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Assessing the benefit of sample drying for AE33 aethalometers: evidence from long-term field observations

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Abstract. Aethalometers measuring equivalent black carbon (eBC) are widely used in both research and regulatory air quality monitoring networks. However, uncertainties regarding the influence of moisture in eBC measurements persist. While many networks recommend or require sample drying, there is limited long-term field evidence quantifying the benefits of humidity control for aethalometers operated under real-world conditions. Here we present a multi-year field intercomparison of aethalometers (AE33, Aerosol Magee Scientific) operated with and without sample drying at an urban background site in Sydney, Australia. Three extended tests (December 2015 – August 2016, November 2016 – June 2017, January 2018 – March 2019) were conducted using four instruments in total. Instruments were co-located within the same climate-controlled enclosure and configured identically, differing only in sample humidity conditioning (membrane dryer). Across all tests, wavelengths and averaging periods, strong agreement was observed between dried and non-dried instruments, with correlation coefficients (R^2) consistently exceeding 0.98. For the 880 nm channel, regression slopes for non-dried vs dried sampling ranged from 0.97 – 1.07 across the three tests. Similar results were obtained for 1-, 2-, 5-, and 10-minute averages, although variability increased at shorter averaging intervals. Stratification by ambient relative humidity, dew-point temperature, and dew-point deficit showed no systematic degradation in agreement between hourly data at high humidity, and moisture-related effects were small compared with test-to-test variability. These results indicate that, for hourly eBC measurements in a temperate, high-humidity coastal environment, the absence of sample drying introduces only small differences in measured concentrations when compared with humidity-controlled sampling. While short-term variability and instrument-specific effects remain important considerations, these results suggest that long-term, network-scale eBC measurements from AE33 aethalometers can remain highly comparable even without sample drying. This study provides quantitative evidence to inform guidance on humidity control for aethalometers in monitoring networks.

1 Introduction

Black carbon (BC) is the light-absorbing fraction of aerosol produced by the incomplete combustion of carbonaceous materials including fossil fuels (oil, coal, gas), and biofuels (biomass, biogas, etc.). BC exerts notable impacts on human health and the global climate. BC is a component of PM2.5 pollution and can impact cardiovascular mortality and morbidity impacting human health through both short-term and long-term exposures, leading to increased respiratory and

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cardiovascular disease, and increased hospitalization and mortality (Janssen et al., 2011; Song et al., 2022; Tang et al., 2024). Climate impacts from BC occur through direct absorption of solar radiation and interactions with clouds and snow/ice surfaces (Bond et al., 2013; Tucclla et al., 2021; Li et al., 2023; Gustafsson et al., 2026). Mitigating BC emissions would deliver benefits to the climate and substantial co-benefits for air quality and public health worldwide through reduced mortality (Anenberg et al., 2012; Moutet et al., 2025)

BC has been used as a common term for carbonaceous aerosols however the literature distinguishes BC measurements using naming that reflects specific BC measurement techniques. Elemental carbon (EC) refers to the measurement of BC using thermal-optical methods, refractory BC (rBC) refers to BC measurements from laser-induced incandescence and equivalent black carbon (eBC) from optical attenuation such as aethalometry (Hansen et al., 1984; Petzold et al., 2013; Lack et al., 2014). Each BC measurement technique reflects slightly different particle properties due to the variation in measurement techniques and principles. This paper is focussed on aethalometer measurements and hence we use eBC to refer to BC measurements except where the instrument outputs use BC, for example in channel names, i.e. BC1–BC7.

eBC is a proxy for BC mass rather than a distinct chemically or physically unique species. eBC measurements are becoming more common with the benefit of continuous unattended operation of aethalometers and increased temporal resolution of measurements compared to thermal-optical techniques, delivering significantly more data on carbonaceous aerosols in more locations. Aethalometers measure eBC mass concentrations by converting filter-based light attenuation to mass using an assumed mass absorption cross-section (MAC) and/or calibration against collocated EC measurements. Continuous multi-wavelength absorption measurements enable estimates of eBC source characterization, using the wavelength dependence of absorption to apportion eBC between traffic and biomass burning sources with the “aethalometer model” (Sandradewi et al., 2008; Grange et al., 2016). eBC is a widely used, practical monitoring metric but eBC measurements must acknowledge instrument settings, calibration choices, and the distinctions between EC, eBC, and rBC as recommended in various reviews (Petzold et al., 2013; Zhang et al., 2020).

Aethalometer measurements of eBC can be affected by major uncertainties due to the principles of measurement and variations in sampling system design. For example, the multiple-scattering correction factor (C) and the assumed MAC used to convert filter attenuation to mass, can both vary with filter tape type and particle optical properties, leading to site-dependent biases in eBC (Zhao et al., 2020; Miyakawa et al., 2020; Yus-Díez et al., 2021; Yus-Díez et al., 2025). Earlier aethalometer instruments sometimes presented filter loadings artifacts (Weingartner et al., 2003; Massey et al., 2020). While newer instruments such as the AE33 (Aerosol Magee Scientific, Slovenia) use dual-spot loading compensation to reduce filter-loading effects (Drinovec et al., 2015), the correction relies on an aerosol-dependent loading compensation parameter (k). Changes in mixing state or composition can still propagate into eBC uncertainty (Wu et al., 2024), but recently Ferrero et al. (2024) suggest that uncertainties could be reduced by dynamically determining C from the loading compensation data.

Sampling system design can also introduce measurement uncertainty in filter-based absorption photometers/aethalometers due to particle size selection and sample conditioning (or lack thereof). Particle size affects how aerosols penetrate and scatter within the filter, potentially altering the C and MAC factors, such that eBC can be over- or under-estimated depending on the size distribution and mixing state of the deposited particles (Renzi et al., 2025). High ambient relative humidity (RH) enhances aerosol scattering and alters the instrument's multiple-scattering correction factor, leading to overestimation of absorption coefficients unless properly accounted for (Düsing et al., 2019). Humidity artifacts can be enhanced in high-humidity environments such as the tropics and sub-tropics, especially when ambient dew point temperatures are above the temperatures typically set inside temperature-controlled monitoring buildings/sheds/enclosures. In high humidity situations, condensation can form in sample lines and flood the sample, adhere to filter media or lead to hygroscopic particle growth, affecting attenuation and introducing transient artifacts (Vecchi et al., 2013; Lack et al., 2014). However, Düsing et al. (2019) note that the humidity "effect might not be relevant for averaging periods longer than 5 min".

1.1 Monitoring guidance for aethalometers

To reduce uncertainties in eBC measurements from aethalometers and support consistent measurement and quantification of eBC across multiple networks and regions, approaches to measurement standardisation have commenced. For aethalometers this includes recommendations and guidance on instrument configuration (e.g. tape media, time resolution, MAC/C calculations, etc.), sampling design (particle size selection, humidity control) and data reporting. In relation to humidity control, recommendations vary between networks. For example, Global Atmospheric Watch (GAW) aerosol sampling guidelines require sample air to be dried by diffusion or membrane driers to maintain sample RH < 40% (Wiedensohler et al., 2013; Wiedensohler and Birmili n.d.). Guidance from the pan-European Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS), the USA's National Oceanographic and Atmospheric Administration (NOAA) and the European RI-Urbans follow the GAW recommendations (NOAA, 2016; Müller & Fiebig, 2021; ACTRIS, 2024; RI-URBANS, 2024). The USA Environmental Protection Agency (USEPA) recommends using a membrane dryer in high humidity environments but does not define what a high-humidity environment is (USEPA, 2024), while state-based monitoring networks in the USA such as Colorado (Colorado Department of Public Health and Environment, 2022) and Washington (Washington State Department of Ecology, 2024) make no requirements for sample drying. The UK Black Carbon Monitoring Network does not provide guidance or requirements on sample drying, and similarly some jurisdictions with well-established and long operating air quality monitoring networks (e.g. Canada, China, Japan, New Zealand, Australia) provide no guidance on eBC monitoring requirements. Recommendations on humidity control for aethalometers continues to evolve and their application across different networks and regions continues to vary. Until there is harmonisation of measurement guidance for aethalometers like the AE33 there will likely continue to be measurements undertaken in networks both with and without sample humidity control.

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1.2 Aethalometer intercomparisons

While the physical underpinnings of recommending sample drying for aethalometers such as the AE33 are sound, that is rapid humidity changes can cause water uptake in filters and hygroscopic growth of particles, perturbing light attenuation and absorption signals, particularly at short sampling intervals, we are unaware of any long-term field intercomparisons that have quantified these impacts for hourly data. Of the studies that have investigated humidity effects on aethalometer measurements, we find few that have specifically compared side-by-side operation of the same instrument make and model operating both with and without humidity control. Many comparison studies between aethalometers do not investigate humidity effects or do not state humidity control in their experimental designs.

Table 1 provides an overview of published Magee aethalometer intercomparisons, some comparing AE33 and AE31 instruments and others multiple AE33 instruments. Bernardoni et al. (2021) compared AE33 and AE31 measurements for source apportionment in Milan during boreal winter 2017/18 but do not state if the samples streams for each instrument were dried or not. Rajesh and Ramachandran (2018) compared AE33 and AE31 instruments in Ahmedabad, India for 6-months in 2014, and while samples were drawn from a common manifold they did not report on any humidity handling on the manifold. Asmi et al. (2021) compared hourly averaged results from an AE33 and AE31 co-located at Pallas, Finland over a 1-month field campaign in June – July 2019. Both instruments had some drying applied, the AE33 sampled through a PM10 inlet with inline membrane drier and the AE31 through a "slightly heated" TSP inlet. Ferrero et al. (2021) compared AE33 and AE31 instruments in an investigation of light absorbing aerosol heating rate during four weeks in January – February 2018 in Milan, Italy, where although not explicitly stated, it appears that both instruments included dryers in their sampling. In a recent comparison between AE33 and AE31 aethalometers in Guangzhou, China (Wu et. al., 2024), both instruments used Nafion dryers. For published comparisons between AE33 and AE31 instruments, the reported correlation (R^2) and linear slopes between instruments ranged from R^2=0.57–0.98 and slopes from 0.78–1.30 (Table 1).

Table 1: Aethalometer intercomparisons

Reference	Period	Instruments	Sampling	Results (880 nm)	Reference and notes
Milan, Italy	16/01/2018–20/02/2018	AE33, AE31	No drying, PM2.5	Slope=1.22–1.27	Bernardoni et al. (2021). slope from 12-h averages (calculated from Tables 3 & 4)
				Slope=1.05, R^2=0.98	Ferrero et al. (2021)
Ahmedabad, India	Jul – Dec 2014	AE33, AE31	No drying, TSP	Slope=0.90–1.19, R^2=0.71–0.93 (5-min)	Rajesh and Ramachandran (2018)
				Slope=0.78–1.30,	

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				R^2=0.81–0.97 (1-hour)	
Pallas, Finland	19/06/2019–17/07/2019	AE33, AE31	Dryer (<40%), AE31 (TSP), AE33 (PM10),	Slope=1.5, R^2=0.57	Asmi et al. (2021). Slope and R^2 calculated from MAAP comparison data
Guangzhou, China	1/04/2021 31/03/2022	AE33, AE31	Nafion dryer, PM2.5	Slope=1.20, R^2=0.96	Wu et. al. (2024)
Leipzig, Germany	18/02/2013 – 22/02/2013	AE33 x3	No SSI, dried with silica	Slope=0.96-1.03, R^2=0.99-1.00	ACTRIS 2014, reported in Drinovec et. al. (2015) (5-min)
Columbus, OH, USA	28/03/2013 – 07/05/2013	AE33 x2	No drying stated, PM2.5	Slope=1.06-1.07, R^2=0.99	US EPA 2014, reported in Drinovec et. al. (2015) (1-hour)
Klagenfurt, Austria	1/03/2012 – 12/03/2012	AE33 x 2	No drying, no SSI, tape: T60A20,Q250	Not reported	Drinovec et. al. (2015)
Ljubljana, Slovenia	24/08/2013–23/10/2013	AE33 x 3	Inlet and drying not stated	Slope=1.02–1.14, R^2=0.99-1.0	Titos et al. (2015). Comparison time base not stated.
	6/08/2014–12/09/2014	AE33 x 4	1x ambient, 1x dried, 1x denuded, 1x denuded and dried	Not reported	Drinovec et al. (2017). States "k_6 shows a statistically significant difference between all treatments".
Helsinki, Finland	27/12/2016–5/01/2017	AE33 x 2	No drying, PM1	Slope=1.02±0.01, R^2=0.99	Helin et al. (2018). Hourly data comparison.
Beijing, China	20/03 – 24/04/2018 (8060 tape) 15/10 – 19/10/2018 (8050 tape)	AE33 x 2	Dryer (<30%), PM10	Slope=1.08, R^2= 0.99 (8060 tape) Slope=0.95, R^2= 0.87 (8050 tape)	Zhao et al. (2020). Comparison based on 5-min averages.
Leipzig, Germany	14/01/2019–26/01/2019 7/06/2019–21/06/2019	AE33 x 23	Drying not stated, PM10	Slope=0.66-1.17, R^2=0.933–1.0	Cuesta-Mosquera et al. (2021). 1-min data, comparison based on ambient air in test chamber, 2-3 days per test.

A few studies have specifically compared multiple AE33 instruments in field and laboratory settings (Table 1). Titos et al. (2015) compared three AE33 instruments in a test chamber for two days before field deployment in Ljubljana, Slovenia,

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reporting linear regression slopes of 1.02 – 1.14 between instruments, noting that the poorer performing instrument may have been affected by uncertainty in flow calibration. In their report they do not discuss sample humidity conditioning during this comparison nor the time base for the comparison.

Drinovec et al. (2015) report results from several short intercomparisons. They report results from three AE33 instruments at Liepzig, Germany, over a 4-day period as part of an ACTRIS intercomparison with all samples dried via silica-gel diffusion dryer. Comparing 5-minute measurements between instruments they find slopes of 0.96 – 1.03 and R^2 of 0.99 and 1.00. In the same paper they report results from a USA EPA test at Columbus OH, USA, which compared two AE33 instruments over 33 days (US EPA, 2014). This test found correlations between instruments $R^2 = 0.99$ and slope = 1.06, although they do not state if samples were dried or not. Drinovec et al. (2015) also discuss a comparison of two AE33s with different filter tape media at Klagenfurt, Austria over two weeks in March 2012 but do not report inter-instrument precision.

Helin et al. (2018) included a short (10 day) field intercomparison of two AE33 instruments during their sampling campaign in Helsinki, Finland, finding through regression analysis a slope of 1.020±0.005 for hourly averages. Although the instruments sampled through a common inlet (PM1), they do not state if the sample was conditioned for humidity. Zhao et al. (2020) in their comparison of different filter tapes for the AE33, compared two co-located AE33 instruments at a field site in Beijing, China, with common sample inlet that was dried to RH < 30% by Nafion dryer. Comparisons between instruments with the same filter tape were for five weeks (8060 tape) and five days (8050 tape). Comparing 5-min averages and attenuation at 880 nm, they report for 8060 tape, $R^2 = 0.99$ and slope = 1.08, and for 8050 tape $R^2 = 0.87$ and slope = 0.95. A large intercomparison of 23 AE33 aethalometers in Leipzig, Germany (Cuesta-Mosquera et al., 2021) compared short periods (several hours) of 1-minute average ambient air measurements under laboratory conditions finding variations in slope between candidate and control instruments of 0.66–1.17.

Drinovec et al. (2017) in their study investigating the effect on aethalometer measurements of particle coatings of ambient aerosols operated four AE33 instruments in Ljubljana for 5 weeks in 2014. The comparison included one instrument sampling non-dried (ambient) air and the others sampling dried particles using a variety of drying techniques. They found that there were statistically significant differences between each of the instruments when considering the loading compensation factor at 880 nm (k_6), highlighting the impact that different humidity treatments and particle coatings can have on AE33 measurements, but do not report data from their statistical tests.

1.3 Study motivation and aims

A primary motivation of this study is to provide field test data that can inform directions and guidance for humidity control while monitoring eBC using AE33 aethalometers in regulated monitoring networks. As mentioned above, there already exists some guidance on humidity control for aethalometers, primarily in research grade monitoring networks such as GAW

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and ACTRIS. However, in reviewing the literature we find a lack of real-world field studies and data that quantifies the benefits of dried sampling for AE33 instruments in environments and settings typical of regulated air quality monitoring networks. This is critically important for large, regulated networks, which may operate numerous aethalometers in diverse environments. The capital costs, and operational/maintenance requirements for humidity control on AE33 instruments using for example membrane dryers, can be large if the network does not already employ dried sampling apparatus such as that required for GAW and ACTRIS networks.

We aim to quantify and characterise the variation between eBC measurements from humidity controlled (dry) and non-humidity controlled (ambient) aethalometers in a field setting, in our case a coastal temperate location with high humidity. Our study covers an extended period to assist in considering seasonal dependencies. The results can support the estimation of uncertainties in aethalometer measurements in this region that could be applied more widely to support consistent reporting of eBC measurements. While the focus will be on the impacts of moisture on hourly data, the most reported averaging period for air quality monitoring networks, we will also assess impacts on sub-hourly data.

2 Methods

2.1 Monitoring site

Measurements were conducted in Sydney, Australia at the Chullora air quality monitoring station (AQMS) of the NSW air quality monitoring network (AQMN) (Riley et al., 2019). Located approximately 16 km west of the Sydney Central Business District in the grounds of Chullora TAFE (-33.892°, 151.046°, 32 m.a.s.l.) (Figure 1). The site operated from 2003 – 2022 as the principal AQMS in the region. It provided a platform for measuring a wide range of pollutants and facilitated instrument inter-comparisons and major research projects of the NSW AQMN. Nearby land use is primarily light-industrial, commercial premises, food-manufacturing and distribution, and transport logistics. Applying EU designations, this site would be classified as urban background.

The monitoring site consisted of two insulated, air conditioned, temperature controlled portable buildings (Figure 1) and a 10 m mast for wind measurements. The immediate surrounding was well maintained low-cut grass. Ambient and shed internal temperature and humidity were measured by Vaisala HMP155 (Vaisala Oyj, Finland). The external temperature and humidity instrument was housed in a plate style radiation shield (Vaisala DTR500) with passive airflow at a height of 4 m (the same height as the particle sampling inlets). Internal shed temperature was monitored by HMP155 housed on one of the internal walls of the building away from direct air flow from the air conditioner. We use internal and external measurements to calculate the dew point deficit (DPD) as the difference between the ambient dew point temperature and the internal shed temperature.

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Figure 1: Photograph of the Chullora air quality monitoring station (G. Gunashanhar) and location map (NSW Government).

PM2.5 data is available from a Thermo Scientific 5014i beta attenuation monitor which includes pressure measurements from a calibrated pressure sensor, and oxides of nitrogen measurements from an API T200 chemiluminescence analyser.

2.2 Aethalometer instrument and sampling configuration

AE33 instruments were configured slightly differently between some tests, but the two comparison instruments for each test were always identically configured. Common across all tests were flow rates set to 5 slpm, pressure 1013.25 hPa, temperature to 0°C, tape advance ATNmax = 120 and sample time of 60 seconds. Filter tape 8020 was used for Tests 1 and 2 with tape leakage (z) = 0.07 and multiple-scattering enhancement correction (C_0) = 1.57. For Test 3, 8060 tape was used with z = 0.01 and C_0 = 1.39. Yus-Díez et al. (2021) reported that differences in aethalometer measurements between 8020 and 8060 tapes were within the instrument uncertainty. Data was logged by an external data logger at one-minute and one-hour averaging periods. Time stamps (end of period) were provided by the external data logger ensuring consistency in time stamping between instruments.

Both aethalometers were housed in the same climate controlled portable building. The ambient (i.e. non-Nafion equipped) instrument operated in a standard 600 mm rack mount cabinet with samples drawn from a 25 mm (ID) glass manifold with external inlet height at ~4 m and length of approximately 2.5 m, of which approximately 1.5 m is within the building. Ambient air was continuously drawn through the glass manifold via a blower pump at very high volume (~500 slpm). Sample air is then drawn from the glass manifold by the instrument sample line and pump (5 slpm). The instrument inlet line was approximately 500 mm long (0.635 mm, manufacturer supplied), uninsulated, and with no significant bends in the line between the sample manifold and the instrument. The line included an inline coarse material filter/bug trap. Residence time within the sampling system is estimated at <3 seconds.

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The instrument equipped with a Nafion dryer drew sample via a TSP sample head, and stainless steel inlet through the roof of the building. This sample point was approximately 1.5 m distant from the sample manifold for the ambient instrument. Inlet height was the same as the glass manifold. A short (< 500 mm) line of sample tubing (0.635 mm, manufacturer supplied) connected the stainless steel inlet to the dryer with another of similar length connecting from the dryer to the instrument sample inlet. Internal length of the sampling system was ~1.75 m. Residence time in the sampling system is estimated at ~4 seconds.

2.3 Maintenance and regular checks

Routine scheduled maintenance followed manufacturer recommendations and included monthly checks of the insect screen and cleaning of the sample manifolds, sample lines and the TSP sampling head. Annual maintenance included lubrication of the optical chamber sliders, inspection and cleaning of the optical chamber and replacement of the by-pass cartridge filter. Automated clean air tests occurred weekly. Leak checks for the instrument and the sample inlet were performed monthly and flow verification, light-source and detector stability tests were conducted every three months. Neutral density filter tests and tape alignment checks occurred annually.

2.4 Observation period, data quality and data availability

Instruments selected for the study were drawn from the NSW AQMN instrument pool. The study period ran over three test periods based on instrument availability: 10 December 2015 – 29 August 2016 (Test 1), 18 November 2016 – 15 June 2017 (Test 2), and 12 January 2018 – 20 March 2019 (Test 3) (Table 2). Four instruments were tested in total with two instruments used for multiple tests. Instrument S03-00293 was the ambient instrument for Tests 1 and 2 while instrument S03-00297 was used as the dry instrument for Test 1, and as the ambient instrument for Test 3. The differences in test lengths were due to some instrument issues, but also a need to redeploy instruments when required to meet monitoring needs at other sites in the network. In an ideal situation we would have ensured all instruments were used in set configurations for pre-determined periods of time. Nevertheless, the length of the comparison test substantially exceeds similar intercomparisons reported in the literature. Unfortunately, during our tests we did not compare both instruments sampling either ambient or dried air simultaneously.

Table 2: Instrument test details

Test	Start	End	Ambient S/N	Dry S/N	Tape	C	z
Test 1	10/12/2015	29/08/2016	S03-00293	S03-00297	8020	1.57	0.07
Test 2	18/11/2016	15/06/2017	S03-00293	S05-00462	8020	1.57	0.07
Test 3	13/01/2018	20/03/2019	S03-00297	S05-00465	8060	1.39	0.01

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Data was validated based on standard quality control checks and internal instrument status/alarm flags. Data validation is primarily focussed on hourly data calculated from the 1-min data. A valid hour is returned when at least 75% of the 1-min data are flagged as valid. Similarly, when calculating other averaging periods from the 1-minute data, data were only considered valid if 80% or more of the 1-minute data were valid during the averaging period, that is 8 values for a 10-minute average, and 4 values for a 5-minute average. Averaging is arithmetic not geometric. Instrument and data logger failures led to some periods of missing data, notably from 29/08/2016 – 6/09/206 (communication failure), 10/10/2026 – 18/11/2016 (instrument failure), 14/06/207 – 30/06/2017 (datalogger issue). Data are not available from 15/06/2017 – 12/01/2018 due to a major instrument failure. We return over 20,600 valid hourly data points for comparison.

The 1-hour signal to noise ratio (SNR) is calculated from the 1-minute data as SNR = μ/σ where the signal, μ, is the hourly mean of the 1-minute data, and the noise (σ) is the standard deviation of the 1-minute measurements during that hour. The SNR was used to assist in identifying instrument instability and data outliers and to compare mean noise of the ambient and dried samples.

2.3 Data analysis and statistical comparisons

Comparisons are based primarily on ordinary least squares linear regression (OLS) for hourly and 1-, 2-, 5- and 10-minute time periods. We choose these intervals due to the primary time bases used by the instrument (1-minute) and routine air quality reporting (1-hour), but also to provide results in the context of other aethalometer intercomparisons, for example AE31 comparisons with a 5-minute time base. We report slopes and correlations for the OLS regressions, modelling linear relationships with no offsets. Slope estimates are provided with confidence intervals for $\alpha = 0.05$. Comparisons are made across all tests and all channels (BC1– BC7) with a primary focus on the 880nm channel (BC6). We chose OLS regression over Deming regression to support comparisons of our results with the results of other studies (Table 1). A sensitivity test comparing OLS and Deming regression results for slope and intercept on the hourly data showed slope variation of < 1% and absolute variation in intercepts of less than 0.013 μgm^{-3}.

Diurnal and monthly comparisons are provided to assist with understanding temporal dependence on correlations. To further test for variance under different temperature and moisture conditions we stratify data by ambient temperature (T), relative humidity (RH), ambient dew point (T_d) and dew point deficit ($DPD = T_i - T_d$, where T_i is the internal shed temperature). We then test for variance of OLS regression models across the temporally and moisture stratified data. We analysed the data separately within each period/band for each test (Test 1, Test 2, Test 3) and then tested for differences among the slopes associated with the period/band. Specifically, within each comparison band c, we fit a linear model of the form

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$$y_i = \sum_{g=1}^{G_c} \beta_{gc}\, x_i + \varepsilon_i \tag{1}$$

where y_i denotes the dried sample and x_i denotes ambient sample in the selected band (hour, month, temperature, relative humidity, dew point, dew point deficit), β_{gc} is the regression coefficient (slope), g indexes the G_c band levels present within comparison group c. Inference was restricted to within test comparisons (Test 1, Test 2, Test 3), not between test groups.

Formal comparisons among periods/bands were carried out using Wald tests of linearity of the estimated coefficient vector $\hat{\beta}$ (Wald, 1943) with the Wald statistic computed as

$$W = (R\hat{\beta} - r)^{\top}\left[R\widehat{\mathrm{Var}}(\hat{\beta})R^{\top}\right]^{-1}(R\hat{\beta} - r) \tag{2}$$

which is asymptotically χ_q^2 distributed with $q = \mathrm{rank}(R)$. Pairwise tests between two band levels g and g' within the same comparison band evaluated the null hypothesis $H_0: \beta_{gc} - \beta_{g'c} = 0$.

This linear-hypothesis test is like classical tests of coefficient equality such as the Chow test (Chow, 1960) but we implement it in a form that accommodates heteroscedasticity-robust covariance estimation (MacKinnon and White, 1985). Because variance in regression residuals may differ across groups/bands, typical homoscedastic OLS standard errors were not used for inference. Instead, we estimated the variance–covariance matrix of $\hat{\beta}$ using the HC3 heteroscedasticity-consistent estimator,

$$\hat{V}_{\mathrm{HC3}} = (X^{\top}X)^{-1}X^{\top}\mathrm{diag}\left(\frac{\hat{e}_i^2}{(1-h_{ii})^2}\right)X(X^{\top}X)^{-1} \tag{3}$$

where X is the model matrix, $\hat{e}_i$ is the OLS residual for observation i, and h_{ii} is the corresponding diagonal element of the matrix. All coefficient tests, confidence intervals, and pairwise comparisons are based on HC3 robust standard errors. Because multiple pairwise comparisons were conducted among bands within each test group, we controlled the family-wise error rate using the Holm procedure (Holm, 1979). Holm-adjusted p-values were reported for all pairwise comparisons within each group, and statistical significance was assessed at $\alpha = 0.05$.

3 Results

3.1 Mean conditions across tests

The combined test period extended over three years and hence some interannual variability was observed (Figure 2). Test 1 and Test 2 had measurements skewed towards cooler months, and there were no, or very few austral spring (SON)

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measurements during these tests. In contrast, Test 3 extended over 14 months and included additional measurements from warmer months (January – March). The mean temperature and humidity conditions and key pollutants (PM2.5, NO, eBC (880 nm)) for each test period are shown in Table 3 and daily mean values in Figure 2. While temperatures were similar across test periods, mean temperatures were approximately one degree lower during Test 1 than other periods due to a higher proportion of cool month measurements. Consequently, mean relative humidity was higher during Test 1 than other tests, however the lower mean temperatures resulted in mean dew point temperatures during Test 1 being less than other periods. The daily mean DPD, the difference between the ambient dew point and the internal shed temperature, is also shown. There were no occasions where the internal shed temperature was below the ambient dew point.

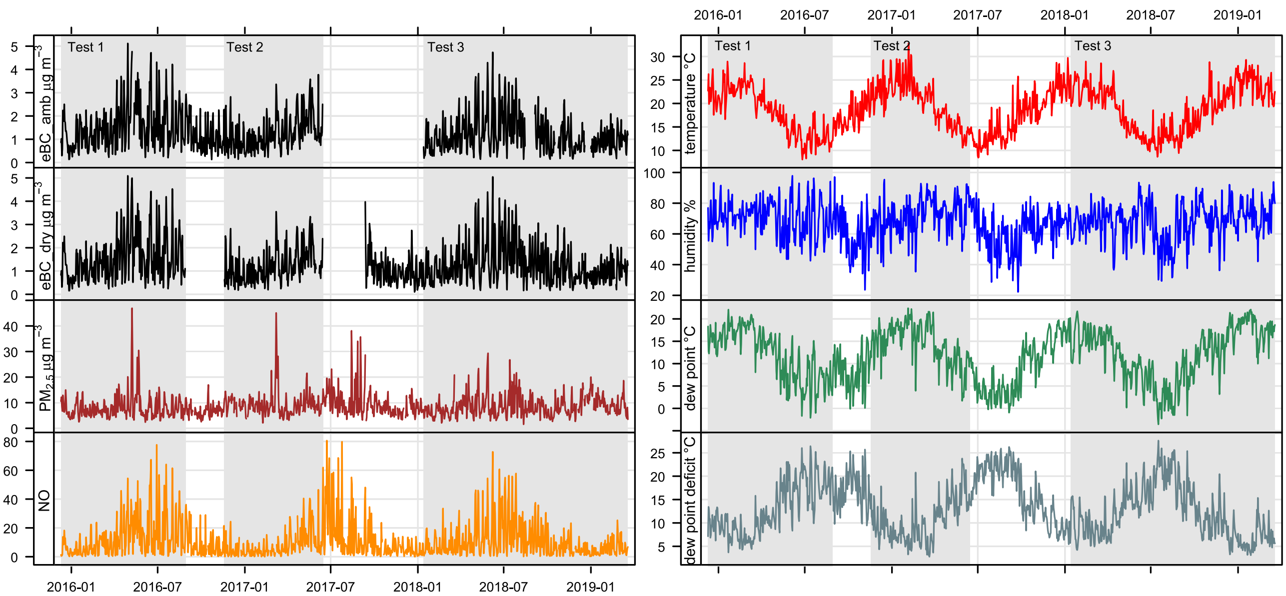

Figure 2: Daily mean air pollution (eBC, PM2.5, NO), temperature and humidity during each test period (shaded).

Mean eBC (880 nm) was higher during Test 1, as was nitric oxide (NO), probably due to the higher proportion of cool month measurements and hence more constrained boundary layer development, on average, over the test period (Table 3). PM2.5 however was lower during Test 1 and highest during Test 2, highlighting the variability of sources of fine particle pollution at Chullora and the impact of smoke from hazard reduction burns for forest fire management in the region during May 2017.

Table 3: Mean air pollution, temperature and humidity across test periods.

Comparison	eBC 880nm (µgm^{-3})		PM2.5 (µgm^{-3})	NO (ppb)	Relative humidity (%)	Temperature (°C)				
	ambient	dried				mean	daily max	daily min	dew point	dew point deficit

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Test 1	1.44	1.54	7.9	12.2	68.0	18.0	23.2	13.6	11.2	13.9
Test 2	1.27	1.16	9.3	10.5	67.0	18.9	24.2	14.5	11.8	13.4
Test 3	1.21	1.28	8.8	10.6	67.6	19.1	24.5	14.8	12.2	12.0

3.2 eBC comparison for various averaging periods

We begin by comparing hourly means for each channel across the three test periods (Table 4). For Test 1, R^2 across all channels is 0.993 – 0.994 with the largest variation in slope from unity occurring at 370 nm (0.958 [0.956–0.960]). Results for Test 2 show R^2 across all channels of 0.991 – 0.992 with the greatest departure at 660 nm (0.961 [0.958–0.963]. Test 3 showed similar strong correlations (R^2 = 0.994–0.995), but with greater variation in slopes compared to Tests 1 and 2. At 470 nm slope is estimated at 1.074 [1.073–1.076]. Focussing on 880 nm channel only (Figure 3), slopes varied from 0.972 [0.969–0.974] (Test 2) to 1.069 [1.068–1.071] (Test 3) and close to one for Test 1 (1.001 [0.999–1.003]). The greatest variations in slopes from unity were for Test 1 where slope agreement moved from 0.958 at 370 nm and to 1.00 at 950 nm. For Tests 2 and 3 slopes remained similar across channels apart from the 370 nm channel in Test 2.

Table 4: Slope and correlation of the hourly eBC for each test. Numbers in brackets represent the 0.95 confidence intervals for the slope.

Channel	Test 1		Test 2		Test 3	
	Slope	R^2	Slope	R^2	Slope	R^2
BC1 (370 nm)	0.958 [0.956–0.960]	0.993	1.015 [1.012–1.018]	0.991	1.062 [1.060–1.064]	0.995
BC2 (470 nm)	0.961 [0.959–0.963]	0.994	0.972 [0.969–0.975]	0.991	1.074 [1.073–1.076]	0.995
BC3 (520 nm)	0.975 [0.973–0.977]	0.994	0.974 [0.971–0.977]	0.991	1.070 [1.068–1.071]	0.994
BC4 (590 nm)	0.977 [0.975–0.979]	0.994	0.968 [0.965–0.970]	0.991	1.060 [1.058–1.062]	0.994
BC5 (660 nm)	0.983 [0.981–0.985]	0.994	0.961 [0.958–0.963]	0.992	1.047 [1.046–1.049]	0.994
BC6 (880 nm)	1.001 [0.999–1.003]	0.994	0.972 [0.969–0.974]	0.992	1.069 [1.068–1.071]	0.994
BC7 (950 nm)	1.000 [0.998–1.002]	0.994	0.969 [0.967–0.972]	0.992	1.068 [1.066–1.069]	0.994

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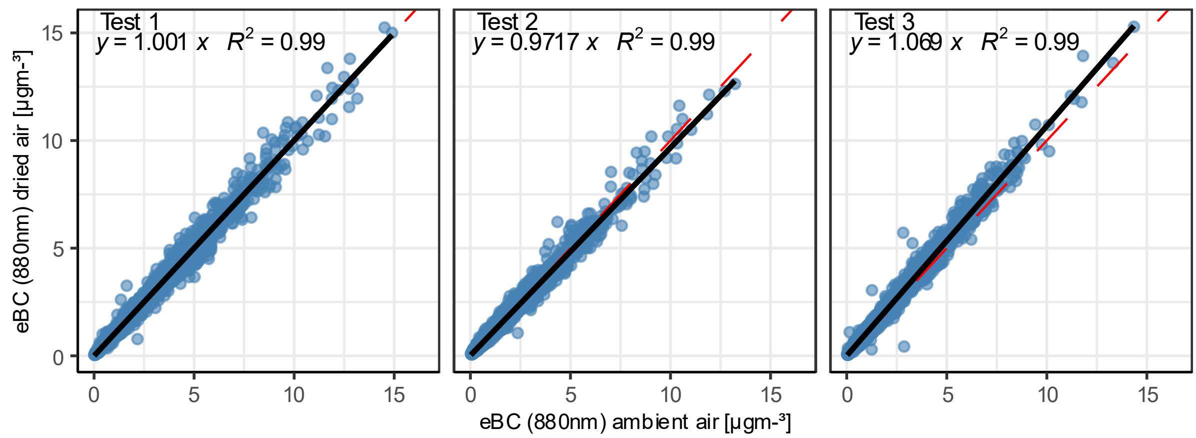

Figure 3: Comparisons of hourly eBC mass concentrations (880 nm) for ambient and dried samples. Red dashed line is 1:1.

Next, we compare the 1-, 2-, 5- and 10-minute data for each test at 880 nm (Table 5). Each of these tests contain substantial numbers of paired 1-minute data (Test 1: 370,623, Test 2: 278,599, Test 3: 568,392). Across all tests and averaging intervals R^2 values remained very high (0.977 – 0.994), with the lowest correlation for 1-minute data in Test 3 (0.977), which covers the longest period and the greatest variation in ambient conditions. As expected, the 1-minute data show the greatest variability (lowest correlation and highest standard deviation) between instruments. The slopes of the regression remained similar for all averaging periods for each test, Test 1: 0.994 – 1.001, Test 2: 0.961 – 0.967, Test 3: 1.065 – 1.072.

Table 5: Statistics and slope of the 1-, 2-, 5- and 10-minute data comparisons for eBC (880 nm) for each test. Numbers in brackets represent the 0.95 confidence intervals for the slope. σ is the standard deviation.

eBC (880 nm)	Avg. time	Ambient		Dried		Regression	
		mean	σ	mean	σ	slope	R^2
Test 1	1-min	1.566	1.820	1.553	1.829	0.994 [0.994–0.994]	0.983
	2-min	1.563	1.810	1.551	1.821	0.997 [0.997–0.998]	0.988
	5-min	1.560	1.794	1.548	1.809	0.999 [0.999–1.000]	0.993
	10-min	1.551	1.771	1.541	1.788	1.000 [1.000–1.001]	0.994
Test 2	1-min	1.270	1.562	1.241	1.501	0.961 [0.961–0.962]	0.983
	2-min	1.267	1.540	1.241	1.494	0.964 [0.963–0.965]	0.988
	5-min	1.265	1.522	1.238	1.470	0.966 [0.965–0.966]	0.993
	10-min	1.257	1.483	1.233	1.447	0.966 [0.965–0.967]	0.994
Test 3	1-min	1.206	1.443	1.288	1.510	1.065 [1.065–1.066]	0.977
	2-min	1.204	1.432	1.286	1.501	1.069 [1.068–1.069]	0.982
	5-min	1.202	1.421	1.284	1.489	1.071 [1.070–1.071]	0.987

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	10-min	1.197	1.403	1.278	1.471	1.071 [1.070–1.072]	0.988

3.2 Seasonal and temporal comparisons

Variations in hourly eBC between instruments over seasonal and diurnal cycles, focussing on the BC6 (880 nm) channel are now considered. Figure 4a shows the normalised regression slopes for each test by hour of day (i.e. for each test the hourly slope has been adjusted against the mean for all hours for that test). The lack of a clear diurnal signal for any of the tests is interesting given that during the day at this location we could expect that there are occasions where internal temperatures in the climate-controlled building are significantly lower than ambient conditions, particularly during the middle of the day. Applying the formal test of significance of variations between months (Wald test with Holm adjustment) we find no significant differences between hourly bands for Tests 1 and 2. For Test 3, 15 of the 276 band-to-band comparisons show significant differences in slope, with 14 of these being comparisons with hour 0200. This may be due to a specific particle source active at this time (and another at hour 16:00) as both Test 1 and Test 2 also show slope estimates at hour 0200 as the largest or second largest departure from the mean OLS slopes across all hours.

Considering monthly results (Table 6) and noting the shorter observation periods and lack of austral spring sampling for Tests 1 and 2, there is an indication of some seasonal pattern. Figure 4b shows the normalised slopes for each test. For Test 3, the longer test period, a seasonal oscillation is apparent indicating that for austral winter and spring the monthly comparisons vary compared to summer. A similar pattern might be evident for Test 1, however the lack of data for spring limits the ability to confirm seasonal differences in this test. Test 2, the shortest test, lacks sufficient data across the year to support a conclusion of seasonal variation. Applying the Wald test with Holm-adjusted *p*-values, we find that for Test 1, 22 of the 36 month-to-month comparisons (61%) show significant differences in OLS slopes. For Test 2, 11 of 28 monthly comparisons (39%) show significant differences, while for Test 3, the longest test and only test with a complete 12-month cycle, 16 of the 66 month-to-month comparisons (24%) show significant differences in OLS slopes (Table 7). Of these 16 statistically significant comparisons, 12 are for the warmest months of the year (January and December) potentially indicating that there are significant differences between the effects of sample drying in the warm season compared to cool seasons. The differences between tests highlights the benefits of having a complete 12-month test period to support robust comparisons.

Table 6: Slope and correlation of seasonal variations in hourly eBC (880 nm). Data in italics represent results from months that did not meet the 75% data availability criteria. Numbers in brackets represent the 0.95 confidence intervals.

Month	n	Test 1		n	Test 2		n	Test 3	
		Slope	R^2		Slope	R^2		Slope	R^2
December	*528*	*1.000 [0.994–1.005]*	*0.996*	744	0.957 [0.950–0.963]	0.991	*480*	*1.046 [1.037–1.055]*	*0.991*

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January	744	0.939 [0.934–0.944]	0.994	744	0.993 [0.985–1.001]	0.987	1213	1.026 [1.020–1.033]	0.989
February	694	0.999 [0.995–1.004]	0.997	664	0.995 [0.988–1.001]	0.993	1313	1.062 [1.057–1.066]	0.994
March	742	0.986 [0.981–0.991]	0.995	741	1.021 [1.015–1.028]	0.992	1222	1.072 [1.068–1.076]	0.996
April	720	0.997 [0.991–1.004]	0.993	717	0.964 [0.958–0.969]	0.994	719	1.047 [1.042–1.052]	0.996
May	691	1.007 [1.002–1.012]	0.995	738	0.932 [0.928–0.936]	0.996	742	1.062 [1.058–1.066]	0.997
June	719	0.960 [0.956–0.965]	0.995	*200*	*0.960 [0.951–0.970]*	*0.995*	718	1.088 [1.084–1.093]	0.991
July	744	1.030 [1.025–1.035]	0.995	0	n.a.	n.a.	741	1.077 [1.072–1.082]	0.996
August	684	1.049 [1.043–1.055]	0.995	0	n.a.	n.a.	*373*	*1.075 [1.068–1.081]*	*0.997*
September	0	n.a.	n.a.	0	n.a.	n.a.	636	1.092 [1.083–1.101]	0.988
October	0	n.a.	n.a.	0	n.a.	n.a.	608	1.082 [1.075–1.088]	0.994
November	0	n.a.	n.a.	*297*	*1.015 [1.000:1.030]*	*0.983*	719	1.066 [1.061:1.070]	0.996

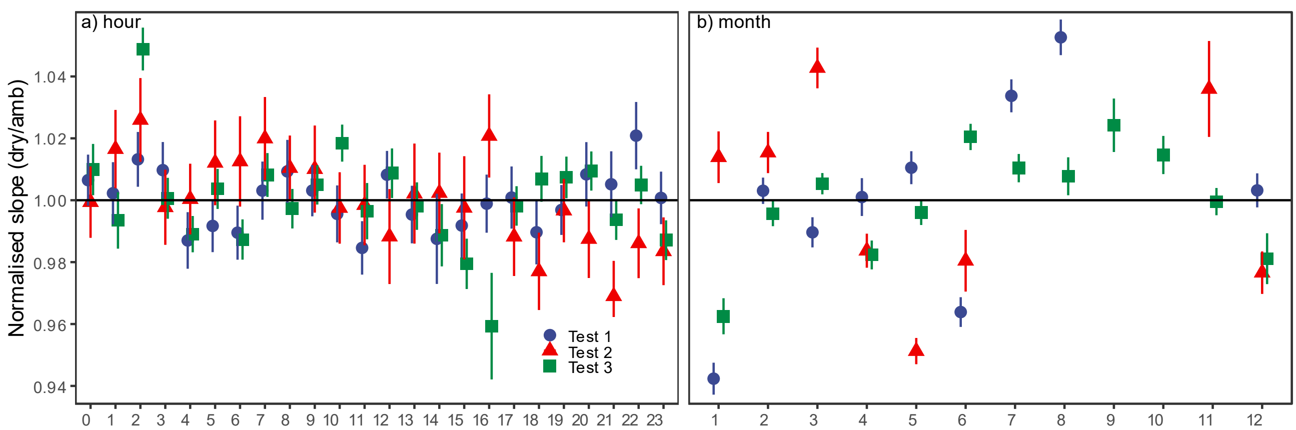

Figure 4: Hourly (a) and monthly (b) regression slopes and 95% confidence intervals for each test. Note that slopes have been normalised (hour/month mean minus total hour/month test mean) to assist comparison.

Table 7: Statistically significant differences between OLS regressions for temperature and moisture bands

Bands	# band comparisons	Test 1		Test 2		Test 3	
		signif. (Holm)	% signif.	signif. (Holm)	% signif.	signif. (Holm)	% signif.
month	36/28/66	22/36	61%	11/28	39%	16/66	24%
hour	276	0	0%	0	0%	15	5%
temperature	66	12	18%	25	38%	13	20%
relative humidity	91	2	2%	0	0%	0	0%
dew point	36	14	39%	18	50%	12	33%

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dew point deficit	78	8	10%	30	38%	13	17%

3.3 Moisture dependence

Next we compare regression results from each test stratified by moisture variables (Table 7, Figure 5). We assign each measurement to bands based on ambient relative humidity (RH), ambient dew point temperature (T_d), and the difference between the ambient dew point and the internal shed temperature (dew point deficit, DPD). Relative humidity bands are in 5% increments plus a band for low humidity representing humidity observations below 30%. Dew point temperature bands are in 3 °C bins with the lowest being all dew points below 0 °C. Dew point deficit bands are similarly described by 2 °C increments, with a band for all observations where DPD > 24 °C. Note that using the hourly observations we recorded no periods where DPD < 0 °C that is, where the hourly mean ambient dew point was below the internal shed temperature.

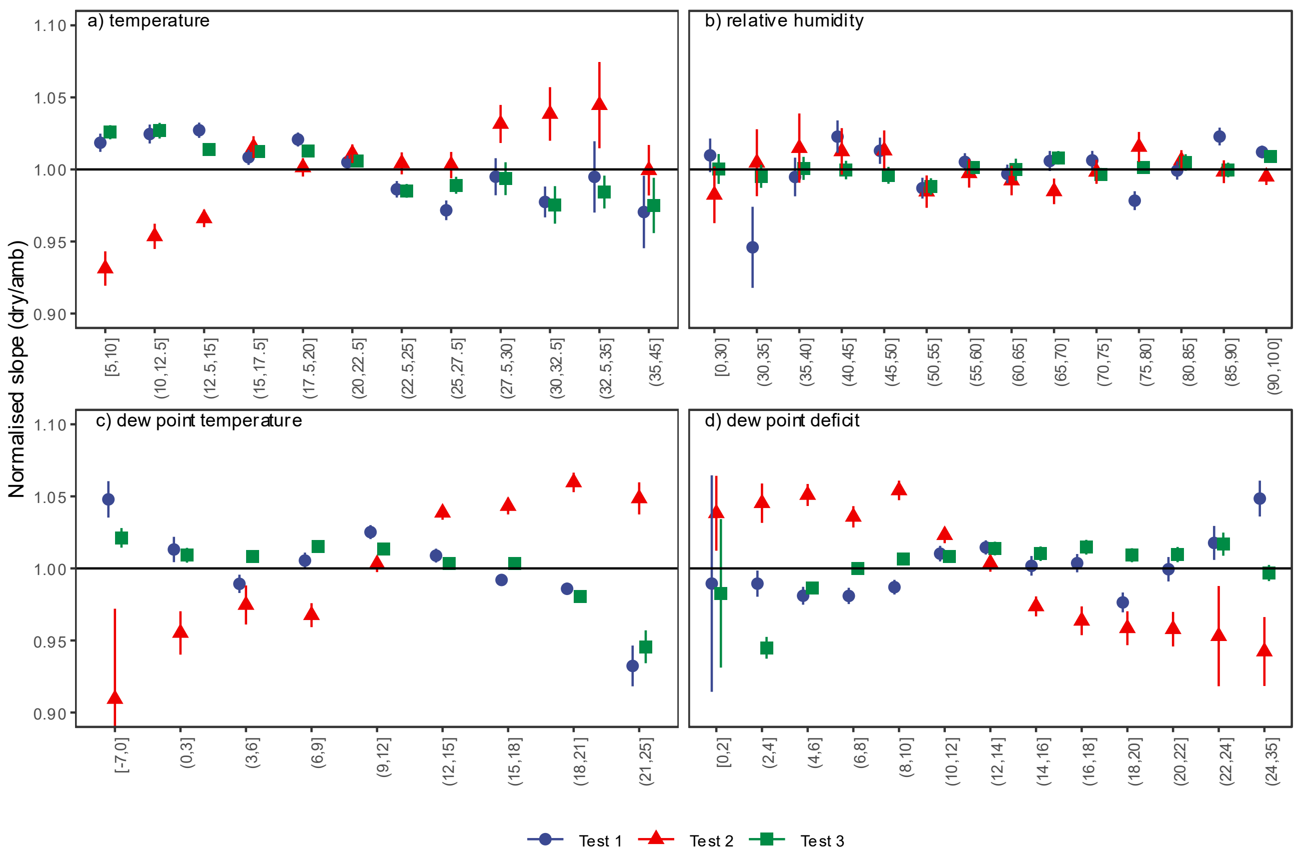

Figure 5: Regression slopes and 95% confidence intervals for each moisture stratification band. (a) ambient temperature (°C) (b) ambient relative humidity (%) (c) ambient dew point temperature (°C) (d) dew point deficit (°C). Note that slopes have been normalised (monthly mean minus total test mean) to assist comparison.

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For RH, all tests and bands showed very high correlation (R^2 = 0.99–1.00). Figure 5b indicates that for Test 2 and Test 3 there is likely no significant variation in the slopes between the bands if assessing overlapping of confidence intervals while for Test 1 there is some variation between bands with the slope and confidence intervals of the 30–35% band having little overlap with other bands. Applying the Wald test with Holm-adjusted p-values we find only 2 of the 273 comparisons showed significant differences between relative humidity bands (Table 7). These results indicate that variations in relative humidity at hourly time steps have little influence in the overall comparability of the dried and ambient sampling. Ambient relative humidity may not be the best measure of the benefits of drying the sample as it does not assess the absolute moisture volume or the difference between the ambient and internal shed environments that the sampling system is exposed to. Schmid et al. (2006), reporting on eBC measurements from the Amazon, found no statistically significant dependences on ambient relative humidity when comparing eBC from an aethalometer sampling ambient air and results from a photoacoustic spectrometer sampling dried air in that high humidity environment.

We next consider ambient dew point temperature which better reflects the absolute volume of water in the sampled air rather than the capacity for the air to hold moisture. There are obvious differences in each test considering the linear relationships at low (<0 °C) and high (>15 °C) dew point temperatures, but results from Test 2 are different to the results from Tests 1 and 3. Unlike relative humidity, applying the Wald test with Holm-adjusted p-values to formally test inter-band significance of dew point temperatures, all tests show 12 or more inter-comparisons bands with significantly different slopes (Table 7). Ambient dew point temperature may be a better measure than relative humidity in assessing the benefits of drying the sample air, but this measure still does not reflect the difference between the ambient and internal shed environments that the sampling system is exposed to.

The dew point deficit comparisons should be more reflective of the conditions likely to produce the moisture artifacts in the sampling system reported elsewhere. While there are some differences between low deficits, that is when internal shed temperatures approximate ambient dew point temperatures, the test data do not provide a coherent narrative of moisture dependence. Applying the Wald test with Holm-adjusted p-values in a formal test of inter-band significance, we find that for Tests 1 and 3, 8 and 13 of the 78 inter-band tests show significant differences, while for Test 2, 30 of the 78 band tests (38%) show significance (Table 7). For Test 3, 10 of the significant differences are between band [2,4] and all other bands except band [22,24], while for Test 1 most of the significant differences occurred between band [>24 °C] and other bands, and the only significant difference for band [2,4] was with this high DPD band. For Test 2 there is variance in the significance of the differences between low and high DPD bands. Dew point and DPD are likely better diagnostic variables for potential moisture effects than RH.

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3.4 Instrument noise and signal-to-noise ratios

We assess the hourly instrument noise and signal to noise ratio for each test and for the pooled test data. Using a paired t-test and Wilcoxon signed-rank test to compare means and medians, we note that there is a statistically significant difference ($p < 0.001$) in mean noise between the ambient and dried samples due to the large sample size, but the magnitude of the difference is small at 0.01 µgm^{-3}. The SNR comparisons similarly showed statistically significant differences ($p < 0.001$), with consistent negative biases ranging from −0.26 to −0.65 demonstrating that the SNR from the dried sampling is consistently higher than from the ambient sampling. Dried sampling increases SNR on average by 5–15%.

Table 8: Instrument noise and signal to noise ratio (SNR).

Test	n	Ambient				Dried				Difference (ambient – dry)			
		σ		SNR		σ		SNR		$\sigma_{amb} - \sigma_{dry}$		$SNR_{amb} - SNR_{dry}$	
		mean	s.d	mean	s.d	mean	s.d	mean	s.d	mean	s.d	mean	s.d
Test 1	6320	0.37	0.43	4.96	3.85	0.36	0.45	5.18	3.81	0.01	0.112	-0.26	1.36
Test 2	4644	0.37	0.54	4.22	3.03	0.33	0.54	4.16	3.15	0.03	0.091	-0.65	1.37
Test 3	10323	0.31	0.34	4.18	3.03	0.31	0.36	4.66	3.14	0.00	0.116	-0.46	1.37
All tests	21287	0.34	0.42	4.43	3.32	0.33	0.43	4.86	3.36	0.01	0.110	-0.44	1.38

Figure 6 shows the distribution of the difference in noise against the key ambient environmental parameters: temperature, relative humidity, dew point temperature and dew point deficit. There is no consistently strong structure or trend in the data beyond increased noise with increasing moisture (dew point and relative humidity).

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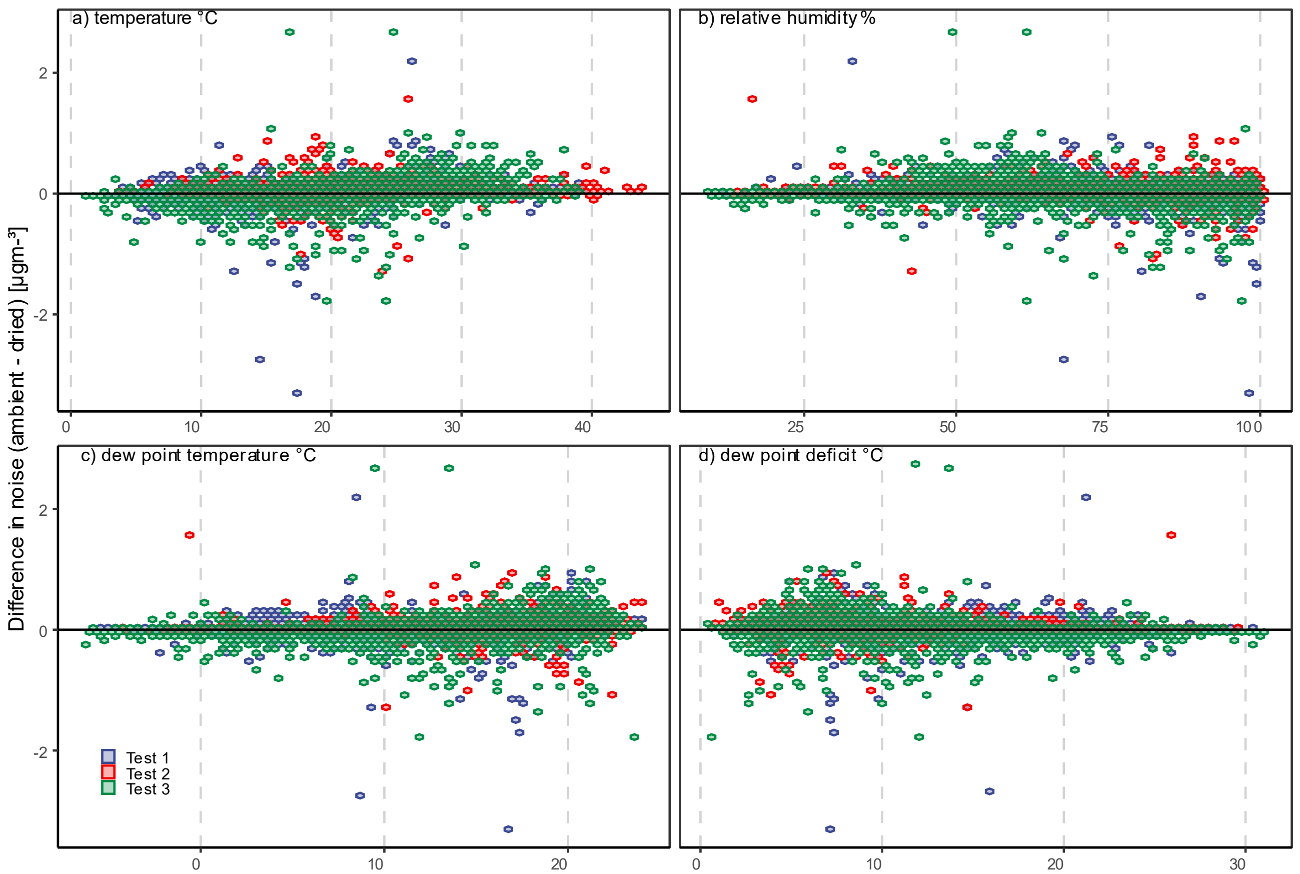

Figure 6 Distribution of measurement noise against ambient temperature, relative humidity, dew point and dew point deficit. Hexagonal bins are used to thin out data points while maintaining data structure.

4 Discussion

Continuous eBC measurements are being increasingly used in research and regulatory air quality monitoring networks as aethalometers can operate for long periods unattended and provide estimates of combustion aerosol at high temporal resolutions. As these measurements are incorporated into more long term air quality monitoring programs, standardisation of methods becomes increasingly important, supporting comparability of measurements across instruments and networks. Sample conditioning remains an important practical issue for filter-based absorption photometers because moisture may affect particle size, filter loading, and light scattering and absorption. Existing guidance from research focussed networks typically requires samples to be dried to RH < 40% but guidance for regulatory networks remains variable. This study addresses a practical question for regulatory networks, whether sample drying materially improves hourly eBC measurements from AE33 aethalometers under field conditions.

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Our results show that for the operating conditions examined here, dried and non-dried AE33 measurements were highly comparable. Across extended field tests at an urban background site in Sydney, the relationship between dried and non-dried samples was highly linear for all wavelengths with R^2 consistently greater than 0.99. For the 880nm channel, slopes ranged from 0.972 – 1.069 across the tests, with Test 1 returning a slope of ~1.00. These differences in slope are comparable to, or smaller than, the instrument-to-instrument differences reported in previous AE33 intercomparisons.

These results were consistent across different time averaging periods. Although 1-minute data showed greater scatter, as expected, the regression slopes for 1-, 2-, 5-, 10-min and hourly data were similar within each test. This indicates that the principal difference between dried and ambient sampling across these tests was not an averaging time dependent moisture affect. The agreement across averaging periods suggests that hourly reporting, as used for example in regulatory monitoring networks, is not sensitive to moisture related short-term fluctuations. Short-term fluctuations at 1-minute averaging may still be important for atmospheric and aerosol process related studies.

A strength of our study is through the multiple tests and the duration of these comparisons. The three test periods covered from 7 to 14 months, far exceeding the duration of AE33 field intercomparisons reported in the literature. Together these tests provided over 20,000 valid, paired hourly observations and more than 1.2 million paired 1-minute observations. These long observations are important because shorter comparisons or campaigns may capture only a subset of the differences in aerosol composition and sources, seasonal meteorology and environmental conditions at a given location. Our monthly analysis shows that the proportion of statistically significant month-to-month differences in OLS slopes varied between tests with the smallest proportion of significant monthly differences observed in Test 3, the only test to span a full seasonal cycle. Shorter comparisons could overstate or understate differences between instruments/sampling systems if these comparisons are conducted in seasonally unrepresentative periods.

The monthly and diurnal results provide little evidence for coherent moisture artefacts in hourly eBC measurements. No significant hour-to-hour dependence was found for Tests 1 and 2, while for Test 3 only a small fraction of hour-to-hour comparisons showed significant differences, and these were mostly associated with a single overnight hour. This suggests that local source variability or instrument specific behaviour is more important than diurnal humidity/moisture effects. Seasonal differences were more substantial than diurnal differences, but the interpretation of seasonal effects is complicated by the lack of full seasonal coverage in Tests 1 and 2. Differences in these tests may be due to the seasonal differences in aerosol sources and boundary layer development and should not be solely attributed to moisture effects.

The moisture stratified analysis indicates that ambient relative humidity is a poor indicator of the differences between dried and non-dried AE33 measurements at hourly timescales. Across RH bands correlations remained very high and only two of the pairwise comparisons were statistically significant. This is an important result as RH is often used operationally as the

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primary indicator of potential moisture artifacts in aethalometer measurements. RH does not describe the absolute water content of the sampled air, nor does it reflect the thermal contrast between ambient conditions and the instrument operating environment.

Dew point temperature and dew point deficit provide more physically relevant diagnostics for moisture effects but neither presented a consistent response across tests. Dew point temperature showed more significant differences between bands than RH, consistent with the expectation that absolute moisture content may be more relevant than relative moisture content. However, the magnitude and direction of differences in dew point response varied between tests. Similarly, DPD, the difference between ambient air and the internal conditions of the temperature controlled enclosure and intended to represent the potential for condensation within the sampling system, did not present a coherent and consistent pattern across all tests. However, we note that no hourly periods across our tests displayed conditions where the internal temperature was consistently below the ambient dew point.

Together these assessments suggest that RH alone should not be used to infer or identify potential moisture artifacts in AE33 measurements. Dew point and DPD likely provide more informative diagnostics of the potential effects of moisture in the sampling system. However, our sampling and test configuration, with short residence time and the absence of observed conditions favourable to condensation, may have limited moisture artifacts during our tests. Our findings should therefore be interpreted as representative of our sampling conditions and be applicable to similar sampling systems and environments. Sites with different sampling systems, such as longer or poorly insulated sampling lines, or with different environmental conditions such as increased fog, cloud or lower DPDs, may experience larger moisture effects than we report here.

Although sample drying did not substantially impact hourly mean eBC concentrations, it did provide measurable reductions in instrument noise at short sampling periods and improvements in hourly signal-to-noise ratios. The dried instruments showed consistently higher SNRs with improvements of 5–15 %, although the absolute difference in hourly noise was small (~0.01 μgm^{-3}). This further indicates that sample drying may be beneficial to studies requiring higher time resolution data such as source identification, aerosol process studies, and investigations of rapidly changing ambient atmospheric conditions, but this benefit reduces at longer averaging periods.

These results highlight the importance of separating sampling system effects from instrument-to-instrument variability. In this study we used four AE33 instruments across three tests, with two instruments used in both configurations (dried and ambient). However, each individual comparison only consisted of one dried and one ambient instrument, and these were not tested synchronously with identical sample handling, hence part of our reported variance in OLS slopes likely represents instrument-to-instrument differences in observations rather than sample conditioning effects alone. This limitation is common in field comparisons but undesirable when the impacts/effects of the intervention or comparison may be small.

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Future studies to further examine moisture effects should explicitly assess and quantify inter-instrument variation, separating instrument bias from sample handling. Where possible sample moisture should be measured immediately upstream of the optical chamber to isolate drying effects and enable them to be similarly estimated separately to instrument and inlet effects.

For monitoring networks, the practical implication of this study is that the benefit of sample drying should be evaluated against the measurement objective. For long term observations of hourly eBC within climate controlled enclosures typical of regulatory air quality monitoring sites, and in urban locations similar to ours, sample drying introduced only small differences to eBC measurements compared to ambient/non-dried sampling. These differences were generally within the range of published AE33 inter-instrument variability. Comparison of dried and non-dried AE33 measurements is feasible where the site configuration, sampling design and instrument configuration is well documented. However, drying remains desirable where the objective is harmonisation with research network protocols, where the sampling environment is likely to regularly produce condensation, or where sub-hourly data is essential to the analysis, for example in process studies.

4 Conclusion

This long term field intercomparison provides evidence that AE33 aethalometers operating with and without membrane driers provide highly comparable eBC measurements in a temperate, high humidity coastal urban environment. Across three separate tests dried and ambient measurements were strongly correlated at 880nm with slopes between 0.97 and 1.07. There was no systematic degradation of agreement at high ambient relative humidity. Moisture related effects characterised by ambient dew point temperature and the dew point deficit (i.e. the difference between ambient dew point temperature and internal shed/enclosure temperature), were smaller than the test-to-test differences, and comparable to inter-instrument variability reported in other studies. Sample drying reduced noise and increased the signal-to-noise ratio for hourly data but did not materially change the mean observations.

These findings support a practical approach to humidity control for aethalometer measurements. Sample drying remains best practice and is important for ensuring harmonised measurements in globally and regionally significant research networks and for studies where highly time resolved observations are necessary. Sample drying is probably less important and provides limited benefit for hourly reporting typical of regulatory monitoring networks. However, these networks should still adhere to best practice for environmental control of enclosures and by minimising residence time in the sampling system. Further multi-instrument comparisons across a broader range of environments are warranted. Similarly, longer term multi-instrument comparisons are required to more accurately reflect unit-to-unit variability of AE33 instruments.

Code and data availability

All code and data are available from the authors upon request. Data will be made available on the NSW Government's environmental data platform seed.nsw.gov.au

Author contributions

Conceptualization and methodology: MLR and GG, Data collection: GG, Data curation and validation: MLR, Formal analysis: MLR, Writing (original draft preparation): MLR and GG, Writing (review and editing): MLR and GG.

Competing interests

The authors declare no competing interests.

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