The lowest 50 m of backscatter data were masked due to near-surface noise. The raw ceilometer data-stream was initially processed by Vaisala's CL-View software, but subsequent data analysis and plotting were performed using Mathwork's Matlab software package (Version 7.1.0). The original data were filtered using a six-point (90 min) temporal running average and an 11-point (55 m) vertical running average.

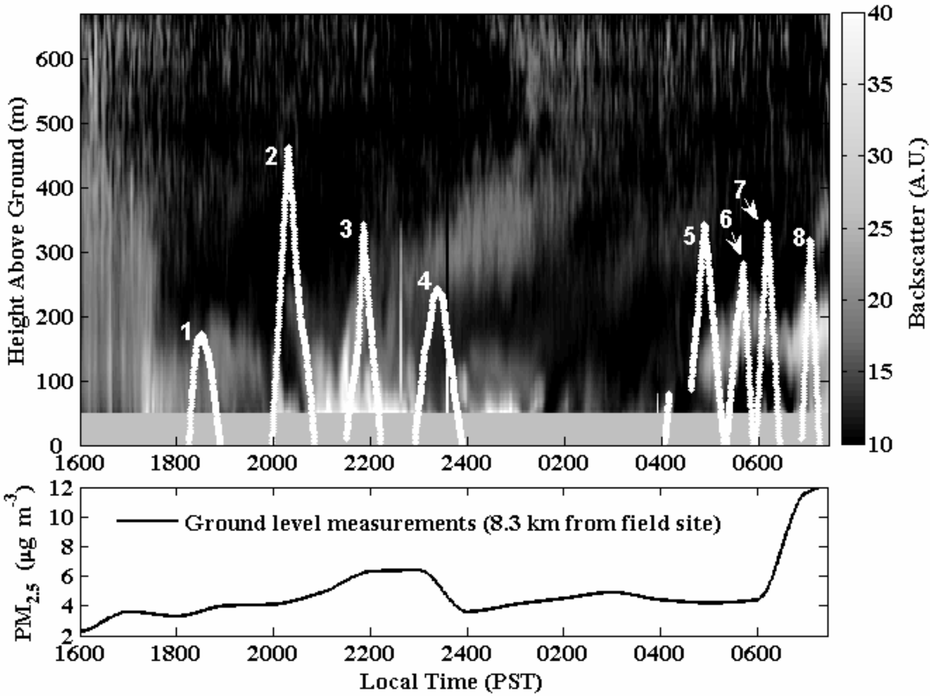
3.2 Aerosol spectrometer

Deployment and evaluation of a commercially available *GRIMM 1.108* 'Dustcheck' (Labortechnik Ltd., 1996) on a tethered balloon is described in detail by Maletto et al. (2003) and McKendry et al. (2004). In summary, a 2.4 kg (including rechargeable battery) light-scattering instrument was deployed on a 5 m^3 kytoon. The *GRIMM* provides PM particle counts in 15 different size classes from 0.3 to 20 μm. These data may be converted to a volume distribution (based on the PM diameter and assuming spherical particles) or a mass distribution (μg m^{-3}). In calculating the latter, particulate density information is required. Generally, as such information is not available, a uniform density is assumed. Consequently, calibration of the instrument is essential in order to accurately represent the PM mass distribution at a given site. This may be achieved by comparing the *GRIMM* mass distribution with data collected using other measurement principles (e.g. gravimetric techniques). The accurate measurement of PM (and particularly its size distribution) is notoriously difficult. Standard instruments such as the tapered element oscillating microbalance (*TEOM*) suffer from a variety of deficiencies, including the volatilisation of small particles due to heated inlets and humidity effects (Charron et al., 2004). In an intercomparison between two *TEOM*s and two gravimetric (filter based) Partisol samplers, Charron et al. (2004) found that *TEOM*s on average capture only half of the total mass recorded by the gravimetric instruments. Most of the mass lost is in the fine mode ($PM_{2.5}$). Furthermore, this effect is accentuated when temperatures are low, humidity is high, or pollutant concentrations are elevated. Charron et al. (2004) also emphasised that the filtration-based mass measurements are prone to significant errors associated with volatilisation, temperature, humidity and other effects (including particle-bound water). In the present study, given the mild summer nocturnal conditions and the availability of only *TEOM* and gravimetric instruments for calibration, the *GRIMM* measurements were not corrected on the basis of comparison with other instruments. Instead, the *GRIMM* was run with the calibration factor (1.0) shown to be appropriate in a marine urban setting (Maletto et al., 2003; McKendry et al., 2004).

3.3 Tethered balloon

During vertical profiling through the boundary layer, the *GRIMM* aerosol-spectrometer was suspended approximately 1 m below a 5 m^3 helium-filled kytoon. In addition, a commercially available *Kestrel 4500* meteorological package (*Pocket Weather Tracker*) was slung immediately below the *GRIMM* in order to provide wind speed, wind direction, temperature, humidity and altitude every 10 s during the ascent and descent sequence. Meteorological information was logged on the 102 g *Kestrel 4500*, while PM data were recorded on a memory card in the spectrometer at six-second resolution. This application of the *Kestrel 4500* on a tethered balloon is novel and was based on its excellent performance in field comparisons involving collocation with a standard Campbell Scientific surface weather station (e.g. correlations of ~0.97 for temperature and windspeed), and short vehicle transects over ~1000 m elevation in which altitudes were compared with those derived from GPS (The *Kestrel* specifies 1 m resolution and +/− 15 m accuracy). *Kestrel* wind direction is based on a two-axis solid-state magnetoresistive sensor mounted perpendicular to the unit plane, with a +/− 5° resolution. When the *Kestrel* was deployed on the kytoon, wind direction was based on the fact that the instrument was attached such that it was constrained to always point in the direction of the kytoon (which points into the wind). Timing information enabled the meteorological data and spectrometer data to be merged. Ascent and descent of the balloon was controlled by an electric winch with a typical ascent/descent sequence reaching 300–400 m AGL within a total duration of 45 min. This gave a mean vertical resolution for the meteorological and particulate matter data of 2.4 m and 1.5 m, respectively. A total of eight flights (giving 16 individual profiles) were conducted between 1815 PST 14 August and 0715 PST 15 August 2007. Flights 1, 3, 4, 5, 6, 7 and 8 carried both the meteorological instrument and the *GRIMM* optical particle counter; the *GRIMM* was not used during Flight 2. The time/height locations of the tethered balloon ascents are shown in Figure 1, overlain on the ceilometer data.

Figure 1 Ceilometer observations from 1600 14 August to 0800 15 August (PST) tethersonde flight locations are also shown along with flight numbers, surface $PM_{2.5}$ TEOM measurements from a nearby air-quality station are shown in the lower panel



Note: Backscatter values are in Arbitrary Units (A.U.) and reflect the fact that a persistent noise signal has been removed

4 Results

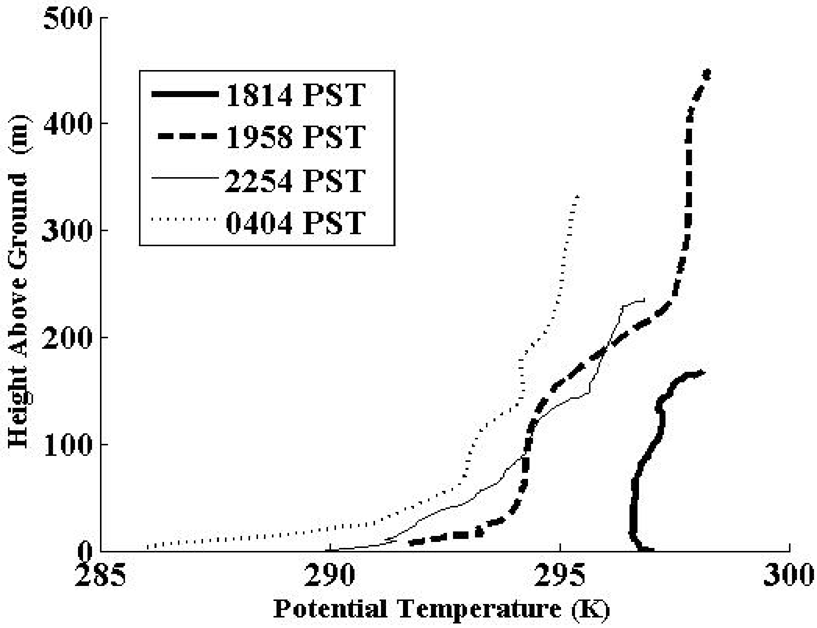
4.1 Meteorology and ceilometer observations

Validation (14–15 August, 2007) was conducted during a fair-weather anti-cyclonic event in which a ridge of high pressure developed over the south-west coast of British Columbia. This development was preceded by the passage of a depression associated with unsettled weather conditions and relatively low PM concentrations. Temperatures at the Vancouver International Airport (YVR) reached above-average values of 23°C and 25°C on the 14th and 15th respectively, with west to south-west daytime winds of ~ 4 m s^{-1} transitioning to north-east winds of ~ 1–2 m s^{-1} at night. Condensation was not observed during the observational period; ground-level relative humidity measurements remained below 85%, while above 50 m (the lowest ceilometer altitude bin) measurements remained below 65%. It, therefore, can be assumed that the ceilometer signal is due almost entirely to the presence of PM.

The boundary-layer structure observed by the ceilometer is shown in Figure 1. A few conspicuous features are apparent. Firstly, there is a subtle backscatter transition at around 200 m throughout the first half of the night, as well as a peak in backscatter between ~2100 and 2400 PST, corresponding to a peak in surface $PM_{2.5}$ concentrations. This peak is likely due to the onset of a particulate-laden down-valley drainage flow. Also of note is the appearance of an elevated layer at 150 m at approximately 0500 PST.

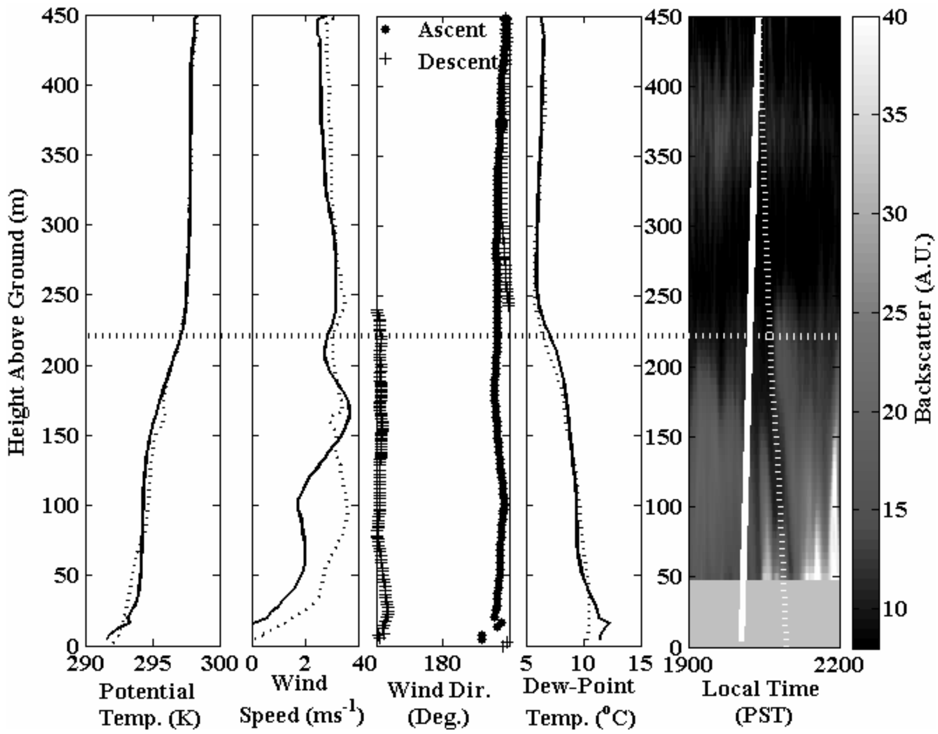
Profiles of temperature throughout the night (Figure 2) indicate that the mixed layer evident around 1800 PST quickly gave way to a growing stable layer that was most pronounced near sunrise, when it reached 200–250 m in depth. This is contrary to observations in other urban environments, which show a neutral or even unstable urban nocturnal boundary layer (Oke, 1995). Although the tethered balloon flights were performed within a park, a large majority of the observed profiles were likely indicative of air that was in equilibrium with the surrounding urban area rather than the cooler, moist, park-like surface of the cemetery. Garrett (1992) presents a formulation for the growth of a stable internal boundary layer as air is advected across a cooler surface, such as a park. A conservative estimate suggests that only the first few metres would be in equilibrium with the park surface, given the rate of advection from the surrounding urban areas.

Figure 2 Potential temperature profiles from selected tethered balloon soundings during case study



In routine ceilometer observations at this site, a backscatter transition between 200 and 250 m is a commonly observed feature. In this case, the same feature is evident, and when compared against tethered balloon meteorological data at around 2200 PST (Figure 3), the transition is coincident with the top of a nocturnal stable layer characterised by relatively light winds and enhanced humidities. This rather subtle backscatter transition, therefore, appears to be physical (i.e. based on a transition in aerosol loading associated with an inversion 'lid'), and indicates the top of a stable nocturnal layer that regularly develops over the city of Vancouver.

Figure 3 Meteorological and ceilometer observations for Flight # 2



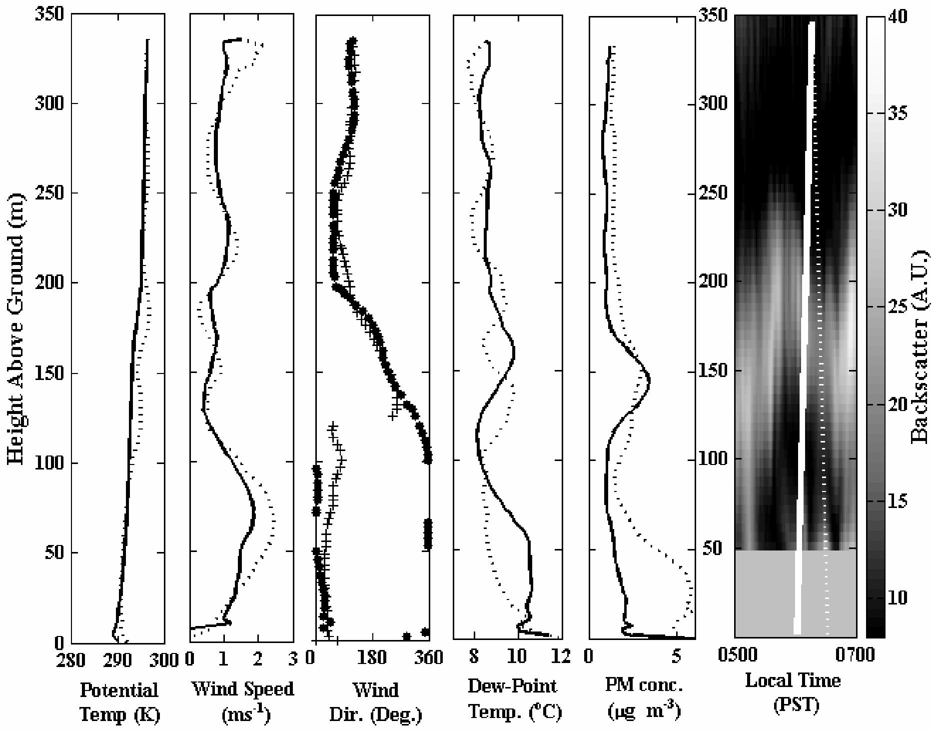
Note: Ascent: solid line; Descent: dotted line

In Figure 3, an increase in backscatter is evident in the lower portion of the profile between 1900 and 2200 PST. Both the tethered balloon and surrounding weather stations show a transition from north-westerly to north-easterly winds at this time. This transition may be associated with the onset of nocturnal out-valley flow, a phenomenon commonly observed in the Lower Fraser Valley during anti-cyclonic conditions (Banta et al., 1997).

4.2 Particulate matter profiles

Deployment of the *GRIMM* optical particle counter on a tethered balloon provided an opportunity to validate features evident in the lidar ceilometer data. The most conspicuous feature in this case was the arrival of an elevated layer at about 150 m at approximately 0500 PST (Figure 4). The meteorological profiles indicate that this layer had a westerly origin, in contrast to the air of easterly origin above and below it. The PM profiles derived by the *GRIMM* clearly show a peak corresponding to the ceilometer layer and indicate that $PM_{2.5}$ concentrations within the layer were ~ 3 μg m^{-3}.

Figure 4 Meteorological, $PM_{2.5}$ and ceilometer observations for flight # 7



Note: Ascent: solid line; Descent: dotted line

Size distributions above, within and below this layer (Figure 5) all show a mode at ~6 μm diameter and when normalised (by setting the integral of each distribution to unity: bottom panel) all show a similar distribution. This suggests that the pollutants in the layer had a similar origin and history to those below and above the layer. The layer was, therefore, likely a result of advection from a source area with different source strength, rather than an aged layer as observed by Maletto et al. (2003) or a layer of different origin (McKendry et al., 2004). Such layers are common within the Lower Fraser Valley, and the coastal location and mountainous terrain mean that a variety of processes can lead to the formation of elevated pollutant layers (McKendry and Lundgren, 2000).

Finally, based on the 14 tethersonde profiles on which the *GRIMM* was deployed, the relation between backscatter and PM concentration for the entire nocturnal period of the case study, at all heights, is shown in Figure 6 (for $PM_{2.5}$). Despite overall low concentrations observed during the case study, a linear relation between backscatter and PM concentrations is evident. Pearson correlation coefficients (ρ) of 0.72, 0.67 and 0.45 were calculated for $PM_{1.0}$, $PM_{2.5}$ and PM_{10}, respectively. This reduction in correlation values as particle size increases is to be expected. According to Mie scattering theory, backscatter intensity is strongest for particle sizes comparable to the wavelength of light, which in this case is 910 nm. These results are consistent with Münkel et al. (2007), in which *Vaisala CL31* backscatter in the lowest range gates was correlated with PM_{10} measurements at a height of 43 m.

Figure 5 Particle diameter distributions derived form GRIMM aerosol spectrometer at three elevations (top panel) and normalised [bottom panel derived from flight #7(Figure 4)]

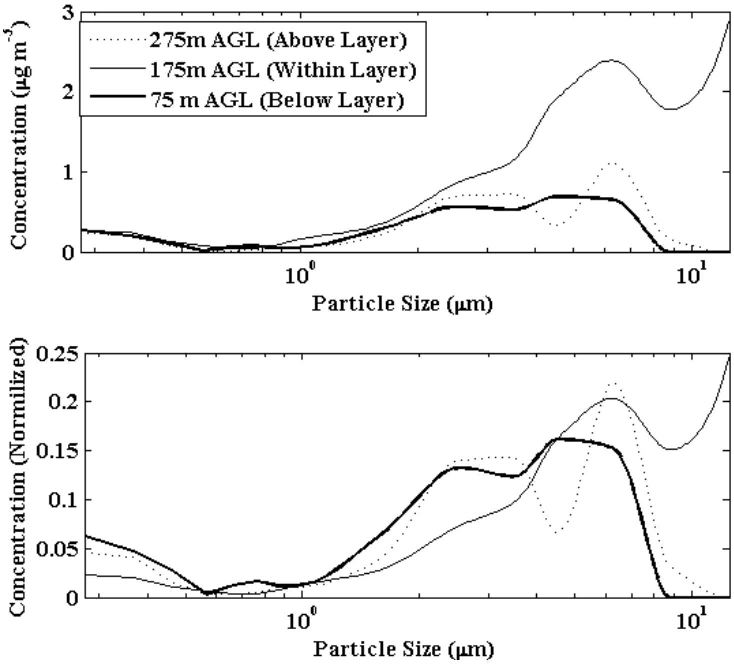
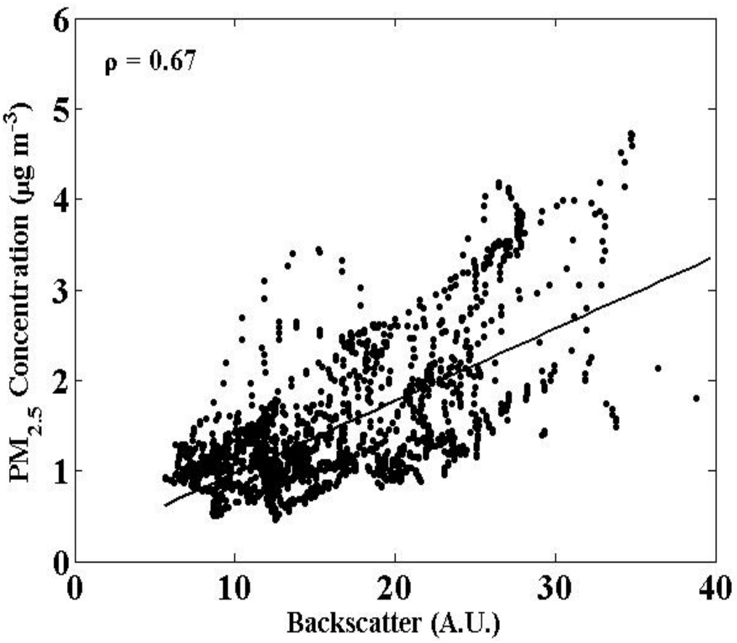


Figure 6 Scatter plots of $PM_{2.5}$ (bottom) and ceilometer backscatter for all vertical profiles conducted with GRIMM aerosol spectrometer (14 profiles), ρ refers to the Pearson correlation coefficient



5 Discussion and conclusions

A novel comparison of lidar ceilometer backscatter with meteorological and size-segregated vertical PM profiles is presented for a nocturnal urban case in which an elevated PM layer was observed. The boundary-layer structure indicated by ceilometer was confirmed by both meteorological and the PM vertical profiles. This result is especially significant due to the low PM concentrations present during the observational period (in which a mean PM_{10} concentration of 10.6 μg m^{-3} was recorded), suggesting that the ceilometer is able to resolve boundary-layer structure more subtle than that normally present during periods of poor air quality. However, with only a single case examined herein, under relatively 'clean' conditions, there is clearly scope for further studies addressing the effectiveness of the *CL31* for routine monitoring of boundary-layer structure and PM loading.

These results also confirm a direct relation between backscatter intensity and PM concentration as reported by Münkel et al. (2007) for surface-based data. This relation suggests that not only may these relatively cheap, robust ceilometers be used to elucidate boundary-layer structure, but that they also represent a promising alternative to the measurement of PM concentrations that complements standard surface-based instrumentation. This is particularly important in regions of complex urbanised terrain (such as the Lower Fraser Valley) where pollutant layering and advection are significant processes (McKendry and Lundgren, 2000).

Although previous projects have undertaken validation of ceilometer data, they have all involved comparisons with either other remote sensing techniques (e.g. lidar, wind-profiler and SODAR), stationary PM concentrations, or radiosonde measurements that were often located kilometres away from the ceilometer. The results presented here represent a novel validation using vertical profiles of in situ, co-located, high-resolution measurements of size-segregated PM concentrations and a full suite of meteorological variables. Consequently, this study extends and confirms the growing body of evidence supporting the utility of ceilometers for making detailed, cost-effective measurements of the boundary layer.

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