Estimation of Surface Particulate Matter (PM_{2.5} and PM₁₀) Mass Concentrations from Ceilometer Backscattered Profiles

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ABSTRACT

In this study, we used remotely sensed backscattered profiles from a ceilometer to characterize the vertical and horizontal mixing of aerosols in the polluted planetary boundary layer (PBL). These profiles revealed the structure of the boundary layer, which included the mixed layer, the nocturnal residual layer and the elevated aerosol layer far above the mixed layer over Delhi. The accumulation of aerosols near the surface during feeble turbulence and the mixing of aerosols from the residual layer into the surface layer during convection was captured very well by a ceilometer. The backscattered signal from a height of 45 m above the ground was strongly correlated (82%) with the observed surface PM_{2.5} and PM₁₀ mass concentrations. We developed an empirical regression model based on this relationship, which was then tested and validated against independent measurements of the concentrations from November 2018. Although local meteorological conditions, particularly cloudiness and rain, influenced the strength of the correlation between the observed PM_{2.5} and PM₁₀ mass concentrations and the backscattered signal, the magnitude of the mean bias between the observed and the values for PM_{2.5} (−21 µg m^{−3}, RMSE = 75) and PM₁₀ (31 µg m^{−3}, RMSE = 118) indicated that the predicted values were fairly accurate. The model overestimated the PM_{2.5} by 7% and underestimated the PM₁₀ by 6% on clear days.

Keywords: Pollution event; PM_{2.5} and PM₁₀; Ceilometer backscatter.

INTRODUCTION

The poor air quality and increasing particulate matter (PM_{2.5}: diameter < 2.5 µm and PM₁₀: 2.5 µm < diameter < 10 µm) mass concentration is a growing threat to public health in India (Dey *et al.*, 2012; IHME, 2017; Gorai *et al.*, 2018). It is reported that 91% of the world populations are living in places where the air quality is deteriorated beyond the prescribed limit of the World Health Organization (WHO) guideline (WHO, 2016). India is the world's second most populated country, and an excessive amount of PM_{2.5} emissions from big urban centers are thought to be one of the causes of premature deaths in India (Chowdhury *et al.*, 2016; Ghude *et al.*, 2016; David *et al.*, 2018). During winter months (November–February), the air quality is poor over

north India, including the National Capital Region (NCR), Delhi. The western part of NCR is surrounded by the Thar Desert of Rajasthan and the hot plains of central India are situated to the south. This unique feature of topography, stable conditions during the winter months (Ghude *et al.*, 2017), emissions from the variety of local emission sources and crop burning over the Punjab and Haryana causes frequent high pollution episodes in NCR (Tiwari *et al.*, 2012; Jain *et al.*, 2014; Parkhi *et al.*, 2016; Ghude *et al.*, 2017; Cusworth *et al.*, 2018; Ghei *et al.*, 2018; Liu *et al.*, 2018; Dumka *et al.*, 2019). Therefore, monitoring of PM_{2.5} and PM₁₀ mass concentration has become an important issue in the NCR, Delhi.

The PM_{2.5} and PM₁₀ mass concentrations are routinely monitored with limited spatial resolutions due to the expensive operational and maintenance cost involved in a dense network of air quality stations. A recent study highlighting gaps in the air quality measurement network in India indicates that India will require 1600–4000 PM_{2.5} and PM₁₀ monitors at an estimated operating cost of US\$212–540 (\$106–270) million (Baurer *et al.*, 2019). Therefore, it is advantageous to retrieve

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the levels of particulate matters using satellite and remote sensing-based instruments (Münkel *et al.*, 2007; Li *et al.*, 2017; Krishna *et al.*, 2018). Further advantages of remote sensing instruments are the availability of reliable backscattered data in real time all over the globe with no operational/maintenance cost to end users (Wiegner *et al.*, 2014). Although ceilometers were originally developed to estimate the cloud-base height, with the improvement in the technology it is capable of detecting mixing layer height and aerosol information near the surface. Earlier studies have presented a fairly good correlation between ceilometer backscattered profiles and surface PM mass concentration in heavily polluted regions (Munkel *et al.*, 2007). Using ceilometer backscattered data for clear days, Munkel *et al.* (2007) found a fairly good correlation ($R = 0.83$) between the aerosol backscatter and in situ PM_{10} concentration. Li *et al.* (2017) used an empirical method to retrieve the $PM_{2.5}$ during cloudy and nighttime periods. They found 56%, 34% and 42% of the variability in the average $PM_{2.5}$ during the daytime clear sky, daytime cloudy sky, and nighttime, respectively. These studies highlighted the capability of ceilometer backscattered signals to estimate the surface $PM_{2.5}$ concentrations in the polluted environment during cloudy conditions and nighttime.

In this study, to estimate the surface $PM_{2.5}$ and PM_{10} concentrations using ceilometers' backscattered profiles, we developed a regression model based on backscattered ceilometer data and $PM_{2.5}$ and PM_{10} observations during the winter season of 2017–2018. The ceilometer was operational during 2017–2018 and 2018–2019 at Winter Fog Experiment (WiFEX) observational site (Indira Gandhi International Airport, IGIA), New Delhi (Ghude *et al.*, 2017). Similarly, collocated $PM_{2.5}$ and PM_{10} observations were available for the same period. The regression model was then tested and validated against the measurement of surface $PM_{2.5}$ and PM_{10} during the winter 2018–2019 period. The data and regression model is described in Section 2; the evaluation of the regression model is illustrated in Section 3.

DATA AND METHODOLOGY

In this study, the data were obtained from the WiFEX field campaign site located in IGI Airport, New Delhi (28.55°N, 77.09°E, MSL of 229 m), shown as Location A in Fig. 1. The site has a wide range of collocated instruments to collect the number of weather parameters including PM sampler, cloud-base height using ceilometer, etc. (Ghude *et al.*, 2017). The Lufft CHM 15k Nimbus (see in Fig. 2) ceilometer was used to retrieve the aerosol backscatter at the observational site. This ceilometer is a ground-based monostatic active remote sensing LiDAR (Light Detection and Ranging) based instrument (Martucci *et al.*, 2010; Madonna *et al.*, 2015; Jin *et al.*, 2018). It observes backscattered profiles from the surface (~15 m) up to 15,000 m range with 15 m vertical resolution averaged for each 15 s temporal resolution. The technical summary of the CHM 15k Nimbus ceilometer is given in Table 1. The ceilometer data has been processed using the CHM Viewer (version 1.7) software to get 2-D backscattered profiles. In the present study, we used the normalized and range-corrected backscattered signal from the aerosol layer below 500 m and $PM_{2.5}$ and PM_{10} observations from 10 November 2017 to 29 November 2017 to develop a regression model. For validation, we have used attenuated backscattered signals and $PM_{2.5}$ and PM_{10} observations from 1 November 2018 to 30 November 2018. The photon-counting-based CHM 15k Nimbus ceilometer uses the LiDAR technique to emit short light pulses into the atmosphere in a vertical direction. These are scattered back by aerosols present in the atmosphere, cloud cover, and precipitation. Using the counted pulse, flight time and intensity of backscattered signals are then analyzed and using this data as input, aerosol, cloud layers, etc. can be determined. The dispersion and transport of lower tropospheric aerosol concentration mainly depend on the planetary boundary layer height (PBLH) (Tyagi *et al.*, 2017). Therefore, the estimation of PBLH is significant to analyze air pollution events. In this study, the topmost aerosol layer retrieves in

Fig. 1. The Google Satellite image of the study region where the observations were taken inside the IGI Airport, New Delhi, which is represented by letter A.

Fig. 2. Ceilometer CHM 15k Nimbus at IGI Airport, New Delhi.

Table 1. Technical specifications of CHM 15k Nimbus ceilometer.

Parameters	Description/Values
Laser source	Nd:YAG solid-state laser
Wavelength	1064 nm
Operating mode	Pulsed
Pulse energy	7 μ J
Pulse repetition frequency	5–7 kHz
Filter bandwidth	1 nm
Field of view receiver	0.45 mrad

the atmosphere by ceilometer backscatter is directly used to represent PBLH for available periods (Seibert *et al.*, 2000). The expression used to receive the normalized backscattered signal power is given below (Lufft, 2016):

$$P_{c(r)} = \frac{P_{raw} - b}{C_s \times O_{(r)} \times P_{calc}} \quad (1)$$

where $P_{c(r)}$ is normalized backscattered signal power, P_{raw} is

raw backscattered profile (photon counts), b is the baseline, C_s is calibration constant, $O_{(r)}$ is overlap function, and P_{calc} is average test pulse intensity.

This normalized data is calibrated to get attenuated backscattered values. In this case study, we filtered out the negative attenuated backscattered signal of ceilometer data from the observational site during the period of November 2017 and November 2018 respectively. In the month of November PM_{10} and $PM_{2.5}$ concentrations in Delhi is frequently influenced by variety of local and non-local emissions sources such as emissions from the stubble burning in the states of Punjab and Haryana (which is mostly over by 15 November), dust influence from Thar Desert, firecracker emissions on account of Diwali festival and also from the local emission sources within Delhi (Jain *et al.*, 2005; Ghude *et al.*, 2008; Parkhi *et al.*, 2016; Beig *et al.*, 2019). In addition, meteorological conditions in Delhi show large variability in wind-speed wind direction, temperature and relative humidity. Therefore, backscattered data from the ceilometer for the month of November provide an ideal test case to capture the frequent variability in PM mass concentration in a manner that can be correlated with large variability in PM_{10} and $PM_{2.5}$ observations.

Several recent studies have suggested that within 500 m of PBL height, the PM concentration shows significant variation (Bisht *et al.*, 2016; Zhao *et al.*, 2017). Therefore, hourly averaged attenuated backscattered data for November 2017 month at different vertical backscattered ranges from 15 m to 495 m, as shown in Table 2, have been analyzed.

The observational PM concentration data in the IGI Airport area were monitored using PM sampler based on the beta attenuation method. The PM_{10} and $PM_{2.5}$ samplers were operated approximately 800 m away from the ceilometer. Hourly averaged PM_{10} and $PM_{2.5}$ concentration is reported by PM sampler which is kept at the same height as that of the ceilometer. For comparison with PM concentration, CHM 15k Nimbus ceilometer attenuated backscatter with 15 m vertical resolution has been averaged over a period of 60 min. The Radiometer Physics GmbH (RPG) humidity and temperature profiler (HATPRO) is a ground-based passive remote sensing microwave radiometer (MWR) which was kept ~30 m away from the existing ceilometer. It is continuously operated at IGI Airport, New Delhi, during the WiFEX campaign for observations of vertical profiles of temperature

Table 2. Cross-validation of correlation coefficient and RMSE at different vertical backscatter range.

Vertical range (m)	$PM_{2.5}$		PM_{10}	
	Correlation	RMSE	Correlation	RMSE
15 m	0.81322	49.33839	0.7967	84.35515
30 m	0.79245	51.71046	0.7606	90.61428
45 m	0.84528	45.30031	0.82409	79.06335
60 m	0.82753	47.59802	0.79896	83.93748
75 m	0.79315	51.63314	0.76306	90.21037
105 m	0.71188	59.54115	0.70310	99.25051
210 m	0.43825	76.20521	0.45215	124.4924
300 m	0.31090	80.57888	0.33443	131.53805
405 m	0.18481	83.31980	0.20802	136.52161
495 m	0.02765	84.74786	0.04192	139.45203

and relative humidity (RH), in the range 0–10 km, and the total amount of liquid water in the atmospheric column. In addition, we used the cloud-base height (CBH) and liquid water path (LWP) data from the RPG-HATPRO radiometer (Rose and Czekala, 2011). Visibility information for air traffic operation at an observational site is provided from the runway visual range (RVR) at every 15 s. In this case study, visibility data has provided the information for differentiating between fog and haze atmospheric phenomena.

RESULTS AND DISCUSSION

Observational

IGI Airport (observational site) is an open area with the frequent formation of the fog/haze during the winter season (Ghude *et al.*, 2017). Fig. 3(a) shows the satellite images from MODIS Aqua for the month of November 2017. It can be seen that the entire Indo-Gangetic region was covered with the thick blanket of haze layer prevailing throughout the study period. Fig. 3(b) shows the temporal evolution of visibility and RH for the month of November 2017. From 10–16 November 2017, RH was lofty, but less than 90% and visibility were in between 1000 m and 2000 m indicating hazy conditions prevailed over the Delhi (Wu *et al.*, 2006; Vautard *et al.*, 2009). Due to the passage of Western Disturbances (WDs) a sharp rise in RH (above 90%) was noticed on 16–

18 November 2017 (IMD report), however, most of the daytime period visibility was above 2000 m indicating clear sky conditions. During nighttime visibility was below 1500 m suggesting the formation of haze for a few hours. Whereas, a significant decrease in RH (below 60%) was noticed during 18–29 November 2017. During this period visibility was more than 2000 m, which indicates dry and clear conditions.

Time series of $PM_{2.5}$ and PM_{10} overlaid with the boundary layer height are shown in Fig. 4(a) for 10–30 November 2017 periods. Similarly, the time series of wind speed is shown in Fig. 4(b). Vertical cross-section of ceilometer backscatter (below 5000 m) is shown in Fig. 5, respectively. Worst air quality episode occurred on 10–14 November 2017. Surface $PM_{2.5}$ and PM_{10} concentrations reached up to $600 \mu g m^{-3}$ and $800 \mu g m^{-3}$ during this period. As per the Central Pollution Control Board (CPCB) air quality criteria, air quality during this event was reported to be in a severe category. It is evident from Figs. 4(a) and 4(b) that very stable meteorological conditions prevailed during this period (boundary layer height was quite low (100–300 m) and very low surface winds) that kept pollutants trapped close to the surface and $PM_{2.5}$ and PM_{10} concentration grew rapidly. The aerosol backscattered profile shown in Fig. 5 also illustrates less vertical mixing and trapping of pollutants close to the surface layer. The lower PBLH can weaken the exchange of aerosol concentration between the boundary

Fig. 3. (a) MODIS Aqua corrected reflectance imagery of aerosol transport in Indo-Gangetic Plain during November 2017 and orange dot indicate observational site. (b) Visibility and RH for the month of 10–29 November 2017.

Fig. 4. Temporal variation of (a) the observed surface PM concentration (black: PM_{10} and Red: $PM_{2.5}$) with PBL height (blue) and (b) temporal variation of wind speed from 10–29 November 2017.

Fig. 5. Temporal variation of a ceilometer backscattered profile from 10–29 November 2017 (green dots shows the aerosol layers).

layer and free troposphere, because of feeble turbulence. From the ceilometer backscattered profile, it is clearly seen that the gradual decrease in aerosol concentration and shallow mixing of aerosols was built up progressively above 1 km. Combination of long-range transport of $PM_{2.5}$ and PM_{10} (dust from that region, biomass burning in the north-western region of NCR) along with the local emissions in NCR region and stable meteorological conditions was the main factor for extremely poor air quality during this event (Beig *et al.*, 2019).

The gradual decrease in $PM_{2.5}$ and PM_{10} concentration was seen from 14 to 19 November 2017. During this period PBL was relatively well developed and the magnitude of surface winds was high, which developed a favorable meteorological condition for strong vertical and horizontal mixing of aerosols. Aerosol backscattered profiles in Fig. 5 showed an increase in backscatter from the higher vertical heights indicating that the vertical mixing of the aerosols was well captured by the ceilometer. After sunrise, the convective boundary layer was developed every day, eventually reaching

the vertical extent of the aerosol mixing up to 2500 m. After sunset, the aerosol backscattered profile still showed significant backscatter from higher altitudes indicating the presence of aerosol residual layer above the nocturnal boundary layer. It is quite apparent from Fig. 5 how turbulence became stronger and mixing height grow after sunrise which eventually led to the mixing of accumulated aerosols from the nocturnal boundary with the aerosols present in the residual layer during 14–19 November 2017. Looping of aerosols in the atmosphere caused due to turbulent conditions and higher wind speed caused aerosol dispersion in vertical as well as horizontal extent. Also, the transport of dust and emissions from biomass burning was reduced during this period (Beig *et al.*, 2019). The climatological mean of fire counts in the north-western region of NCR shows very little fire activities after the 2nd week of November suggesting that the impact of the fires emissions on $PM_{2.5}$ level in the NCR region is negligible after this period. During this period air quality in the NCR region improved from severe to poor/moderate category.

Lowest $PM_{2.5}$ ($100 \mu g m^{-3}$) and PM_{10} ($120 \mu g m^{-3}$) values were recorded on 17 November 2017. The backscattered profile on the same days (Figs. 6(a) and 6(b)) showed lower-level clouds (CBH: ~ 3 km) due to the passage of WD and shallow precipitation (less than 2 mm) multiple times in a day as evident by increase in LWP recorded by the

microwave radiometer (Fig. 6(b)). The shallow precipitation was not so effective to wash out aerosols throughout the mixed layer and therefore aerosol mixing still occurred for the next two days. Furthermore, it can be seen from Fig. 5 that a very stable aerosol layer close to the surface persisted from 20–29 November. Shallow convective PBL and drop in the wind speed during this period abridged vertical and horizontal mixing of aerosols to a greater extent. Aerosol backscattered profiles in Fig. 5 also shows that most of the aerosols were confined in the lowest level close to the surface (below 700 m). However, some day-to-day variability was seen with little higher $PM_{2.5}$ and PM_{10} concentrations after 26 November in the nighttime, which may be associated with the variability in local emissions within the NCR region. Overall, these observations illustrate the significant correlation between $PM_{2.5}$ and PM_{10} mass concentrations and the magnitude of the aerosol backscatter.

Estimation of Particulate Matter (PM) from Ceilometer Backscatter

Given the small attenuation within a short distance, attenuated backscattered within a mixed layer can be reasonably taken as an indirect measure of the aerosol concentrations (Munkel *et al.*, 2007). We selected 10 layers of backscattered measurements from the surface (15 m) to 500 m from the ceilometer to estimate the $PM_{2.5}$ and PM_{10}

Fig. 6. (a) Diurnal variation of backscatter profile from ceilometer on 17 November 2017 (green dots shows the aerosol layers and red lines show the shallow precipitation at 03 UTC and 20 UTC). (b) Radiometer-derived cloud base height (black) and liquid water path (red) for the same day.

concentration. The selection of 500 m is arbitrary, and the correlation test shows that the backscattered retrievals above 100 m can only explain less than 50% of the variability in PM concentration. This is consistent with the finding of Li *et al.* (2017) who reported that retrieval results are quite similar for layer from the surface to 150 m and 90–300 m. Table 2 demonstrates the correlation (and RMSE) between hourly $PM_{2.5}$ and PM_{10} mass concentration and attenuated backscattered signals from 10 vertical heights. A total of 474 observations were available between 10–29 November 2017 based on hourly averaged PM mass concentrations and attenuated backscattered signals to fit the regression model. Few earlier studies found that aerosol optical properties under the high relative humidity condition can result in the reduced aerosol backscatter ratio compared to dry and clear day conditions due to the aerosol hygroscopic growth (Li *et al.*, 2017). This can impact the correlation between the backscattered ratio and PM mass concentration. In the present study, we filtered out the ceilometer backscattered data and corresponding PM concentrations for the cloudy and rainy days/hours and whenever RH was above 90%. After eliminating these data points we got 97.67% data points representing dry, fog-free and clear sky data sets. This data set was then used to cross-validate the relationship between PM mass concentration and attenuated backscattered signal at different vertical backscattered ranges as shown in Table 2. The strong correlation between PM mass concentration and attenuated backscattered signal exist between 15 m and 100 m. Above 100 m, very poor correlation between ceilometer backscattered and surface PM was noticed. In other words, the backscattered retrievals below 100 m explain more than 70–80% of the variability in surface PM concentration, while above 200 m it can only explain 30–40% of the variability in surface PM concentration. Therefore, it is evident from Table 2 that the relationship between surface PM mass concentration and attenuated backscatter above 100 m of a backscattered range is not useful for fitting the regression

model.

Among all vertical levels, the strongest correlation between attenuated backscattered signal and surface PM concentrations (for $PM_{2.5}$, $r = 0.84$ and $RMSE = 45.3$, and for PM_{10} , $r = 0.82$ and $RMSE = 79$) was observed for 45 m, which was then further used to fit the regression model. The ceilometer used in the present study has closely spaced transmitter and receiver assembly. One of the regions for the best match found at 45 m altitude could be due to the fact that the field-of-view (FOV) overlap between the transmitted and received beam is more than 60% at about 50 m altitude. Figs. 7(a) and 7(b) show the relationship between the attenuated backscattered signal from 45 m and surface $PM_{2.5}$ and PM_{10} , respectively, and the red line shows the regression fit using the linear model. The regression equation for $PM_{2.5}$ and PM_{10} is given below:

$$E_{PM_{2.5}} = 4.51E^{-5} \times B_{45} + 51.2 \quad (2)$$

$$E_{PM_{10}} = 7.25E^{-5} \times B_{45} + 81.5 \quad (3)$$

where $E_{PM_{2.5}}$ and $E_{PM_{10}}$ are estimated $PM_{2.5}$ and PM_{10} mass concentrations in $\mu g m^{-3}$; B_{45} is the attenuated backscattered signal in $m^{-1} sr^{-1}$ at 45 m.

This regression equation was then tested and validated from the independent ceilometer backscattered observations from 45 m height and surface $PM_{2.5}$ and PM_{10} for the month of November 2018. In order to examine the performance of the regression model, time series of hourly $PM_{2.5}$ and PM_{10} mass concentrations estimated from Eqs. (2) and (3) were compared with the independent surface $PM_{2.5}$ and PM_{10} respectively (Figs. 8(a) and 8(b)). Similarly, daily mean estimated $PM_{2.5}$ and PM_{10} mass concentrations were compared with daily mean surface $PM_{2.5}$ and PM_{10} mass concentrations respectively (Figs. 9(a) and 9(b)). It can be seen that the estimated PM mass concentrations were able to capture the diurnal and day-to-day variation associated with the synoptic-scale variability. The performance statistics based on hourly

Fig. 7. Linear correlation between observed (a) $PM_{2.5}$ and (b) PM_{10} with attenuated backscattered signal retrieved from CHM 15k Nimbus ceilometer.

Fig. 8. Comparison between estimated (black) and observed (red) (a) $\text{PM}_{2.5}$ and (b) PM_{10} from 1–30 November 2018 month.

Fig. 9. Daily mean variation of estimated and observed (a) $\text{PM}_{2.5}$ and (b) PM_{10} during 1–30 November 2018. The vertical bar shows the standard deviation.

data show that magnitude of mean bias between observed and estimated $\text{PM}_{2.5}$ and PM_{10} was $-21 (\pm 56) \mu\text{g m}^{-3}$ (RMSE = 75) and $31 (\pm 95) \mu\text{g m}^{-3}$ (RMSE = 118) respectively for the entire study period indicating that estimated PM in a manner close to the observations on an hourly scale. In comparison with hourly PM estimate, performance statistics for daily mean estimated PM show that magnitude of bias was $-24 (\pm 39) \mu\text{g m}^{-3}$ (RMSE = 33) and $33 (\pm 62) \mu\text{g m}^{-3}$ (RMSE =

53). Also, it was noticed that the data sets along with cloudy and rainy days give inferior statistical results. In particular, the sharp spike in air pollution levels seen at the observational site on 8 November 2018 was because of the large number of firecrackers burning on account of Diwali festival. $\text{PM}_{2.5}$ and PM_{10} mass concentrations of the order of $970 \mu\text{g m}^{-3}$ and $1120 \mu\text{g m}^{-3}$ respectively were recorded on this day. The magnitude of estimated $\text{PM}_{2.5}$ and PM_{10} on this day was

297 $\mu\text{g m}^{-3}$ and 560 $\mu\text{g m}^{-3}$, respectively. It was noticed that the estimated percentage of $\text{PM}_{2.5}$ and PM_{10} was ~69% and ~62% less than the observations, indicating that the magnitude of the attenuated backscattered signal was not proportionally larger at 45 m. On the other hand, $\text{PM}_{2.5}$ and PM_{10} concentration was overestimated by ~61% and ~18% respectively on 13 November 2018. It was related to cloudy conditions and shallow rain ($< 1 \text{ mm h}^{-1}$) throughout the day, which developed strong backscattered signal from 45 m. This indicates that estimation of PM mass concentrations from the ceilometer backscatter is sensitive under cloudy and rainy meteorological conditions. On remaining days, estimating $\text{PM}_{2.5}$ mass concentration found to be overestimated by 7% while estimating PM_{10} mass concentration found to be underestimated by 6%.

CONCLUSIONS

In this study, ceilometer backscattered profiles were analyzed to characterize the variability of aerosols in the mixed layer, which was influenced by the following factors: the weak exchange of aerosols between the boundary layer and the free troposphere during feeble turbulence; the strong vertical and horizontal mixing and dispersion of aerosols during convection and high wind; the partial washout of aerosols following light rain; the formation of an aerosol residual layer above the nocturnal boundary layer; the mixing of the accumulated aerosols from the nocturnal boundary layer with aerosols in the residual layer; and emissions from biomass burning. Using these profiles and WiFEX observations at IGI Airport, Delhi, our primary objective was to develop an empirical regression model for predicting surface $\text{PM}_{2.5}$ and PM_{10} mass concentrations based on the relationship between the observed concentrations and the attenuated backscattered signal from a height of 45 m, as the signal from this height exhibited the strongest correlation with the $\text{PM}_{2.5}$ (0.84) and PM_{10} (0.82) concentrations. The predictions were then compared with independent observations of $\text{PM}_{2.5}$ and PM_{10} from November 2018 data sets. Our model accounted for ~82% of the variation in hourly PM concentrations over the entire study period, and the magnitude of the mean bias between the observed and the predicted values for $\text{PM}_{2.5}$ ($-21 \mu\text{g m}^{-3}$, RMSE = 75) and PM_{10} ($31 \mu\text{g m}^{-3}$, RMSE = 118) indicated that the predicted values were fairly accurate. However, we found that the accuracy of the predictions significantly decreased during rainy or cloudy conditions, whereas it increased during clear conditions, as shown by a 7% overestimation of $\text{PM}_{2.5}$ and a 6% underestimation of PM_{10} on clear days.

Our case study offers insights into how backscattered signals from a ceilometer can be used to estimate surface PM concentrations in a polluted environment, but several limitations must be noted. Because the optical properties of aerosols depend on the relative humidity and the chemical composition of the $\text{PM}_{2.5}$ and PM_{10} , which vary over time, Eqs. (2) and (3) should be used only for ceilometer backscattered profiles from November, although the methodology described in Section 3.2 can easily be applied to other months. Furthermore, the current network of ceilometers

across India is not widespread, but the India Meteorology Department (IMD) has been steadily expanding it, e.g., by developing fifty indigenously designed ceilometers in collaboration with DRDO, particularly for obtaining cloud data at major airports in northern India. A recent study by Baruer *et al.* (2019) demonstrated that supporting air quality studies in India will require 1600–4000 monitors (1.2–3 monitors per million persons) at an estimated capital (annual operating) cost of US\$212–540 (\$106–270) million. Therefore, alternative methods are necessary and will help to fill the gaps in air quality measurement networks. The results from this case study suggest that utilizing ceilometers in the existing network or installing ceilometers in a wide network would provide a cost-effective means of examining the three-dimensional aspects of regional air pollutants as well as distinguishing between regional and local sources of pollution.

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