Environ Monit Assess (2022) 194: 610
https://doi.org/10.1007/s10661-022-10293-4

Bias in $PM_{2.5}$ measurements using collocated reference-grade and optical instruments

Meenakshi Kushwaha · V. Sreekanth · Adithi R. Upadhya · Pratyush Agrawal · Joshua S. Apte · Julian D. Marshall

Received: 19 December 2021 / Accepted: 11 July 2022 / Published online: 25 July 2022

Abstract Optical $PM_{2.5}$ measurements are sensitive to aerosol properties that can vary with space and time. Here, we compared $PM_{2.5}$ measurements from collocated reference-grade (beta attenuation monitors, BAMs) and optical instruments (two DustTrak II and two DustTrak DRX) over 6 months. We performed inter-model (two different models), intra-model (two units of the same model), and inter-type (two different device types: optical vs. reference-grade) comparisons under ambient conditions. Averaged over our study period, $PM_{2.5}$ measured concentrations were 46.0 and 45.5 µg m^{-3} for the two DustTrak II units, 29.8 and 38.4 µg m^{-3} for DRX units, and 18.3 and 19.0 µg m^{-3} for BAMs. The normalized root square difference (NRMSD; compares $PM_{2.5}$ measurements from paired instruments of the same type) was ~ 5% (DustTrak II), ~ 27% (DRX), and ~ 15% (BAM). The normalized root mean square error (NRMSE; compares $PM_{2.5}$ measurements from optical instruments against a reference instrument) was ~ 165% for DustTrak II, ~ 74% after applying literature-based humidity correction and ~ 27% after applying both the humidity and BAM corrections. Although optical instruments are highly precise in their $PM_{2.5}$ measurements, they tend to be strongly biased relative to reference-grade devices. We also explored two different methods to compensate for relative humidity bias and found that the results differed by ~ 50% between the two methods. This study highlights the limitations of adopting a literature-derived calibration equation and the need for conducting local model-specific calibration. Moreover, this is one of the few studies to perform an intra-model comparison of collocated reference-grade devices.

Keywords Light scattering · Local calibration · DustTrak · Beta attenuation monitor · Bengaluru, India

M. Kushwaha · A. R. Upadhya · P. Agrawal
ILK Labs, Bengaluru 560046, India

V. Sreekanth (✉)
Center for Study of Science, Technology & Policy, Bengaluru 560094, India
e-mail: sree_hcu@yahoo.co.in

J. S. Apte
Civil and Environmental Engineering, University of California, Berkeley, CA 94720, USA

J. D. Marshall
Civil and Environmental Engineering, University of Washington, Seattle, WA 98195, USA

Introduction

Air pollution, one of the biggest environmental threats, has detrimental effects on global climate, public health, ecology, and economy. $PM_{2.5}$ (mass concentration of particulate matter with an aerodynamic diameter of less than 2.5 µm) is a criteria air pollutant and the largest contributor to the global burden of diseases attributable to environmental risks in general and to air pollution specifically (HEI, 2020). Quantification of $PM_{2.5}$ concentration plays a major role in risk assessment and air pollution management.

$PM_{2.5}$ monitors are available at various levels of operating complexity, accuracy, and cost. The gravimetric method (weighing aerosol samples collected on a filter paper using a pump with a prescribed flow rate and size-selective inlet) is considered the gold standard for measuring $PM_{2.5}$ concentration and was designated as a Federal Reference Method (FRM) by the United States Environmental Protection Agency (USEPA). Gravimetric measurements are time-integrated. Alternatively, real-time (e.g., minutely or hourly) $PM_{2.5}$ measurements can be obtained using instruments such as tapered element oscillating microbalance (TEOM), beta gauges, and photometers. Among these, TEOMs and beta attenuation monitors (BAMs) have been designated as Federal Equivalent Methods (FEMs) by the USEPA, indicating that they are not FRMs but are functionally "equivalent" to FRMs (Noble et al., 2001). These labels generally indicate that measurements from "reference-grade" (i.e., FRM or FEM) instruments require no further correction or calibration and can be directly used for regulatory purposes. Although reference-grade instruments are appealing for their accuracy and reliability, they are often bulky, expensive, and require expert guidance to install and maintain.

In contrast, non-designated methods, such as laser photometry, offer several advantages. Instruments built on light scattering laser photometry principles are generally portable (some are handheld or wearable), less expensive and easier to operate than reference-grade instruments, and capable of providing high-temporal-resolution data (e.g., one hertz). DustTrak aerosol monitors (TSI Incorporated, Shoreview, MN, USA) are a suite of portable real-time PM measurement instruments intended for several applications, including emissions monitoring, outdoor and indoor air-quality investigations, and aerosol research studies. DustTrak II (desktop model 8530; "DTII") and DustTrak DRX (desktop model 8533; "DRX") are the most commonly used versions of DustTrak. Based on the size-selective inlet chosen, DTII can measure the mass concentration of one PM size fraction at a time: PM_1, $PM_{2.5}$, PM_4, PM_{10}, or total PM, whereas DRX can measure all five of these size fractions simultaneously. DRX combines photometric and optical pulse measurements to estimate aerosol mass concentrations and provides size information (Wang et al., 2009). In general, DustTrak monitors are calibrated at the factory using Arizona road dust before being shipped to customers. In addition, calibration with aerosol particles that are not representative of local aerosol characteristics can contribute to observed discrepancies in $PM_{2.5}$ measurements from DustTrak monitors.

$PM_{2.5}$ measurements obtained using DustTrak are highly precise but are less accurate than those obtained using FRM and FEM instruments (Chung et al., 2001; Holstius et al., 2014; Kim et al., 2004; Kingham et al., 2006; Kumar et al., 2018; McNamara et al., 2011; Moosmüller et al., 2001; Yanosky et al., 2002; Zhu et al., 2011). Light scattering-based PM measurements are sensitive to meteorological and aerosol microphysical properties; the accuracy of DustTrak measurements can be significantly impacted by local aerosol properties because light scattering is a strong function of aerosol size and refractive index (Hinds, 1999). In addition, atmospheric moisture uptake can lead to the hygroscopic growth of aerosols, which also impacts the refractive index of aerosols and the accuracy of DustTrak measurements. The hygroscopic growth of particles occurs when the relative humidity (RH) exceeds the deliquescence point of the particulate matter. Ambient $PM_{2.5}$ consists of hygroscopic matter, which can absorb moisture and grow in size at RH values as low as 70% (Jayaratne et al., 2018). Larger particles can scatter more light in a DustTrak and can result in $PM_{2.5}$ overestimation (e.g., Kumar et al., 2018). All these phenomena warrant correction for moisture-induced biases in DustTrak PM measurements and its local calibration before using the data for research purposes.

When more than one instrument is involved in a measurement campaign, collocation experiments are important to investigate the precision and accuracy of the measurements. Indian cities are often at the top of the list of the most polluted cities in the world, which indicates extremely high PM concentrations compared to high-income countries with lower PM concentrations where most collocation studies are conducted. Additionally, given the heterogonous and unique pollution sources (such as diesel vehicles, biomass for cooking, and garbage burning) in Indian urban centers, it is important to characterize the performance of popular PM monitors before application of the data from these instruments in air quality management projects.

In this paper, we reported the results obtained from a set of collocation experiments involving $PM_{2.5}$ measurements from six instruments of different makes and models in a major urban center in India (Bengaluru, Karnataka). The precision and accuracy of these instruments were investigated. We performed inter-model (compared two different models), intra-model (compared two units of the same model), and inter-type (compared two different device types: portable vs. reference-grade) comparisons. To the best of our knowledge, this is one of the few studies to perform comparisons of two collocated reference-grade devices of the same model in India.

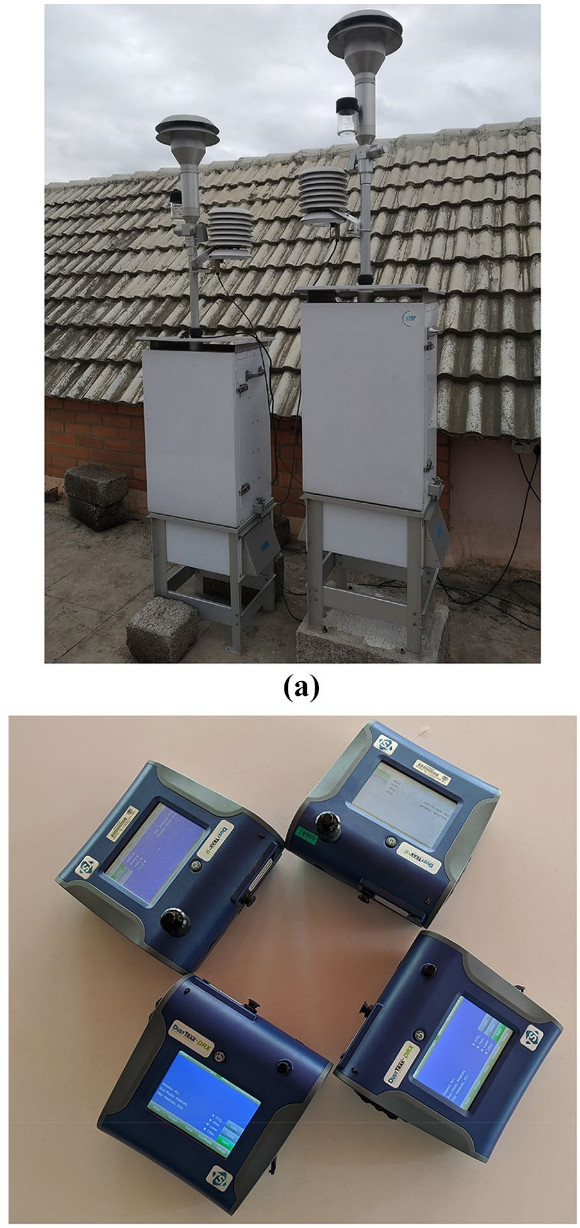
We also explored two different methods to compensate for RH bias in DustTraks $PM_{2.5}$ measurements—a literature-derived mathematical method and an experimental method; the former is a popular RH correction method for optical $PM_{2.5}$ measurements as proposed by Chakrabarti et al. (2004). Although many DustTrak studies have adopted this method (e.g., Kumar et al., 2018), to our knowledge, ours is the first attempt to experimentally verify this correction method.

Materials and methods

Study location

All measurements (Fig. 1) were conducted at the Center for Study of Science, Technology and Policy (CSTEP) campus in northern Bengaluru, India. The BAMs were installed on the building terrace, ~ 10-m above ground level and ~ 110 m from a major roadway. Inter and intra-model DustTrak comparisons were conducted at a semi-open terrace location on the CSTEP campus. Experiments were conducted between July 2019 and January 2020.

Bengaluru, an inland city in South India, has a population of ~ 10 million and a tropical savanna climate with an average ambient temperature of ~ 24 °C and an average RH of ~ 80% during the wet season and ~ 50%–70% during the dry season. A recent modeling study by Guttikunda et al. (2019) highlighted vehicle exhaust, dust, and open waste burning as the major sources of $PM_{2.5}$. Measurements at our reference site in Bengaluru typically indicate high black carbon concentrations, accounting for 20–40% of $PM_{2.5}$ mass.



(a)

(b)

Fig. 1 **a** Collocated beta attenuation monitors (BAMs) on the terrace of the CSTEP building, and **b** DustTrak units

Instruments

This study involved collocation of six devices: two DTIIs, two DRXs, and two BAMs (model 1022; MetOne Instruments Inc, Grants Pass, OR, USA). DTII and DRX operate at a flow rate of 3 L per minute (LPM; 2 LPM sample flow and 1 LPM sheath flow). DustTraks sample untreated air at ambient RH. As mentioned above, DTII can measure only one size fraction at a time, whereas DRX provides simultaneous mass concentration data corresponding to five size fractions (PM_1, $PM_{2.5}$, PM_4, PM_{10}, and total PM). In this study, DTIIs were operated with a 2.5-µm size-cut impactor assembly to measure $PM_{2.5}$. In the DustTrak optical chamber, a laser diode illuminates monochromatic light (655 nm) onto the sample flow and the light scattered at 90° by the aerosol particles is focused toward a photodetector. The instrument then converts the response level of the photodetector into PM mass concentration using a factory conversion factor. All four DustTraks used in this study were programmed to measure and record data at a 1-min averaging interval. Further technical details on DustTraks can be found at www.tsi.com and, e.g., Rivas et al. (2017).

Before collocation experiments, DustTraks were zero calibrated using the manufacturer-provided HEPA filter assembly. Date and time settings were synchronized among all four units. The instrument manufacturer (TSI, Inc.) recommends that the DustTrak be factory calibrated annually (including photometric and flow calibration); all four DustTraks used in this study were within the validity period of factory calibration.

The reference-grade monitor employed in this study, BAM1022, uses the beta attenuation technique (beta source: ^{14}C) to measure the mass concentrations of aerosol particles collected onto a glass fiber tape. The accuracy of BAM1022 meets the USEPA class III FEM requirements. BAM1022 (equipped with a manufacturer-supplied 2.5-µm-size cut cyclone) operates at 16.7 LPM, with an inbuilt heating arrangement to avoid humidity-related errors. The detection limit for BAM1022 is < 1 µg m^{-3} (24 h). BAM1022 is equipped with ambient temperature and RH sensors. Additional technical details on BAM1022 can be found at https://metone.com/products/bam-1022/.

RH calibration experiment

In a two-day (48-h) side experiment, we explored the effect of moisture uptake by aerosol particles on $PM_{2.5}$ measurements by attaching a diffusion dryer (TSI Diffusion Dryer 3062) to the inlet of one of the DTIIs and collocating it with another DTII without dryer assembly and BAM. The measurements from the DTII without dryer were corrected using the method prescribed by Chakrabarti et al. (2004). In this method, the raw $PM_{2.5}$ value is divided by a correction factor (CF), which is derived for ambient RH measurements. This CF is applied when RH is observed to be above 60% using the following equation:

$$PM_{2.5-RHcorrected} = \frac{PM_{2.5-raw}}{CF} \tag{1}$$

$$CF = 1 + \frac{0.25RH^2}{(1 - RH)} \tag{2}$$

Data analysis

Measurement bias between reference and non-reference-grade devices was quantified in terms of root mean square error (RMSE) and normalized RMSE (NRMSE). Here, the word "error" reflects that for any difference between the instruments, the non-reference grade is considered incorrect (erroneous) relative to the reference-grade instrument. In contrast, when comparing without a reference concentration (i.e., intra-model and inter-model comparisons), we use the terms root mean square difference (RMSD) and normalized RMSD (NRMSD); the word "difference" (not "error") reflects that two units provide different values but neither is considered "correct" or a "gold standard." The relevant equations are as follows:

$$RMSE\ or\ RMSD = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - y_i\right)^2}{n}} \tag{3}$$

$$NRMSE\ or\ NRMSD\ (\%) = \frac{RMSE\ or\ RMSD}{mean\ PM_{2.5}} X100 \tag{4}$$

where i is the number of observations and x and y are $PM_{2.5}$ observations from two different instruments. Instrument comparisons without a "gold-standard" (here, "reference-grade" instrument) indicate precision but not accuracy; to determine accuracy, a gold-standard measurement (reference-grade instrument) is required. Because the collocation experiments were conducted on multiple non-continuous days during the study period, inter-comparisons (e.g., Fig. 2a) are displayed based on observation number rather than the time-of-day.

Results

Inter-model comparison of $PM_{2.5}$ measurements from DustTraks (non-FEM precision testing)

This section presents a comparison of $PM_{2.5}$ measurements obtained by the two DTIIs ("DTII-1" and "DTII-2") and two DRXs ("DRX-1" and "DRX-2"). Averaged over our study period, concentrations

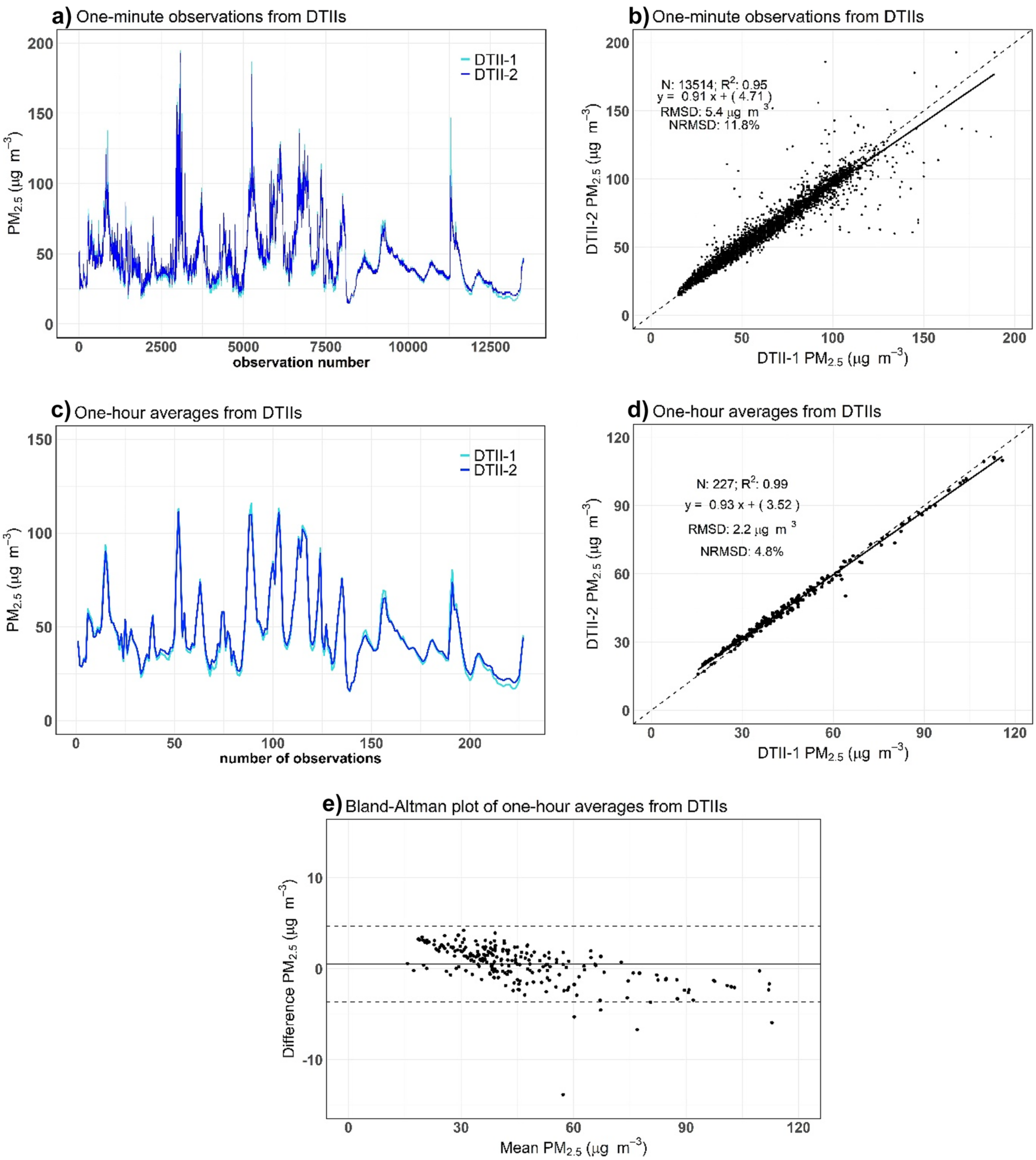


Fig. 2 Intra-model comparison of collocated DustTrak II units based on (**a**) and (**b**) 1-min observations and (**c**), (**d**), and (**e**) 1-h averages. These plots indicate good agreement (high precision and low bias) and exhibit better agreement for hourly averages than for 1-min observations

of 46.0 and 45.5 μg m^{-3} for DTII-1 and DTII-2, respectively, and 29.8 and 38.4 μg m^{-3} for DRX-1 and DRX-2, respectively, were reported. Intra-model comparison of DTIIs (Fig. 2) revealed that the $PM_{2.5}$ measurements from DTII-1 and DTII-2 were highly precise ($R^2=0.95$). Using the 1-min measurement data, the RMSD between the two $PM_{2.5}$ measurements was found to be 5.4 μg m^{-3}, which is approximately 12% of the mean value. We also averaged the data to estimate the statistics for 1 h (Fig. 2c and d). The intra-model agreement of hourly $PM_{2.5}$ measured by DTIIs was noticeably improved relative to the minute averages: RMSD (for hourly data) was 2.2 μg m^{-3} (5% of the mean) and R^2 was 0.99. In addition, regression coefficients were improved for 1-h-averaged $PM_{2.5}$ (slope closer to unity; intercept closer to zero) relative to minute averages. The Bland–Altman plot showed low bias (mean of difference = 0.5 μg m^{-3}) between the two units. A summary of results is listed in Table 1, and detailed statistical parameters and regression coefficients are listed in Table 2.

The intra-model comparison of DRXs (Fig. 3) shows a surprising bias: $PM_{2.5}$ measurements from DRX-2 were consistently higher than those from DRX-1, with an RMSD of ~ 9.1 μg m^{-3} and NRMSD of ~ 27%. The RMSD did not improve with 1-h averaging (Table 1). The Bland–Altman plot (Fig. 3c) also revealed a high bias (8.6 μg m^{-3}) between the two units. The linear regression coefficients (Table 2) were comparable for 1-min and 1-h-averaged $PM_{2.5}$. Comparing the five size fractions individually, measurements for all size fractions were higher for DRX-2 than for DRX-1, although the amount of bias between the two units differed by size fraction (see Table 3). The average $PM_{2.5}/PM_{10}$ ratios were 0.73 (DRX-2) and 0.85 (DRX-1).

The inter-model comparison of all four DustTraks (Fig. 4) showed that $PM_{2.5}$ measurements from DTIIs were consistently higher than those from DRXs (Table 1).

Intra-model comparison of $PM_{2.5}$ measured by BAMs (FEM precision testing)

The average values during the study period from the two reference-grade instruments (two units of BAM model 1022) "BAM-1" and "BAM-2" were 18.3 and 19.0 μg m^{-3}, respectively (Table 1). In addition, 1- and 6-h-averaged $PM_{2.5}$ time-series and scatter plots (Fig. 5) revealed that the BAMs agreed well with each other ($R^2=0.81$ and RMSD = 2.6 μg m^{-3}, which is ~ 15% of the mean $PM_{2.5}$). The between-instrument agreement was better for 6-h averaging time than for 1-h averaging time (Fig. 5; Table 2).

Inter-type comparison of $PM_{2.5}$ measured using DTII and BAM (accuracy testing)

Given DTII units were more precise than DRX (Figs. 2 and 3; Table 1), we used the former for inter-type comparisons. Specifically, DTII-1 and BAM-1 were collocated (on the building terrace; see site description above). Consistent with the literature, the time-series and scatter plots for both time-averages (1 h and 6 h) showed that DTII overestimated ambient $PM_{2.5}$ (Fig. 6, Table 2).

To compensate for the aerosol hygroscopic-growth-related overestimation by DTII, we applied RH correction factors to DTII-measured $PM_{2.5}$. Ambient RH measurements from BAM1022 were used to derive the RH correction factors following the procedure reported by Chakrabarti et al. (2004). After applying the RH correction, RMSE between $PM_{2.5}$ measurements from BAM and DTII was improved by ~ 54% (13.1 μg m^{-3}; Table 2). The RMSE further improved (4.8 μg m^{-3}) after applying BAM correction.

Table 1 Summary of intra-model and inter-type comparisons

	RMSD μg m^{-3} (NRMSD)	RMSE μg m^{-3} (NRMSE)	Average $PM_{2.5}$ concentration μg m^{-3}
DTII	One-hour: 2.2 (5%) One-minute: 5.4 (12%)	One-hour: 28.9 (165%)	45.7
DRX	One-hour: 9.1 (27%) One-minute: 9.3 (27%)	Not performed	34.1
BAM	One-hour: 2.6 (15%) Six-hour: 1.3 (8%)	Not applicable	17.5

Table 2 Statistics quantifying the bias in $PM_{2.5}$ measurements from various instruments

		One-hour average						One-minute observations					
		N	R^2	Slope	Intercept	RMSD/E* μg m^{-3}	NRMSD/E*	N	R^2	Slope	Intercept	RMSD/E* μg m^{-3}	NRMSD/E*
DTII	DTII-1 vs. DTII-2	227	0.99	0.93	3.52	2.2	5%	13,514	0.95	0.91	4.71	5.4	12%
DRX	DRX-1 vs. DRX-2	228	0.97	1.11	5.41	9.1	27%	13,575	0.96	0.88	−4.13	9.3	27%
DRX vs. DTII	DRX-1 vs. DTII-1	227	0.96	1.54	−0.26	17.6	44%	13,514	0.92	1.50	0.78	18.6	46%
	DRX-1 vs. DTII-2	227	0.96	1.44	3.15	17.7	44%	13,514	0.89	1.38	4.97	18.6	47%
	DRX-2 vs. DTII-1	227	0.93	1.34	−5.93	10.2	25%	13,514	0.90	1.34	−5.92	11.6	29%
	DRX-2 vs. DTII-2	227	0.94	1.26	−2.36	9.8	24%	13,514	0.87	1.23	−1.27	11.5	28%
BAM	BAM-2 vs. BAM-1	1582	0.81	0.88	2.19	2.6	15%	Six-hour average					
								280	0.91	0.93	1.35	1.35	8%
Sensitivity analysis for DTII vs. BAM	DTII-1 vs. BAM-1	290	0.35	0.21	8.36	28.9	165%	55	0.53	0.25	6.86	27.9	157%
	DTII-1_RH vs. BAM-1	290	0.23	0.24	11.19	13.1	74%	55	0.31	0.24	11.19	12.2	68%

N represents the number of available data points for comparison. For deriving linear regression coefficients, $PM_{2.5}$ from the first instrument was considered a dependent variable and that from the second instrument was considered an independent variable. *Terminology: RMSD is used to compare instruments of the same type. RMSE is used to compare instruments of different types among which one is a reference. Both are expressed in μg m^{-3}

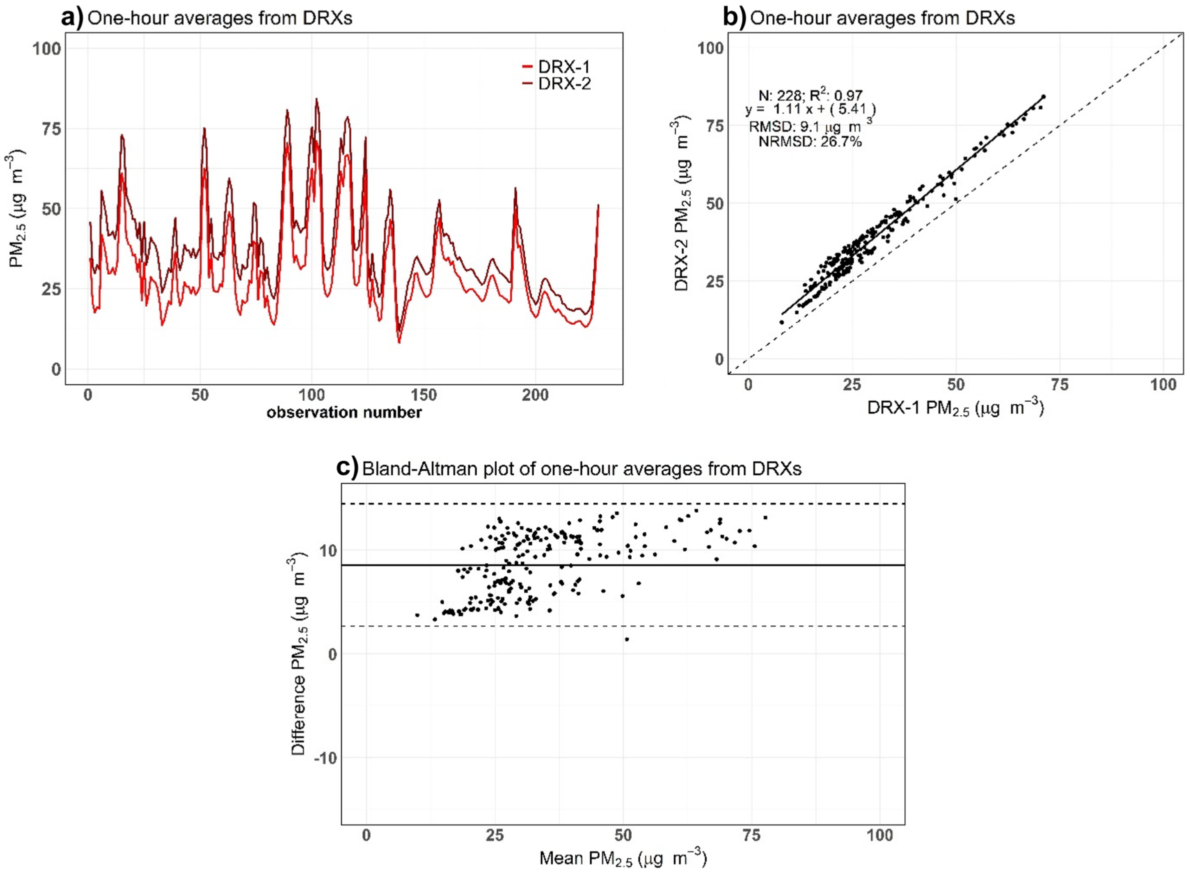


Fig. 3 Intra-model comparison of collocated DustTrak DRX units for (**a**), (**b**), and (**c**) 1-h-averaged $PM_{2.5}$ concentrations. These plots indicate moderate bias between the two units (higher measurements for DRX-2 than for DRX-1)

Diffusion dryer experiments

We controlled the RH of the DustTrak sample flow using a diffusion dryer. We used two Omega RH sensors to measure the sample flow RH upstream and downstream of the dryer. On average, the dryer reduced the RH of the sample flow by 78% (~55 percentage units, from an average RH of ~70% at the inlet to ~15% at the outlet). Figure 7 shows a comparison of measurements from DTIIs with and without the dryer along with collocated BAM data. We found that even after attaching the dryer, which should minimize the effect of humidity, DTII continues to report biased values compared with BAM. The methodology

Table 3 Statistics quantifying the precision of measurements from DustTrak DRX for PM_1, PM_4, PM_{10}, and total PM

DRX-1 vs. DRX-2	One-hour average						One-minute observations					
	N	R^2	Slope	Intercept	RMSD µg m^{-3}	NRMSD	N	R^2	Slope	Intercept	RMSD µg m^{-3}	NRMSD
PM_1	228	0.96	0.84	−3.71	10.4	31%	13,575	0.95	0.85	−4.05	10.6	32%
PM_4	228	0.98	0.91	−3.81	7.9	21%	13,575	0.96	0.91	−3.81	8.2	22%
PM_{10}	228	0.98	1.00	−4.1	5.1	11%	13,575	0.96	0.99	−3.96	6.1	14%
Total PM	228	0.99	1.01	−3.02	6.26	9%	13,575	0.86	0.92	3.66	24.9	34%

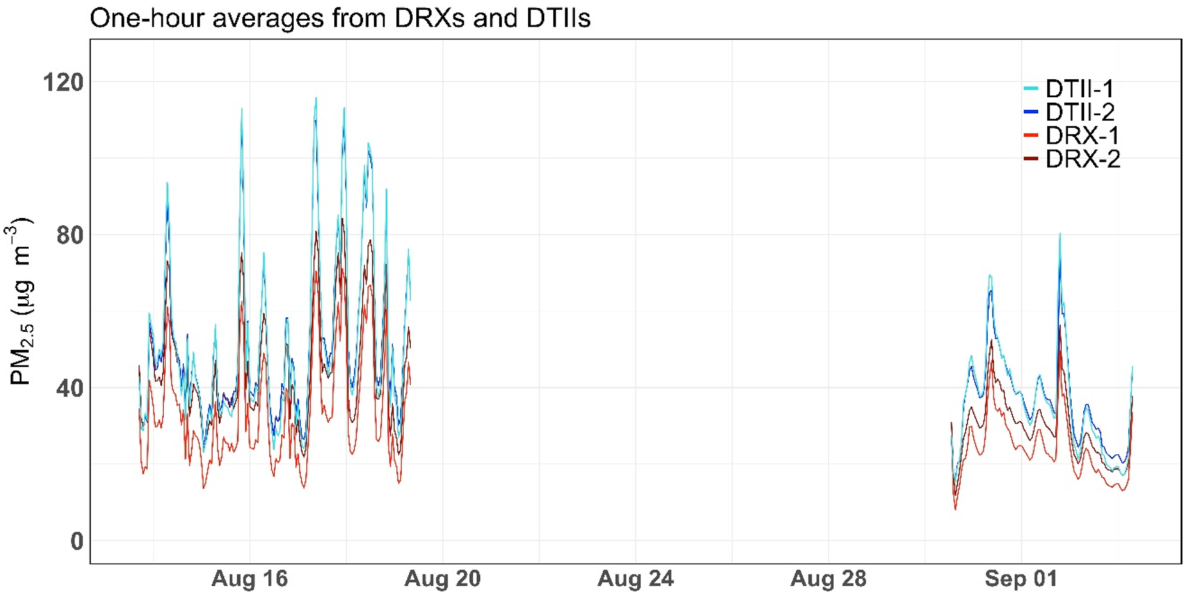


Fig. 4 Inter-model comparison of DustTraks. The panel shows the time-series plots of 1-h-averaged $PM_{2.5}$ values from the four collocated DustTraks (two DustTrak II and two DustTrak DRX). Measurements from DTIIs were consistently higher than those from DRXs. These results (similar to those shown in Figs. 2 and 3) indicate that DTII-1 and DTII-2 agree reasonably well; however, the readings are higher for DRX-2 compared to DRX-1

by Chakrabarti et al. (2004) seemed to overcompensate for RH, decreasing the bias further. Specifically, RMSD (NRMSD) between untreated $PM_{2.5}$ and Chakrabarti et al. corrected $PM_{2.5}$ was ~ 44.1 µg m^{-3} (~ 68%). RMSD (NRMSD) between diffusion-dried $PM_{2.5}$ and Chakrabarti et al. corrected $PM_{2.5}$ was ~ 32.8 µg m^{-3} (~ 50%). The regression results in Fig. 8 indicate a poor correlation between DTIIs with and without the dryer ($R^2 = 0.41$).

Discussion

In this study, we observed that the $PM_{2.5}$ measurements from DRX exhibited bias when compared with other DRX and DTII units. The reasons for the observed discrepancies are largely unknown and need further exploration. One possible reason for the observed bias between $PM_{2.5}$ measurements from DTII and DRX can be the difference in the size separation mechanism. DTII distinguishes size based on the inertial impaction (using an external impactor assembly), whereas DRX segregates size based on optical pulse height measurements. Previous studies by Rivas et al. (2017) and Viana et al. (2015) have reported artifact jumps in $PM_{2.5}$ values (from few µg m^{-3} to hundreds of µg m^{-3}) measured in DRX units. Our results, in conjunction with the existing literature, also indicate lower precision and reproducibility for DRX than for DTII.

We further explored two methods for humidity correction by collocating two DTIIs (with and without a diffusion dryer). The former method uses a diffuser dryer (an experimental method) to control the RH of the ambient air sample fed to the DTII. The latter (DTII without the dryer) method applies a literature-based RH correction algorithm to the raw $PM_{2.5}$ observations (a post hoc mathematical correction) made by the DTII. The use of a diffusion dryer allowed us to lower the RH of the sample air and thus experimentally verify the literature-derived correction method (which aims to correct for the effect of RH mathematically). As observed from the time series data (Fig. 8), the latter method seemed to overcorrect for humidity.

In the current study location (Bengaluru), we locally derived a linear equation to explain the relationship between RH-corrected DTII and BAM-measured $PM_{2.5}$ (local calibration). Table 2 and Fig. 6 present the equation/regression coefficients. A similar

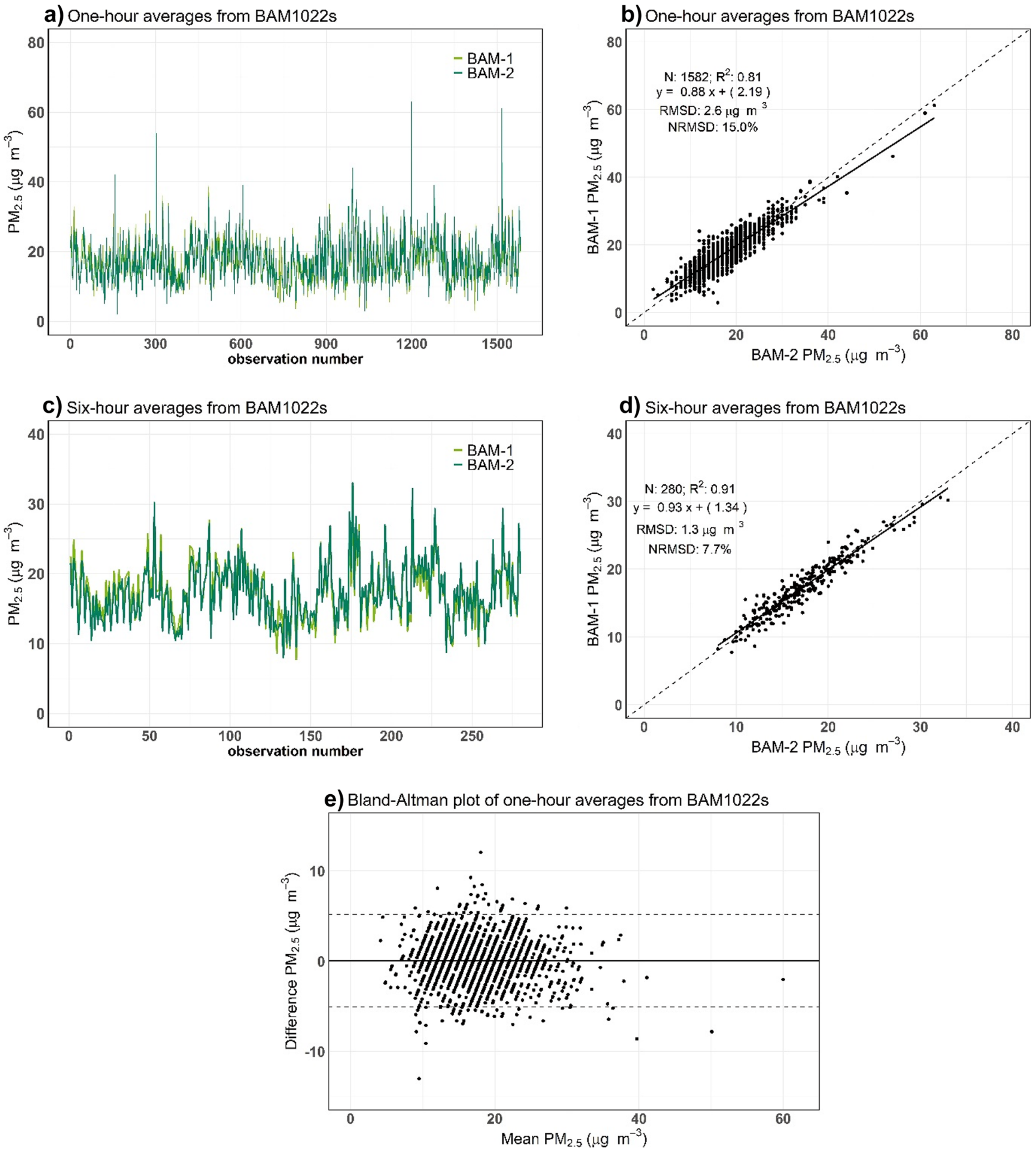


Fig. 5 Intra-model comparison of collocated beta attenuation monitors (BAMs) for (**a**), (**b**), and (**e**) 1-h averages and (**c**) and (**d**) 6-h averages. These plots indicate good agreement (high precision and low bias) and exhibit better agreement for 6-h averages than for 1-h readings

linear calibration equation has been reported (Kumar et al., 2018) and employed (Sanchez et al., 2018) for a study in rural Hyderabad, India. In contrast, in an earlier study in Delhi, India, Apte et al. (2011) derived a power law relationship between RH-corrected $PM_{2.5}$ measured using DustTrak (model 8520, which is an older model) and gravimetric method-estimated $PM_{2.5}$. In a study by Both et al. (2011), this power

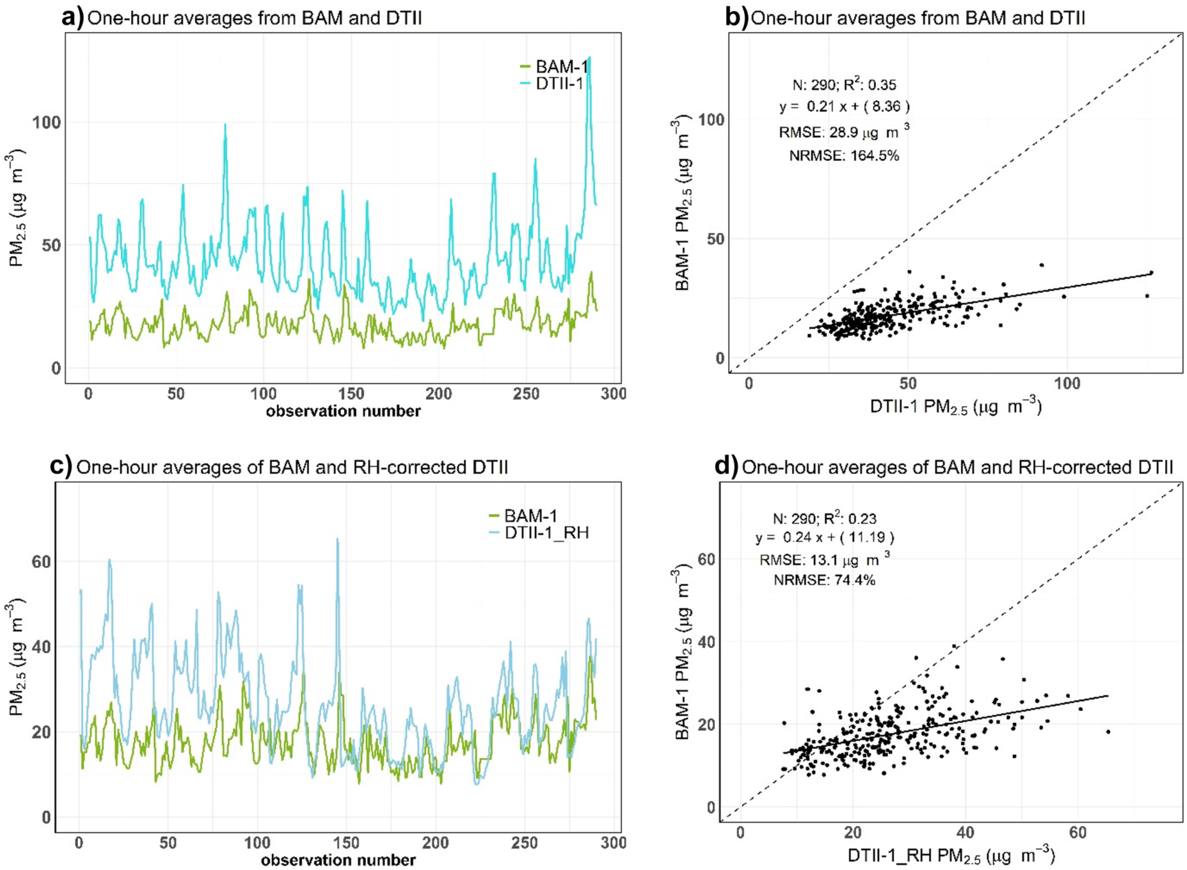


Fig. 6 Inter-type comparison. Panels **a** and **b** show a comparison of dry $PM_{2.5}$ measured using beta attenuation monitor (BAM) and $PM_{2.5}$ measured using DTII at ambient relative humidity. Panels **c** and **d** show a comparison of dry $PM_{2.5}$ measured using BAMs and relative-humidity-corrected $PM_{2.5}$ measured using DTII. The latter consistently overestimates $PM_{2.5}$ compared with BAM. Relative humidity correction of DTII values improves the root mean square error (RMSE) considerably

law relationship has been applied to RH-corrected DustTrak observations in Bengaluru, India. In a more recent study by Goel et al. (2015) in Delhi, a power law relationship between RH-corrected DRX $PM_{2.5}$ and gravimetric $PM_{2.5}$ has been reported. Overall, global studies indicate that RH-corrected $PM_{2.5}$ measurements from DT-8520 are 2–3 times higher than reference measurements. This number has been observed to be in the range 1.4–2.2 when DTII is used to measure $PM_{2.5}$ emitted from wood stove burning (Rivas et al., 2017). In summary, the local calibration equations varied (i) in their form (e.g., linear or power law), (ii) in their regression coefficients, (iii) with DustTrak model, (iv) with emission source, and (v) with location. In a recent study, Hagan and Kroll (2020) developed a physics-based evaluation framework to assess the accuracy of the optical particle sensors by estimating the error in particle mass loading for given variations in RH, aerosol optical properties, and particle size distribution. In addition to the above-discussed sensitivities, light scattering-based low-cost particulate matter sensors suffer from non-adherence of the particle size detection ranges declared by the manufacturers (Kuula et al., 2020).

In interpreting the results of this study, some limitations should be considered. First, no seasonality was considered while aggregating the data for constructing the linear models. Second, the experiments were non-simultaneous in nature (i.e., all intercomparisons reflected simultaneous measurements, but the various intercomparisons occurred at different times). Third, the TSI dryer may produce dust (from

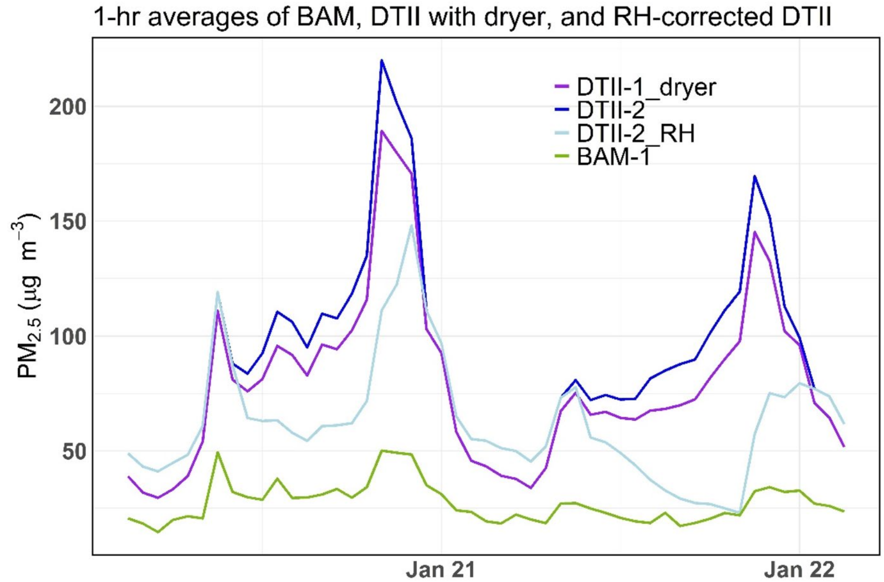


Fig. 7 Comparison of different methods of humidity correction: using a dryer vs. applying a literature-derived equation. DTII-1_dryer: DustTrak with a dryer assembly, DTII-2: DustTrak without a dryer, and DTII-2_RH: DustTrak (without a dryer) and measurements corrected for RH using a literature-derived equation. Although both methods reduced the bias, a dryer-connected DTII reports higher biased values compared with the literature-derived equation method

the silica beads) when subjected to vibration, which could lead to DTII measurement artifacts.

Overall, we found that optical devices are generally highly correlated with each other, and at an hourly resolution, they exhibit good unit-to-unit agreement, indicating good precision (R^2 values = 0.97–0.99; NRMSD = ~ 5–27%); however, without local calibration, they tend to be strongly biased relative to the reference-grade devices. In contrast, BAM is accurate but not quite as precise. The question remains as to what qualifies as "local," and how such calibrations vary with different microenvironments (and in general across time and space), warranting further studies. Using a dense network of low-cost optical $PM_{2.5}$ sensor data, Chu et al. (2020) demonstrated the effectiveness of the spatial calibration approach against global calibration in improving the accuracy of optical $PM_{2.5}$.

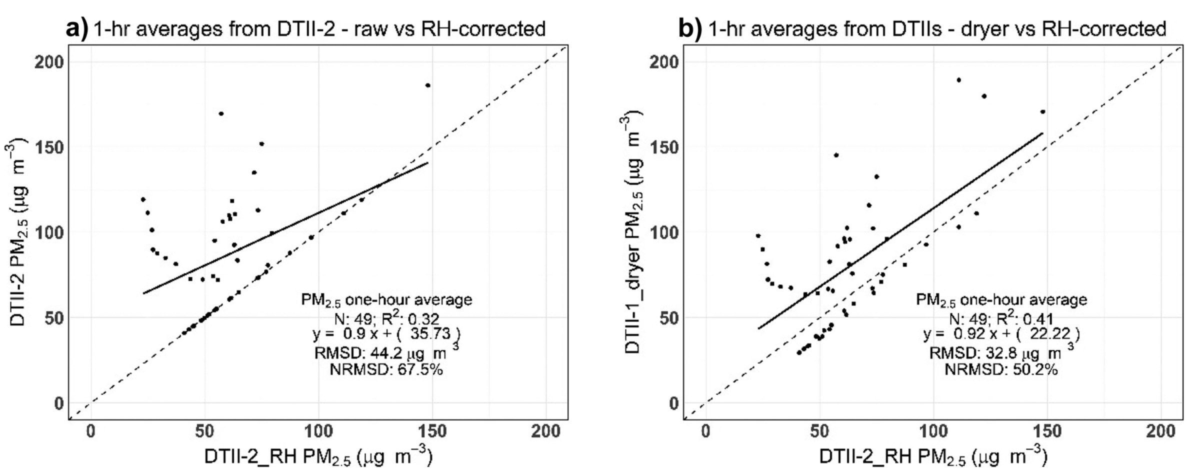


Fig. 8 Correlation plots of 1-h-averaged $PM_{2.5}$ values from DTII units (with and without a dryer). DTII-2: DustTrak without a dryer, DTII-2_RH: DustTrak (without a dryer) measurements corrected for RH using an analytical equation available in the literature, and DTII-1_dryer: DustTrak with a dryer assembly. RH_corrected values correlate poorly with raw DTII values (panel **a**) and with dryer-connected-DTII values (panel **b**)

Conclusions

We presented a comparison of $PM_{2.5}$ measurements obtained using both optical and reference-grade instruments. We collocated two-reference grade and four optical $PM_{2.5}$ instruments. $PM_{2.5}$ measurements obtained from DustTrak DRX were consistently lower than those obtained from the DustTrak II model (RMSD = 9.8 μg m^{-3}–17.7 μg m^{-3}). The within-model $PM_{2.5}$ difference was higher for the paired DustTrak DRX (RMSD = 9.1 μg m^{-3}) than for the paired DustTrak TII model (RMSD = 2.2 μg m^{-3}). Although optical instruments are highly precise, they are strongly biased when compared with reference-grade instruments. In view of these results, it is highly recommended that optical non-reference-grade instruments be locally calibrated (in addition to factory calibration) to account for local aerosol properties. In addition, we explored different approaches to humidity correction and found that the literature-derived correction methods may overcorrect for humidity, thus indicating a potential limitation of this method. Hence, care should be taken to avoid adopting literature-based calibration coefficients without local verification.

Funding VS is grateful to the MacArthur Foundation for providing financial support to the Center for Study of Science, Technology and Policy for conducting air-pollution studies in Bengaluru, Karnataka.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

Apte, J. S., Kirchstetter, T. W., Reich, A. H., Deshpande, S. J., Kaushik, G., Chel, A., & Nazaroff, W. W. (2011). Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. *Atmospheric Environment, 45*(26), 4470–4480. https://doi.org/10.1016/j.atmosenv.2011.05.028

Both, A. F., Balakrishnan, A., Joseph, B., & Marshall, J. D. (2011). Spatiotemporal aspects of real-time PM2. 5: Low-and middle-income neighborhoods in Bangalore, India. *Environmental Science & Technology, 45(13)*, 5629–5636. https://doi.org/10.1021/es104331w

Chakrabarti, B., Fine, P. M., Delfino, R., & Sioutas, C. (2004). Performance evaluation of the active-flow personal DataRAM PM2. 5 mass monitor (Thermo Anderson pDR-1200) designed for continuous personal exposure measurements. *Atmospheric Environment, 38(20),* 3329–3340. https://doi.org/10.1016/j.atmosenv.2004.03.007

Chu, H. J., Ali, M. Z., & He, Y. C. (2020). Spatial calibration and $PM_{2.5}$ mapping of low-cost air quality sensors. *Scientific Reports, 10(1)*, 1–11. https://doi.org/10.1038/s41598-020-79064-w

Chung, A., Chang, D. P., Kleeman, M. J., Perry, K. D., Cahill, T. A., Dutcher, D., & Stroud, K. (2001). Comparison of real-time instruments used to monitor airborne particulate matter. *Journal of the Air & Waste Management Association, 51*(1), 109–112. https://doi.org/10.1080/10473289.2001.10464254

Goel, R., Gani, S., Guttikunda, S. K., Wilson, D., & Tiwari, G. (2015). On-road $PM_{2.5}$ pollution exposure in multiple transport microenvironments in Delhi. *Atmospheric Environment, 123*, 129–138. https://doi.org/10.1016/j.atmosenv.2015.10.037

Guttikunda, S. K., Nishadh, K. A., Gota, S., Singh, P., Chanda, A., Jawahar, P., & Asundi, J. (2019). Air quality, emissions, and source contributions analysis for the Greater Bengaluru region of India. *Atmospheric Pollution Research, 10*(3), 941–953. https://doi.org/10.1016/j.apr.2019.01.002

Hagan, D. H., & Kroll, J. H. (2020). Assessing the accuracy of low-cost optical particle sensors using a physics-based approach. *Atmospheric Measurement Techniques, 13*(11), 6343–6355. https://doi.org/10.5194/amt-13-6343-2020

Health Effects Institute (HEI). (2020). *State of Global Air 2020*. Special Report.

Hinds, W. C. (1999). *Aerosol technology: Properties, behavior, and measurement of airborne particles*. John Wiley & Sons.

Holstius, D. M., Pillarisetti, A., Smith, K. R., & Seto, E. J. A. M. T. (2014). Field calibrations of a low-cost aerosol sensor at a regulatory monitoring site in California. *Atmospheric Measurement Techniques, 7*(4), 1121–1131. https://doi.org/10.5194/amt-7-1121-2014

Jayaratne, R., Liu, X., Thai, P., Dunbabin, M., & Morawska, L. (2018). The influence of humidity on the performance of a low-cost air particle mass sensor and the effect of atmospheric fog. *Atmospheric Measurement Techniques, 11*(8), 4883–4890. https://doi.org/10.5194/amt-11-4883-2018

Kim, J. Y., Magari, S. R., Herrick, R. F., Smith, T. J., Christiani, D. C., & Christiani, D. C. (2004). Comparison of fine particle measurements from a direct-reading instrument and a gravimetric sampling method. *Journal of Occupational and Environmental Hygiene, 1*(11), 707–715. https://doi.org/10.1080/15459620490515833

Kingham, S., Durand, M., Aberkane, T., Harrison, J., Wilson, J. G., & Epton, M. (2006). Winter comparison of TEOM, MiniVol and DustTrak PM10 monitors in a woodsmoke environment. *Atmospheric Environment, 40*(2), 338–347. https://doi.org/10.1016/j.atmosenv.2005.09.042

Kumar, M. K., Sreekanth, V., Salmon, M., Tonne, C., & Marshall, J. D. (2018). Use of spatiotemporal characteristics of ambient

$PM_{2.5}$ in rural South India to infer local versus regional contributions. *Environmental Pollution, 239*, 803–811. https://doi.org/10.1016/j.envpol.2018.04.057

Kuula, J., Mäkelä, T., Aurela, M., Teinilä, K., Varjonen, S., González, Ó., & Timonen, H. (2020). Laboratory evaluation of particle-size selectivity of optical low-cost particulate matter sensors. *Atmospheric Measurement Techniques, 13*(5), 2413–2423. https://doi.org/10.5194/amt-13-413-2020

McNamara, M. L., Noonan, C. W., & Ward, T. J. (2011). Correction factor for continuous monitoring of wood smoke fine particulate matter. *Aerosol and Air Quality Research, 11*(3), 315. https://doi.org/10.4209/aaqr.2010.08.0072

Moosmüller, H., Arnott, W. P., Rogers, C. F., Bowen, J. L., Gillies, J. A., Pierson, W. R., & Norbeck, J. M. (2001). Time resolved characterization of diesel particulate emissions. 1. Instruments for particle mass measurements. *Environmental Science & Technology*, *35*(4), 781–787. https://doi.org/10.1021/es0013935

Noble, C. A., Vanderpool, R. W., Peters, T. M., McElroy, F. F., Gemmill, D. B., & Wiener, R. W. (2001). Federal reference and equivalent methods for measuring fine particulate matter. *Aerosol Science & Technology, 34*(5), 457–464. https://doi.org/10.1080/02786820121582

Rivas, I., Mazaheri, M., Viana, M., Moreno, T., Clifford, S., He, C., & Querol, X. (2017). Identification of technical problems affecting performance of DustTrak DRX aerosol monitors. *Science of the Total Environment, 584*, 849–855. https://doi.org/10.1016/j.scitotenv.2017.01.129

Sanchez, M., Ambros, A., Milà, C., Salmon, M., Balakrishnan, K., Sambandam, S., & Tonne, C. (2018). Development of land-use regression models for fine particles and black carbon in peri-urban South India. *Science of the Total Environment, 634*, 77–86. https://doi.org/10.1016/j.scitotenv.2018.03.308

Viana, M., Rivas, I., Reche, C., Fonseca, A. S., Pérez, N., Querol, X., & Sunyer, J. (2015). Field comparison of portable and stationary instruments for outdoor urban air exposure assessments. *Atmospheric Environment, 123*, 220–228. https://doi.org/10.1016/j.atmosenv.2015.10.076

Wang, X., Chancellor, G., Evenstad, J., Farnsworth, J. E., Hase, A., Olson, G. M., & Agarwal, J. K. (2009). A novel optical instrument for estimating size segregated aerosol mass concentration in real time. *Aerosol Science and Technology, 43*(9), 939–950. https://doi.org/10.1080/02786820903045141

Yanosky, J. D., Williams, P. L., & MacIntosh, D. L. (2002). A comparison of two direct-reading aerosol monitors with the federal reference method for $PM_{2.5}$ in indoor air. *Atmospheric Environment, 36(1)*, 107–113. https://doi.org/10.1016/S1352-2310(01)00422-8

Zhu, Y., Smith, T. J., Davis, M. E., Levy, J. I., Herrick, R., & Jiang, H. (2011). Comparing gravimetric and real-time sampling of $PM_{2.5}$ concentrations inside truck cabins. *Journal of occupational and Environmental Hygiene, 8(11)*, 662–672. https://doi.org/10.1080/15459624.2011.617234