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TECHNICAL ASSISTANCE DOCUMENT FOR CONTINUOUS CARBONACEOUS AEROSOL MONITORING IN AMBIENT AIR

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TECHNICAL ASSISTANCE DOCUMENT FOR CONTINUOUS CARBONACEOUS AEROSOL MONITORING IN AMBIENT AIR

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DISCLAIMER

REVISION HISTORY

Revision Number	Theme	Description of Change(s)	Section(s)/ Table(s)

CONTENTS

FIGURES

TABLES

ACRONYMS

AOD	aerosol optical depth
AAE	absorption Ångström exponent
AQS	Air Quality System
AQCSV	AirNow Air Quality Comma Separated Values file format
AT	ambient temperature
BC	black carbon
BC_{bb}	black carbon from biomass burning/wood burning
BC_{ff}	black carbon from fossil fuels
BC_{wb}	black carbon from biomass burning/wood burning
BH	Bayern-Hessen protocol
BP	barometric pressure
BrC	brown carbon
C	carbon
CAAT	carbonaceous aerosol analysis tool, software available from Aerosol Magee Scientific
CARB	California Air Resources Board
CASS	Carbonaceous Aerosol Speciation System
CFR	Code of Federal Regulations
CO_2	carbon dioxide
CSN	Chemical Speciation Network
CV	coefficient of variation
DAS	data acquisition system
DQI	data quality indicator
DQO	Data Quality Objective
EC	elemental carbon
EDXRF	Energy dispersive X-ray fluorescence spectrometry
EGA	evolved gas analysis
EJ	environmental justice
EPA	United States Environmental Protection Agency
GAW	Global Atmosphere Watch
HAP	hazardous air pollutant
HMS	Hazard Mapping System
IC	ion chromatography
IMPROVE	Interagency Monitoring of Protected Visual Environments
k	loading compensation parameter
L	liter(s)

LC	local or ambient temperature and pressure readings
LIMS	laboratory information management system
LII	laser induced incandescence
LPM	liters per minute

M	molar
m	meter(s)
m^3	cubic meter(s)
MAC	mass absorption coefficient (σ_{abs})
MATES	Multiple Air Toxics Exposure Study
MDL	method detection limit
MFC	mass flow controller
mg	milligram(s)
min	minute(s)
mL	milliliter(s)
ML	minimum level
MLH	mixing layer height
mm	millimeter(s)
mM	millimolar
MQO	Measurement Quality Objective
µg	microgram(s)
µL	microliter(s)
µm	micrometer(s)

n	number
NAAQS	National Ambient Air Quality Standards
NCore	National Core
ND	non-detect
NDIR	non-dispersive infrared
ng	nanogram(s)
NIST	National Institute of Standards and Technology
nm	nanometer(s)
NOAA	National Oceanic and Atmospheric Administration

OAQPS	U.S. Environmental Protection Agency’s Office of Air Quality Planning and Standards
OC	organic carbon
OMB	U.S. Environmental Protection Agency’s Office of Management and Budget

PAMS	photochemical assessment monitoring station
PBL	planetary boundary layer
PEMS	Portable Emissions Measurement System
PM	particulate matter
$PM_{2.5}$	particulate matter with aerodynamic diameter ≤ 2.5 micrometers
PM_{10}	particulate matter with aerodynamic diameter ≤ 10 micrometers
POA	primary organic aerosol

POA_{BrC}	primary organic aerosol, brown carbon
$POA_{non\text{-}abs}$	primary organic aerosol, non-absorbing
POC	parameter occurrence code
ppb	part(s) per billion
ppbC	parts per billion carbon
ppbV	part(s) per billion by volume
ppm	part(s) per million
ppt	part(s) per trillion
psi	pound(s) per square inch
PTFE	polytetrafluoroethylene
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control
RH	relative humidity
SLAMS	State and Local Air Monitoring Stations
SLT	state, local, tribal
SOA	secondary organic aerosol
SOA_{BrC}	secondary organic aerosol, brown carbon
$SOA_{non\text{-}abs}$	secondary organic aerosol, non-absorbing
SOP	standard operating procedure
SP2	single particle soot photometer
SQL	sample quantitation limit
STN	Speciation Trends Network
STP	standard temperature and pressure (0 °C and 101325 Pa)
TAD	technical assistance document
TC	total carbon
TOR	thermal optical reflectance
TOT	thermal optical transmittance
U.S.	United States
UV	ultraviolet
UVPM	UV-light absorbing particulate matter
VOC	volatile organic compounds
WHO	World Health Organization
WMO	World Meteorological Organization

1. INTRODUCTION

1.1. Scope and Purpose

This Technical Assistance Document (TAD) is published to aid air monitoring agencies interested in implementing continuous carbonaceous aerosol measurements into their existing air monitoring networks. These measurements are voluntary and are not required by federal regulations. However, continuous carbonaceous aerosol measurements can provide air monitoring agencies with insightful particulate matter (PM) speciation information relevant to air quality management and in support of federal regulatory requirements. For example, insights into carbonaceous aerosol trends and episodes can be leveraged in targeting specific emissions reductions for PM National Ambient Air Quality Standards (NAAQS) attainment and providing evidence of exceptional events, such as wildfire smoke. Additionally, carbonaceous aerosols have important impacts on human health, the climate, and play a role in various biogeochemical processes. For these reasons, it can be advantageous for an air monitoring agency to include continuous carbonaceous aerosol measurements in their air monitoring network.

The purpose of this TAD is to provide a technical overview that enables the capability to routinely and continuously measure carbonaceous aerosol concentrations within existing air monitoring networks. Although many commercial techniques are available (and summarized in brief in Section 3), the guidance in this TAD is focused on the three continuous (or near real-time[1]) instruments currently in use by state, local, and tribal (SLT) air monitoring agencies as reported in the EPA's repository of ambient air quality data, Air Quality System (AQS):

- AE33 Aethalometer® manufactured by Aerosol Magee Scientific (www.aerosolmageesci.com)
- BC 1060 black carbon monitor manufactured by Met One Instruments (www.metone.com)
- TCA08 total carbon analyzer manufactured by Aerosol Magee Scientific (www.aerosolmageesci.com)

The TAD is intended to provide a high-level technical overview, with more detailed descriptions available in the standard operating procedures (SOPs) for the individual instruments. Technical guidance in this TAD is primarily sourced directly from the most recently available technical and service manuals:

- Magee Scientific Aethalometer® AE33 User's Manual, version 1.60 (Aerosol Mageee Scientific, 2021),
- BC 1060 Operation Manual, Version BC1 1060-9800 Rev H (Met One Instruments, 2020),

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[1] We use the term 'continuous' in this TAD to describe these near real-time instruments and differentiate them from 24-hour average discrete measurements used, for example, in the CSN and IMPROVE networks. Sometimes called 'semi-continuous' measurements, we acknowledge that both the AE33 and BC 1060 do not collect data when the filter tape is advancing, resulting in small data gaps of up to several minutes.

- and Magee Scientific/Aerosol TCA08 User's Manual, Version 1.1.1.1 (Aerosol Mageee Scientific, 2022)

as well as other materials from the instrument manufacturers. It also includes best practices and lessons learned from instrument manufacturers, operators, and experts responsible for assessing continuous carbonaceous aerosol measurements.

1.2. Background

The health, air quality, and climate impacts of PM are well established, and concentrations of total particle mass are federally regulated by the NAAQS. In more recent years, insights from total mass aerosol measurements have been enhanced by species-specific aerosol measurements, leading to new insights into species that significantly and uniquely contribute to health and climate effects. Carbonaceous aerosols are one of these important species due to their disproportionate contribution to negative health impacts (Janssen et al., 2012). Carbonaceous aerosols include black carbon (BC) and elemental carbon (EC), which are commonly referred to as soot, and organic carbon (OC) species. The following equation describes the relationship between total carbonaceous aerosol (or total carbon, TC) and its components:

$$\mathrm{TC} = \mathrm{OC} + \mathrm{EC} \approx \mathrm{OC} + \mathrm{BC} \qquad \text{Eq. 1}$$

1.2.1. Black and Elemental Carbon Measurements

EPA defines BC as a solid form of mostly pure carbon that absorbs solar radiation at all wavelengths (U.S. Environmental Protection Agency, 2012). Thermal optical measurements of this absorbing aerosol are reported as EC, and optical absorption measurements are reported as equivalent BC (or eBC).[2] As a light-absorbing species, BC is an important short-lived climate-forcer. BC has an atmospheric lifetime of days to weeks and is resistant to chemical transformation.

The main sources of BC are direct emissions including combustion engines (particularly diesel), residential burning of wood and coal, power stations, prescribed and agricultural burning, and wildland fires (Janssen et al., 2012). BC is estimated to account for 12% of the total mass of particulate matter with aerodynamic diameter ≤ 2.5 microns ($PM_{2.5}$) in the United States (U.S.), but concentrations are commonly higher near roadways (Allen, 2015; Correa-Ochoa et al., 2023; U.S. Environmental Protection Agency, 2012). BC measurements are therefore commonly used as an indicator of combustion-related air pollution.

The World Health Organization (WHO) summarized the state of toxicological studies in Janssen et al. (2012), finding that in addition to the general association of total particle mass with mortality, BC aerosol concentrations specifically have been shown to have more causal associations with negative health effects such as cardiovascular, respiratory, and neurological

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[2] The term 'BC' should be used qualitatively as a descriptive term when referring to light-absorbing carbonaceous particles and should be avoided when reporting measurement concentrations to avoid ambiguity. In the case of carbon mass measurements derived from a mass absorption coefficient (MAC), such as in the AE33 and BC 1060 described in this TAD, Petzold et al. 2013 recommends reporting concentrations of the species as equivalent BC (eBC) (Petzold et al., 2013; Lack et al., 2014).

problems. The WHO therefore concluded that “The use of BC as an additional indicator may be useful in evaluating local action aimed at reducing the population’s exposure to combustion PM (for example, from motorized traffic)” (Janssen et al., 2012). In light of this, WHO has recommended making additional systematic measurements of BC and/or EC.

1.2.2. Total Carbon Measurements

Total carbonaceous aerosol is often the largest contributor to total $PM_{2.5}$ mass. Organic aerosols are the largest fraction of total carbon, the most diverse, and the least understood portion of carbonaceous aerosols. Of the three instruments covered in detail in this TAD (see Table 1), only the TCA08 total carbon analyzer provides quantification of OC. When used in tandem, the TCA and AE33 are called the Carbonaceous Aerosol Speciation System (CASS) by the manufacturer and provide total carbonaceous speciation via direct measurements of BC and TC, allowing for the calculation of OC by difference.

The TCA08 measures TC using a thermal technique involving complete combustion of the sample. The AE33 Aethalometer® and BC 1060 black carbon monitor provide real-time data for equivalent BC concentrations using optical absorption (as well as ultra violet absorbing particulate matter, UVPM).

Table 1. Overview of the species and measurement technique for the instruments covered in this TAD.

Instrument	Carbonaceous aerosol species	Measurement technique
AE33 Aethalometer®	BC and UVPM	Optical absorption
BC 1060 black carbon monitor	BC and UVPM	Optical absorption
TCA08 total carbon analyzer	TC	Thermal analysis
CASS (AE33 + TCA)	BC and TC directly, OC calculated	Optical absorption + thermal analysis

1.3. Relationship to Other Chemical Speciation Programs and Methods

Carbonaceous aerosol samplers have been routinely operating across the United States for over 15 years in the national Chemical Speciation Network (CSN) and the Interagency Monitoring for Protected Visual Environments (IMPROVE) network. These networks mainly differ from continuous carbonaceous aerosol measurements described in this TAD by time resolution: while the networks make a 24-hour averaged measurement every three (or six) days, the continuous instruments described herein are able to make measurements on a minute to hourly time scale.

Both the CSN and IMPROVE networks measure EC, OC, and TC using thermal optical analysis (see Table 2), a technique based on a collection of field-based filter samples followed by laboratory-based instrument analysis that separates EC and OC using a stepped temperature gradient. This analysis technique is similar to the thermal technique used by the TCA08 and is different from the optical absorption technique used by the AE33 and BC 1060. A more detailed comparison of the measurement techniques is discussed in Section 3.

Table 2. Overview of the IMPROVE and CSN networks.

Network	IMPROVE	CSN
Locations	Remote and rural sites across the US	Urban/suburban settings across the US
Technique	Thermal optical analysis	Thermal optical analysis
Species measured	EC and OC	EC and OC
Current instrument	DRI model 2015 carbon analyzers	Sunset Laboratory model 5L TOA
Time period	Filters collected for 24 hours every 3rd day.	Filters collected for 24 hours every 3rd or 6th day.
Particle size	$PM_{2.5}$ (mass and speciation) and PM_{10} (mass only)	$PM_{2.5}$
References	IMPROVE website (https://vista.cira.colostate.edu/Improve/), (Chow et al., 1993; Hand, 2023)	CSN website (https://www.epa.gov/amtic/chemical-speciation-network-csn)

1.3.1. IMPROVE

The IMPROVE network has sites in mainly remote and rural locations across the U.S. IMPROVE was initially established as a national visibility network in 1985 and consisted of thirty monitoring sites, primarily located in national parks. In 1999, the IMPROVE network expanded to include 110 additional monitoring sites in Class I national parks and wilderness areas that were deemed representative of regional haze conditions. There are currently a total of 155 sites in the network, shown in the map in Figure 1.

The IMPROVE network collects 24-hour samples, every three (or six) days. For carbonaceous aerosol measurements, quartz fiber filters are collected with subsequent analysis by thermal optical reflectance for OC and EC. This network has used DRI Model 2015 carbon analyzers for sample analysis since 2016 (Schichtel, 2019).

The sites have four total modules for sampling $PM_{2.5}$ and PM_{10}. The filters are analyzed for (1) $PM_{2.5}$ gravimetric fine mass, elemental concentration, and light absorption; (2) sulfate, nitrate, nitrite, and chloride anions using ion chromatography; (3) OC and EC; and (4) PM_{10} gravimetric mass. Some sites also include a nephelometer for optical monitoring, and a webcam for documenting scenic appearance. A comprehensive summary of measurements in the IMPROVE network is available in Schichtel et al. (2021).

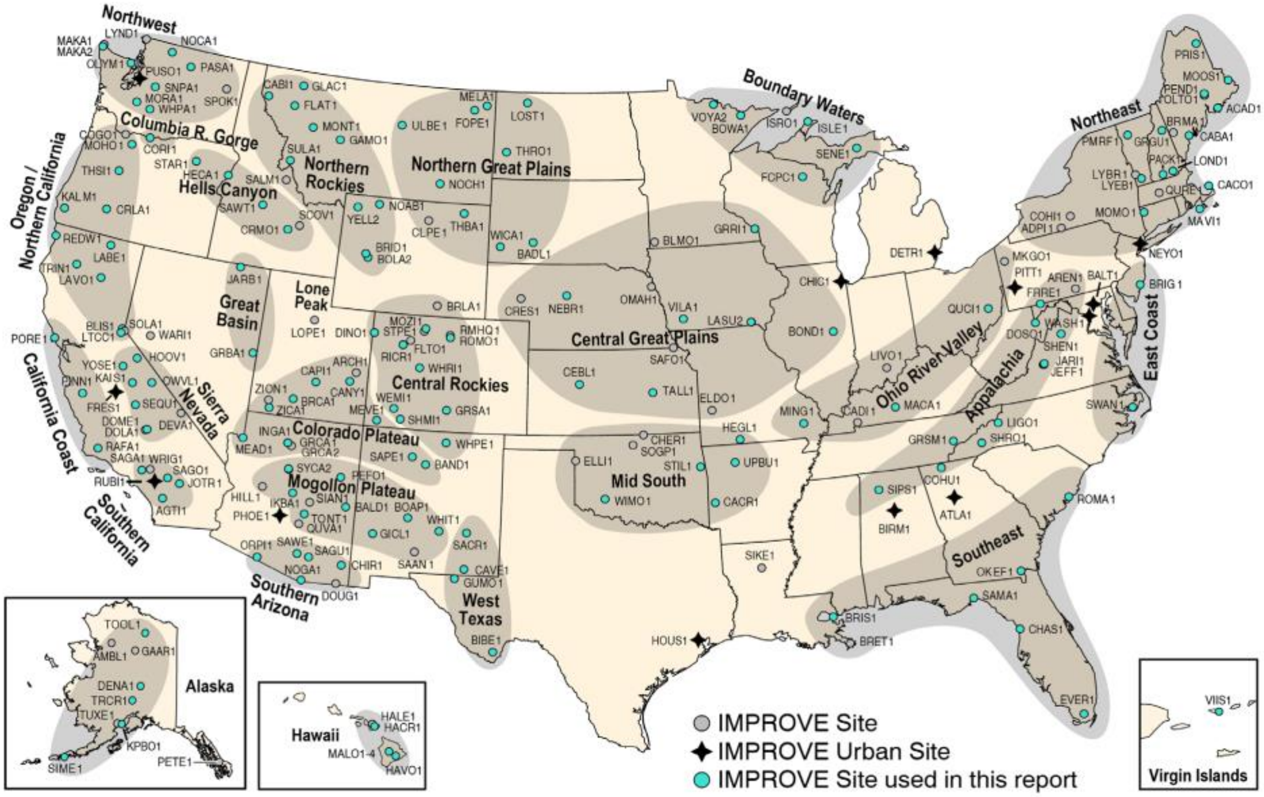

Figure 1. Map of all IMPROVE sites from the 2023 IMPROVE IV report. The sites are grouped by region (shading) based on categorization of similar aerosol species concentrations and seasonal patterns. Active, rural sites are marked by cyan circles; active, urban sites are identified by stars; and sites that have historic data but are no longer operating are marked by gray circles (Hand, 2023).

1.3.2. CSN

The CSN includes about 150 sites located in mostly urban and suburban locations across the U.S., as shown in the map in Figure 2. Filters are collected for 24 hours every 3rd day at the STN and 6th day at the Supplemental monitoring sites.

A URG 3000N carbon sampler is used to collect $PM_{2.5}$ on quartz filters for subsequent quantification of OC and EC using thermal optical reflectance. This network has used a Sunset Laboratory model 5L TOA for carbonaceous analysis since 2018 (Zhang, 2021). In addition to the quartz filters used for carbon measurements, the sites also collect polytetrafluoroethylene (PTFE) filters and nylon filters. The PTFE filters are analyzed using energy dispersive X-ray fluorescence (EDXRF) for a suite of thirty-three elements, and the nylon filters are analyzed using ion chromatography (IC) for a suite of six ions.

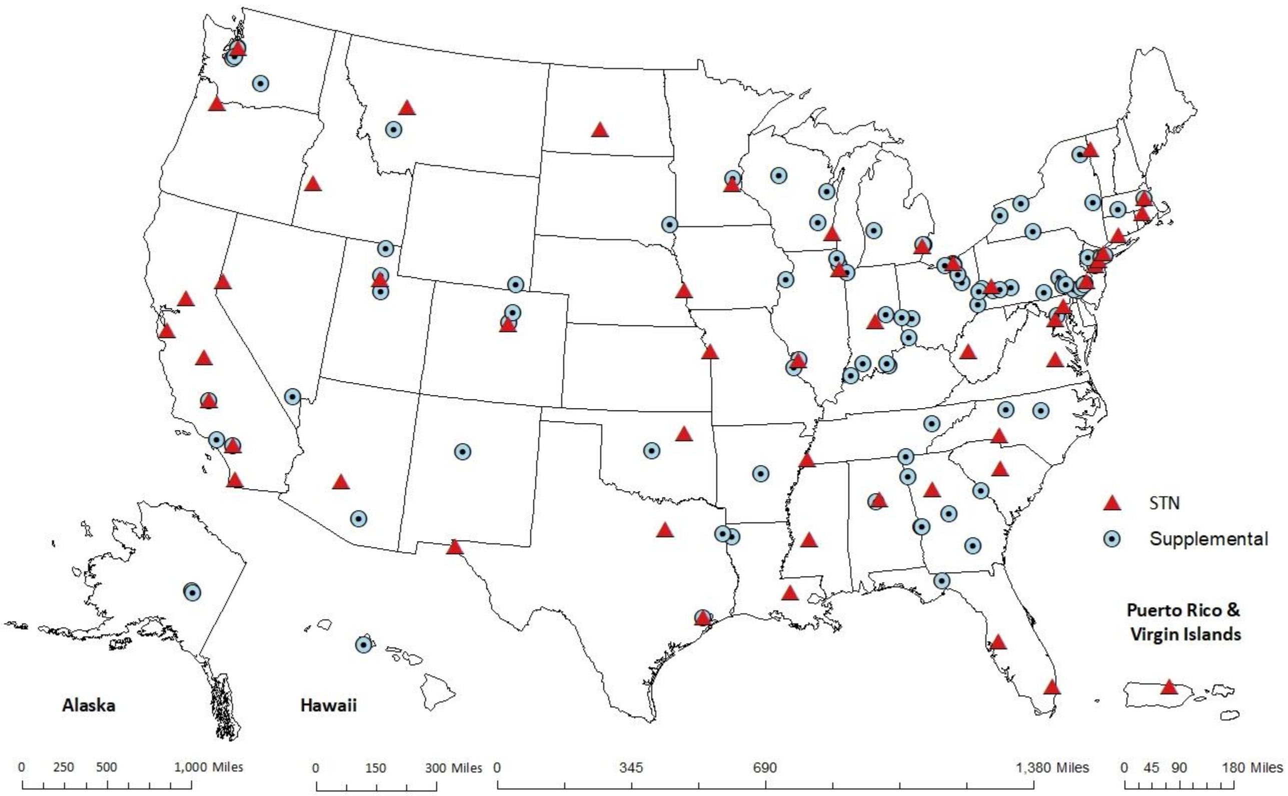

Figure 2. Map of CSN $PM_{2.5}$ sites. Figure from U.S. Environmental Protection Agency (2024).

2. SUMMARY OF PUBLISHED SCIENTIFIC PAPERS ON CONTINUOUS CARBONACEOUS AEROSOL MEASUREMENTS

The summary of the scientific literature on carbonaceous aerosol measurements in this TAD is non-exhaustive, but rather aims to supply the reader with a foundational understanding of how these measurements can be integrated into existing air quality networks. This overview includes (1) health and climate background information, (2) a summary of measurement techniques, (3) comparisons of results from different measurement techniques, (4) examples of regional monitoring and special purpose field studies, and (5) source apportionment techniques.

2.1. Health and Climate Background

Carbonaceous aerosols have garnered significant attention due to their profound impacts on human health and climate. BC is well known for its adverse effects on human health (Grahame et al., 2014; Janssen et al., 2012; Janssen et al., 2011; Smith et al., 2009; Wei et al., 2023). In addition to the general association of total particle mass with mortality, BC aerosol concentrations specifically have been shown to have more causal associations with negative health effects such as cardiovascular, respiratory, and neurological problems compared to total $PM_{2.5}$ mass or particulate matter with aerodynamic diameter ≤ 10 microns (PM_{10}), suggesting that BC measurements are a better indicator of harmful substances in particles than unspeciated PM mass measurements (Janssen et al., 2012; Smith et al., 2009). Additionally, due to the porous BC surface, BC may operate as a universal carrier of combustion-products of varying toxicity to sensitive targets in the human body, making BC a potent health hazard.

Additionally, BC particles are defined by their ability to strongly absorb all solar wavelengths present in the troposphere, and thus can directly influence climate change as a short-lived climate forcer (Bond et al., 2013; Chung & Seinfeld, 2005; Janssen et al., 2012; Janssen et al., 2011; McConnell et al., 2007; Ramanathan & Carmichael, 2008; U.S. Environmental Protection Agency, 2012). BC is estimated to be the second most important climate-forcing human emission after carbon dioxide (CO_2) (Bond et al., 2013), with Chung and Seinfeld (2005) reporting that direct radiative forcing from BC is about 70% that of CO_2. Carbonaceous aerosols can also indirectly modify the climate through their role in condensation, precipitation, and cloud formation, and are well-known to have snow/ice albedo reduction effects (Flanner et al., 2007; Ramanathan & Carmichael, 2008; Reddy & Boucher, 2007). Uncertainties in quantifying total net warming capabilities are substantial due to the involvement of BC in secondary cloud interaction impacts and because BC is commonly co-emitted with particles and gases that may have cooling effects (Bond et al., 2013; U.S. Environmental Protection Agency, 2012). The combined negative public health and strong climate effects demonstrate why accurate measurements are crucial for improving the understanding of and mitigating the impacts of carbonaceous aerosols.

The EPA 2012 Report to Congress on Black Carbon provides extensive reporting on the impacts of BC on the global and regional climate, approaches to reduce BC emissions, and an analysis of the climatic effects and other environmental and public health benefits of those approaches (U.S. Environmental Protection Agency, 2012).

2.2. Summary of Measurement Techniques

Several techniques are used in measuring carbonaceous aerosols. Two of the most common techniques are ground-based monitors that function by (1) optical absorption techniques that measure light absorption, and (2) thermal techniques that separate EC and OC using a stepped temperature gradient during the analysis. Thermal analysis measurements of this absorbing aerosol are reported as EC, and optical absorption analysis measurements are reported as BC. These measurement techniques and the differences amongst them are well described in several review papers (Correa-Ochoa et al., 2023; Lack et al., 2014; U.S. Environmental Protection Agency, 2012; Watson et al., 2005; Zhang et al., 2023), and are briefly summarized below and in Table 3.

- **Optical absorption analysis.** Optical analysis instruments measure BC via the attenuation of light transmitted through a filter as a particulate matter sample is collected on the filter. The measured attenuation is converted to a concentration using a wavelength-dependent and empirically derived factor called a mass absorption coefficient (MAC or σ_{abs}) and the Beer-Lambert law. Instruments using this measurement technique include the Aethalometer® (AE33 and earlier models) and the BC 1060.

  Uncertainties associated with this analysis type include the fact that the MAC is highly variable by source type, e.g., the absorption of BC from diesel exhaust can differ from that of wood combustion. Additionally, light scattering by the filter tape and a filter loading effect (a saturation of the instrumental response due to increasing accumulation of the sample on the filter) can bias measurements. (Bond et al., 1999; Moosmüller et al., 2009; Weingartner et al., 2003). Lastly, there are other contributors to light absorption that can bias these measurements, including the contribution of dust, brown carbon (BrC), and enhanced absorbance from the "lensing effect" of materials coated on BC (Zhang et al., 2020).

- **Thermal analysis**. Thermal analysis techniques measure EC, and work on the basis that EC is unreactive at the temperatures that will volatilize and oxidize OC and inorganics, enabling the separation of OC and EC. In this technique, the sample is collected on a filter and is heated to increasingly higher temperatures to convert the carbon species to measured amounts of CO_2. The temperature and number of steps is determined by the "protocol" used; commonly used protocols include IMPROVE_A (currently used in the IMPROVE and CSN monitoring networks), NIOSH 5040, and EUSAAR2. Differences in the results based on different protocols are summarized in Karanasiou et al. (2015) (Karanasiou et al., 2015); Watson et al. (2005). Examples of instruments using this technique include the Sunset Lab OC-EC aerosol analyzers used in the CSN, and the DRI Model 2015 carbon analyzers used in the IMPROVE network. The TCA08 works on a simplified application of this technique based on total combustion rather than a stepped temperature gradient.

  This technique can include an optical step of using transmitted or reflected light to better separate EC and OC concentrations, in which case the technique can be referred to as thermal optical transmittance (TOT) or thermal optical reflectance (TOR), such as in the CSN and IMPROVE network instruments. Additionally, thermal analysis is also often referred to as evolved gas analysis (EGA), due to the direct measurement of CO_2. For further reading see Chow et al. (1993) and Karanasiou et al. (2015).

- **Other techniques.** Other techniques for measuring carbonaceous aerosols include laser induced incandescence (LII, commercially available as the single particle soot photometer [SP2] instrument [Droplet Measurement Technologies, Boulder, CO]), photoacoustic analysis, and ramen spectroscopy. See U.S. Environmental Protection Agency (2012), Zhang et al. (2023), Lack et al. (2014), Correa-Ochoa et al. (2023), and Watson et al. (2005) for additional details on these techniques.

Table 3. Summary of measurement techniques, modified from Lack et al. (2014).

Parameter	Optical	Thermal	Laser induced incandescence (LII)
Measures	BC (absorption converted to equivalent BC by mass absorption coefficient MAC)	EC	BC (by refractive BC or rBC)
Units	Mm^{-1}, mass	Mass	Mass concentration
Collection media	In situ	Filter substrate	None – in situ
Collection time	Seconds	Hours	Milliseconds to seconds
Uncertainty	12 % – 30 %	±20 % – 50 %	5 % – 10 %
Calibration	No standard calibration material. Corrections are made based on extensive manufacturer laboratory experiments to derive empirical mass calculation factors.	Can be calibrated to model compounds but there currently is no generally accepted method for calibration of ambient EC.	Commercially available light absorbing particles, which are fullerene for the SP2.
Biases	Elevated relative humidity (RH) levels, possible elevated levels of OC Light scattering by the filter tape and filter loading artifact MAC variability by source type	Pyrolysis of OC species, inorganics	In the SP2 instrument, underestimation of mass if significant mass is in particles smaller or larger than lower or upper size threshold Refractive index variability
Measures BrC?	Multi-wavelength units can provide qualitative to semi-quantitative estimates	No	No

Ground-based measurements of carbonaceous aerosol can be loosely categorized as continuous (near real-time or in situ) or filter-based. The instruments discussed in this TAD, such as the field-based AE33 Aethalometers® and BC 1060 black carbon monitors, conduct continuous analysis by both collecting and analyzing samples in near real-time.[3] Conversely, discrete filter-based measurements generally employ separate sample collection and analysis steps. In these discrete systems, samples are collected and then sometime later transported for analysis via a laboratory-based instrument, such as in the CSN and IMPROVE networks. Note that a challenge in continuous measurements is that no standard reference material exists, and therefore uncertainties are not well constrained. Filter-based CSN or IMPROVE measurements have been used as a reference comparison.

Remote sensing techniques, such as satellites and aircraft-based instruments that use algorithms to obtain BC concentrations from aerosol optical depth (AOD) measurements, have been used to evaluate regional and long-term trends. Remote sensing products associated with BC include absorbing AOD, BC AOD, AOT, and BC surface mass simulations and emissions. These species have recently been used as training inputs for machine learning studies, and may offer additional insights in the future (Wei et al., 2023). Satellite-based measurements report total column concentrations, which are not a direct comparison to ground-level optical or thermal measurements described in this TAD. The MERRA-2 reanalysis dataset (which includes satellite data in the model) has commonly been used to analyze BC data back to 1980, and thus provides insight into long term trends. The correlation between the MERRA-2 dataset and ground-based measurements have shown good agreement at longer time intervals (e.g., monthly averages) and higher concentrations. For example, this dataset showed generally good agreement with ground-based monitors in China where seasonal means ranged from 5-9 $\mu g/m^3$ (Mao et al., 2023; Xu et al., 2020), but lower agreement at lower seasonal means near 1 $\mu g/m^3$ (Mao et al. 2023). These techniques are therefore not typically used when highly time resolved data (such as hourly measurements) is required or when ambient concentrations are less than 1 $\mu g/m^3$.

2.3. Examples of Regional Monitoring and Special Purpose Field Studies

The instruments described in this TAD have been deployed in a variety of field studies. In addition to the CSN and IMPROVE historical records, regional monitoring data have been collected for carbonaceous aerosols in southern California since the early 1960s (Christoforou et al., 2000; Gray et al., 1984), allowing for the determination of long-term trends (Kim et al., 2000; McDonald et al., 2015). Thermal optical analysis techniques were historically used to differentiate and quantify BC and OC contributions to TC mass on each filter, but continuous measurements are now made in the region using an AE33 Aethalometer®, and the results are available in the South Coast Air Quality Management District's most recent Multiple Air Toxics Exposure Study (MATES V, at the time of this publication) (Nastri et al., 2021). These most recent results (2018-2019) showed that annual average BC concentrations are 22% lower than the previous MATES IV study period (2012-2013), and that concentrations are highest during commuting hours and lower on weekends than weekdays based on diurnal and day-of-week trends, respectively.

In addition to regional monitoring efforts such as those conducted in the South Coast Air Basin, continuous carbonaceous aerosol measurements using the AE33, BC 1060, and TCA08 have been used for a variety of other specialized air quality topics. A thorough literature review of

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[3] Sometimes called 'semi-continuous' measurements, we acknowledge that both the AE33 and BC 1060 do not collect data when the filter tape is advancing, resulting in small data gaps of up to several minutes.

carbonaceous aerosol measurement studies by technique and instrument is available in Correa-Ochoa et al. (2023). A non-exhaustive list of example field studies includes:

- Traffic emissions analysis:
    - Measuring emission factors in both a stationary and in a Portable Emissions Measurement System (PEMS) setup (Ježek et al., 2015)
    - Monitoring near-road air quality and the impact of vegetative buffers (Baldauf et al., 2012; Brantley et al., 2014)
    - Evaluating the impact of a city-wide temporary ban of heavy-duty diesel traffic during an air pollution episode (Taheri et al., 2019)
- Residential and exposure analysis:
    - Continuous monitoring at schools and landfills in Los Angeles (Seagram et al., 2016)
    - Monitoring indoor exposure of children in Rwanda (Kalisa et al., 2023)
    - Monitoring wintertime $PM_{2.5}$ episodes (Watson & Chow, 2002; Xue et al., 2018)
- To aid source apportionment:
    - Using source apportionment techniques to differentiate contributions from wood burning and fossil fuels (Brown et al., 2020; Helin et al., 2018)
    - Tracing OC and BrC signatures during wildfires in 2018 (Gobeli & Brown, 2021; Healy et al., 2019; Ivančič et al., 2023)

2.4. Comparison of Optical and Thermal Measurements

Although thermal EC and optical absorption BC measurements are highly correlated, the specific quantitative relationship between them varies across countries, cities, and types of location (e.g., regional, urban, near-road) (Janssen et al., 2011), with differences by a factor of 2 being commonly reported. Several papers offer summaries of observed concentration differences using collocated measurement techniques. Early work from Watson et al. (2005) found that factor of 2 differences between BC and EC measurements are common. Park et al. (2006) deployed seven different continuous instruments ranging in averaging time from 1 minute to 1 hour, including an AE31 (the predecessor to the AE33), and compared the results to 24-hr integrated filter measurements in the IMPROVE network (Figure 3). Most of the instruments captured similar seasonal trends of increasing BC contributions to total $PM_{2.5}$ mass in winter. However, the measured concentrations showed greater variability across the instruments in winter than in summer, likely driven by the change in aerosol composition in the winter.

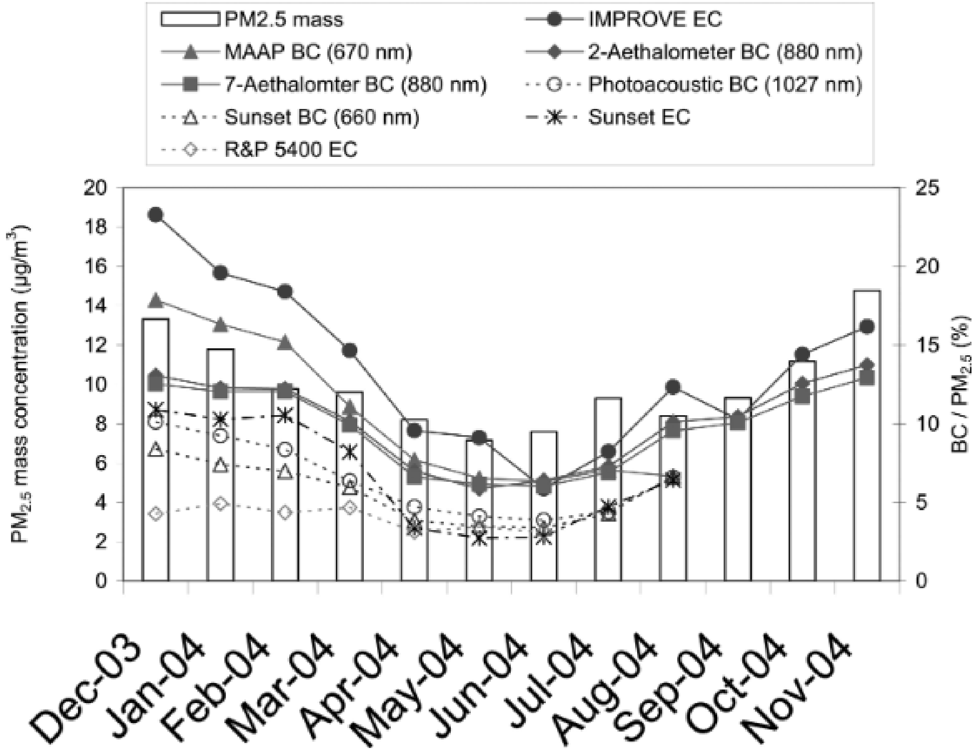

Figure 3. Monthly averages of $PM_{2.5}$ concentrations (bars) and the ratio of BC or EC concentrations to $PM_{2.5}$ concentrations recorded by various instruments (points) at the Fresno Supersite from December 2003 to November 2004. The 7-Aethalometer BC (880 nm) refers to an Aerosol Aethalometer® model preceding the AE33. From Park et al. (2006).

More recently, Brown et al. (2019) also conducted a collocated study in California comparing BC concentrations measured by the Aethalometer® to EC concentrations measured by the CSN and a Sunset continuous field instrument. This paper similarly found that differences by a factor of 2 in the optical and thermal techniques were common. This study observed that the Aethalometers® consistently measured BC concentrations about twice as high as analogous thermal EC measurements (although lower at one location), and that the thermal EC measurement concentrations were similar to nearby CSN-measured EC concentrations.

2.5. Source Apportionment Techniques

Insights into sources of carbonaceous aerosols can be determined by a combination of measurement techniques and numerical models. Analytical tools can include general source apportionment techniques, such as positive matrix factorization (PMF) (Paatero, 1997; Paatero & Tapper, 1994). Instrument specific techniques are also commonly used such as estimating BC contributions from fossil fuels and wood burning using the multi-wavelength capabilities of the AE33 and BC 1060. Additionally, use of the TCA08 in addition to the AE33 allows for calculation of OC contributions to total carbonaceous aerosol. The OC content can also be further subdivided into primary and secondary organic aerosol using a numerical model which is described below.

2.5.1. Black Carbon: Fossil Fuel and Wood Burning Contributions

Most U.S. emissions of BC come from transportation (52%), particularly diesel engines and vehicles (U.S. Environmental Protection Agency, 2016). The second major domestic source is open biomass burning (35%), including wildfires. For users looking to quantify the unique local contribution of these two factors, the multi-wavelength capabilities of the instrument can be used to estimate their relative contributions. Brown carbon (BrC) is also produced from combustion of wood or other biomass and absorbs primarily in the lower-visible to UV wavelengths (370-470 nm). While BC is measured in the optical analysis techniques in the visible range at 880 nm, the AE33 and BC 1060 both have additional wavelength channels that enable measurements in the UV range as well, and thus allow for insights into the portion of BC emitted from wood burning compared to fossil fuels. A commonly used method, often referred to as the Aethalometer® or Sandradewi model (Sandradewi et al., 2008), is to assume that all BC is only from wood burning and fossil fuel combustion, and then use the absorbance at the UV (470 nm) and IR (950 nm) wavelength channels to calculate the portion of BC emitted from wood burning ($BC_{wb\ or}\ BC_{bb}$) and BC emitted from fossil fuels (BC_{ff}). This method is also summarized in the AE33 User Manual. The resultant calculation of the percent of BC that is due to biomass burning is a direct data output of the AE33 instrument. This method has also been applied to BC 1060 data outputs, but it should be noted that the wavelengths available on this instrument are slightly different (370 and 880 nm). Many studies have employed this technique, with example applications including:

- The AE33 was used to evaluate the effects of wood smoke pollution in Sacramento County, which found BC_{wb} was less common in environmental justice communities and that hazardous air pollutants (HAPs) were more strongly correlated with BC_{ff} (Brown et al., 2020).
- The BC 1060 was used to evaluate BC exposures to school children in Rwanda. Investigators saw a two-fold increase in ambient BC_{ff} concentrations when vehicles were queuing to pick up students on school premises, followed by occasional higher BC_{ff} concentrations indoors as compared to ambient after peak drop-off times (Kalisa et al., 2023).
- The CASS instrument (combined AE33 and TCA08) was used in a wildfire smoke study in California, where higher BC and OC concentrations were observed downwind of a large wildfire, and further increases in OC were observed during the smoldering phase compared to the flaming phase of the wildfire (Ivančič et al., 2023).

High uncertainties are associated with quantifying BC_{ff} and BC_{wb} with this technique. The source apportionment approach described in Sandradewi et al. (2008) uses absorption Ångström exponent (AAE) values at 950 nm of 1.1 for fossil fuel and 1.8-1.9 at 470 nm for biomass burning sources. While the AAE for BC near 950 nm is typically near 1, the AAE values associated with biomass burning (typically between 370-470 nm) are highly variable and can be strongly affected by regional and source characteristics. For example, Healy et al. (2019) found this approach underestimated biomass contributions to BC mass in British Columbia by up to a factor of 3 during a wildfire event. Also note that the two wavelengths available for use on the BC 1060 (370 nm and 880 nm) are different than those used in Sandradewi et al. (2008) and the AE33, so quantifying BC_{ff} and BC_{wb} may yield different results than with the AE33. Additional representative source measurements and more spatially dense ambient monitoring are likely needed to better characterize these parameters.

2.5.2. Organic Carbon: Primary and Secondary Organic Aerosol

Numerical models have been developed to subdivide OC into primary organic aerosol (POA) and secondary organic aerosols (SOA) using the EC tracer method (Turpin & Huntzicker, 1995). This technique assumes that BC and POA are emitted from the same source and are thus correlated, while the correlation between BC and SOA will be low due to their different formation pathways. The application of this technique to CASS data is described in detail in Ivančič et al. (2022), where the technique was applied to a two-year data set in California. The results are shown in Figure 4, with the BC contribution shown in blacks and browns, primary aerosol contributions shown in blues, and secondary aerosol contributions shown in oranges. BC was further divided into BC_{ff} and BC_{bb}, and primary and secondary organic aerosols were also further divided into non-absorbing (non-abs) and BrC. Clear seasonal trends of high SOA concentrations are visible in summer at midday, and increased POA concentrations associated with residential heating are visible on winter nights.

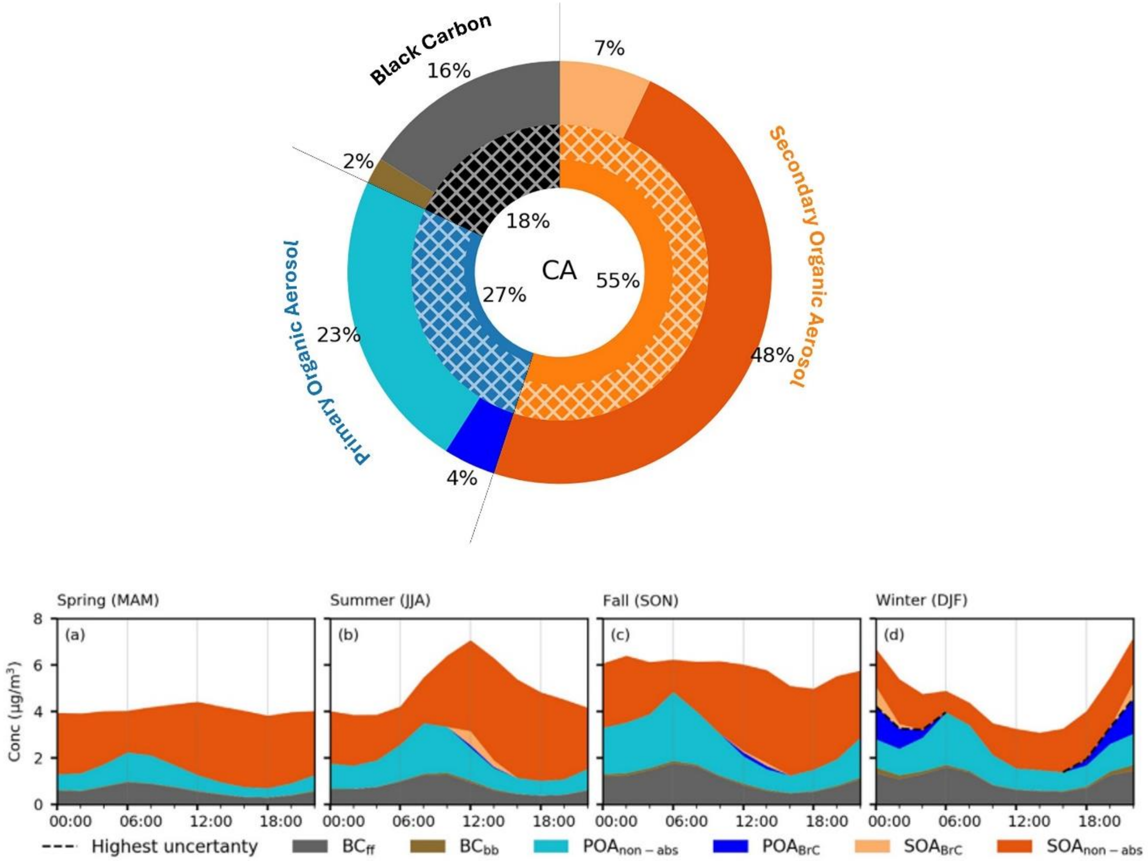

Figure 4. Two-yr average carbonaceous aerosol fingerprint (top) and diurnal median profiles (bottom) in central Los Angeles, with BC apportioned to BC_{ff} and BC_{bb}, and OC apportioned to $POA_{non\text{-}abs}$, POA_{BrC}, $SOA_{non\text{-}abs}$ (non-absorbing SOA), and SOA_{BrC} (brown carbon SOA). The black dashed lines in the diurnal profiles represent the split between POA_{BrC} and SOA_{BrC} during winter nights, where the highest uncertainty is expected to appear. Adapted from Ivančič et al. (2022).

2.6. Outlook

Continuous carbonaceous aerosol measurements offer a useful tool in understanding health exposure and climate impacts of PM pollution, and likely provide a better indicator of harmful substances in particles than unspeciated PM mass measurements. BC measurements may be useful in specifically evaluating local action aimed at reducing the population's exposure to combustion PM. Although advancements in the understanding and accessibility of carbonaceous aerosol measurement techniques have grown, challenges and limitations still exist. Measurement uncertainties have been identified in the variability in concentrations measured during collocation studies of multiple instruments, and in the spatial and temporal variability in composition of carbonaceous aerosols. As a result of these factors, there is no currently accepted reference material that can match the heterogeneity of ambient samples to use for calibration (although filter-based CSN or IMPROVE measurements have been used as a reference comparison). Uncertainties in source apportionment numerical models have also been identified, particularly due to the variability AAE values for biomass burning aerosols. With the continued evolution of measurement techniques and the growing urgency to mitigate the impacts of carbonaceous aerosol on climate change and air pollution, accurate and comprehensive carbonaceous aerosol measurements are essential for informing local and national policy decisions and implementing effective mitigation strategies. The best practices identified and discussed in this TAD are intended to aid air quality monitoring networks in measuring these important species.

3. SUMMARY OF METHODS

3.1. AE33 (Aethalometer®)

3.1.1. Principle of Operation

The Aerosol Magee Scientific AE33 Aethalometer® is the same instrument as the Teledyne Aethalometer® 633, but under a different distributor. The AE33 Aethalometer® is an optical absorption instrument, which measures the light attenuation of aerosol deposited on a filter to determine BC concentration. The general operation of the Aethalometer® has three stages: (1) an air sample is drawn into the Aethalometer® through an inlet, (2) aerosol particles are deposited on a filter tape, and (3) the filter tape is analyzed in situ for the amount of light that can pass through the optically-absorbing aerosol particles on the tape. The attenuation of light is then converted to a concentration of BC via a manufacturer-set mass absorption coefficient (MAC or σ_{abs}), the Beer-Lambert Law, and other instrument-specific correction factors.

3.1.2. Instrument Details

The inlet structure typically includes a size-selective cyclone for $PM_{2.5}$ (which also protects the analyzer from large debris and insects), a dryer and/or water trap for humid conditions, and antistatic tubing to prevent wall loss of particles. Users set their sampling time considering ambient aerosol concentrations (lower sampling time is needed for higher concentrations) as well as data objectives – for example, higher resolution than 24 hour sampling time is needed to investigate diurnal profiles. The filter tape automatically advances to provide continuous measurements (although measurements are not made while the tape is advancing which takes typically about 3 minutes).

The air sample flows (typically at 5 LPM) into the analysis chamber, where the particles are deposited onto the collection spot on the filter tape. The spot is continuously analyzed for the amount of light transmitted through the spot into the detector. As optically absorbing material accumulates on the spot, the intensity of light transmitted through it gradually decreases. BC concentration is calculated using the attenuation of light from one sampling period to the next, the known air-flow volume, and the MAC. The results are mathematically corrected for several instrument-specific effects including a leakage factor, light scattering (the scattering of light when it encounters a discontinuous or rough surface), and filter loading effects (described below).

Users set their sampling time from 1 to 50 seconds after consideration of ambient aerosol concentrations (e.g., smaller time periods for higher concentrations).

3.1.3. Filter Loading Effect Correction

In filter-based optical absorption measurements, the filter can become saturated as a higher amount of particles are deposited, and measured absorption and BC concentrations will become non-linear (**Figure *5***, red and black trace). This is known as the filter-loading effect, and often results in an underestimation of sample concentration on tape with higher PM filter loadings. The AE33 tape can be set to advance at a designated time interval or maximum attenuation to prevent filter saturation.

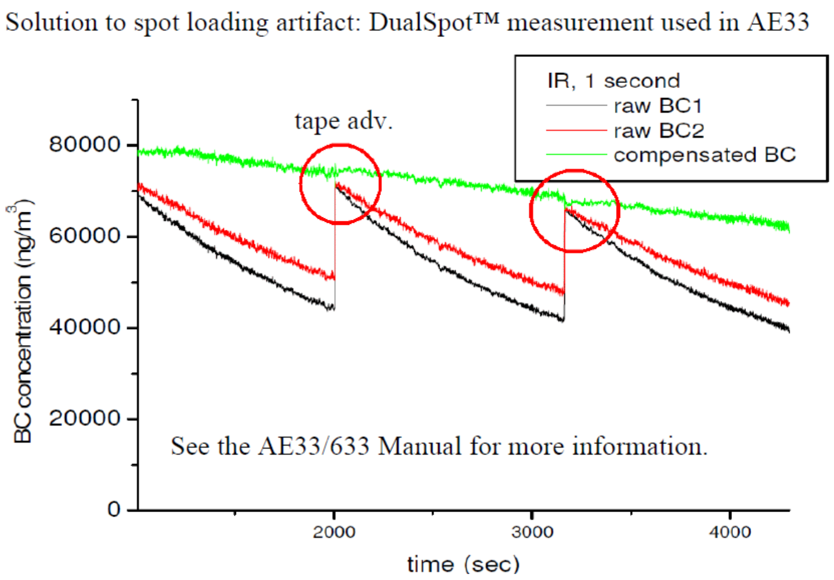

Figure 5. Example of raw and corrected AE33 BC data, from Allen (2015). Raw data from each channel are shown in black and red, while DualSpot® corrected data are shown in green.

The AE33 and newer models use a DualSpot® correction calculation to compensate for the filter loading effect. In this technique, two sample spots are collected from the same input air stream with different accumulation rates and are analyzed simultaneously (Drinovec et al., 2015). The information from the two sample spots is used to calculate a loading compensation parameter (k), which is used in the loading effect corrected concentration, as well as being made available as a data output. **Figure 5** shows an example of both the raw data (red and black trace) and DualSpot® corrected data (green trace).

3.1.4. Multi-Channel Operation

The AE33 Aethalometer® collects data at seven wavelengths of light (or channels) between 370 nm and 950 nm: 370 nm, 470 nm, 520 nm, 590 nm, 660 nm, 880 nm, and 950 nm. Channel 6 (880 nm) is the main channel corresponding to BC. The 370 nm channel measures UVPM. In most routine applications of continuous carbon monitoring, it will not be necessary to have more than the BC and UVPM wavelengths. However, detailed scientific applications may warrant a multi-channel monitor (e.g., for the source apportionment techniques described in Section 2.5). For example, 470 nm and 950 nm channels are used to determine the proportion of BC associated with fossil fuels and biomass burning.

3.2. BC 1060

3.2.1. Principle of Operation

The BC 1060 Portable Carbon Monitor is a continuous, dual wavelength, filter-based optical instrument. The general operation includes: (1) an air sample is drawn into the instrument through an inlet, (2) aerosol particles are deposited on a filter tape, and (3) continuous analysis of the filter tape is performed to determine the amount of light that can pass through the optically-absorbing aerosol particles, which is calibrated to the concentration of BC via a manufacturer-set MAC. The filter tape automatically advances to provide continuous measurements (although measurements are not made while the tape is advancing which takes typically about 3 minutes).

3.2.2. Instrument Details

This instrument includes its own weather-proof, portable shelter. Ambient air is drawn into the instrument at a controlled flow rate through a size selective external inlet (e.g., $PM_{2.5}$). The overall flow rate is fixed at 2 LPM, and adjustments can be made with a dilution flow system. After the inlet system, the sampled air is subsequently drawn through a heated internal inlet section and then through glass fiber filter tape, capturing PM from the air stream. The tape is continuously analyzed for light transmission through the spot into the detector. As optically absorbing material accumulates on the spot, the intensity of light transmitted gradually decreases. The decrease in light intensity from one measurement to the next is interpreted as an increase in collected material. To calculate the BC concentration, the light intensity is divided by the known air-flow volume and corrected for scattering.

Users set their sampling time from 1 minute to 1 hour after consideration of ambient aerosol concentrations (e.g., smaller time periods for higher concentrations).

3.2.3. Filter Loading Effect Correction

The filter loading effect (described in Section 3.1.3) is more pronounced as the PM accumulation on a given spot increases and is more apparent in highly time resolved data when BC concentrations are high. Unlike the DualSpot® correction calculation used by the AE33, the BC 1060 recommends mitigating the filter loading effect by setting the automatic tape advance set point to 0.1 - 0.3 (or 10-30%)[4] to reduce the chance that sufficient PM has been deposited onto the tape to cause the attenuation of the selected channel to exceed the factory-recommended or a user-selected level.

3.2.4. Multi-Channel Operation

The BC 1060 is a two-wavelength BC monitor. It measures and records optical transmission at 880 nm and 370 nm. Measurements at 880 nm are used for BC concentrations and measurements at 370 nm are used to calculate UVPM. These channels have been used in a modified application of the Sandradewi model of source apportionment to determine the contribution of BC from fossil fuels and biomass burning (in place of the 470 nm and 950 nm channels available on the Aethalometer®).

3.3. TCA08

3.3.1. Principle of Operation

The Total Carbon Analyzer, Model TCA08, differs from the AE33 and BC 1060 in that it uses a thermal analysis technique (rather than an optical absorption technique) to measure the TC

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[4] Default setting is 0.3, however a recent presentation by Met One recommended the set point be 0.1.

content of suspended aerosol particles in real-time. When the instrument is used in tandem with the AE33, it allows for the calculation of OC by difference from the TC and BC measurements.

3.3.2. Instrument Details

The Total Carbon Analyzer air sample is drawn through the inlet at a controlled flow rate of 16.7 liters per minute (LPM). The inlet includes a charcoal denuder to remove volatile organic compounds (VOCs) that would interfere with OC aerosol concentration measurements. The instrument collects PM on a quartz fiber filter enclosed in the sampling chamber. The instrument analysis chamber has two identical parallel channels. While one channel is collecting a sample, the second channel analyzes the sample collected during the previous period, providing continuous operation. The sampling time can be set from 20 minutes to 24 hours, depending on the ambient aerosol concentrations, with default measurements set to 60 minutes.

After collection on the quartz fiber filter, two flash-heating elements completely combust the sample instantaneously in a flow of filtered ambient air. Combustion converts all carbonaceous compounds into CO_2 and creates a short, but large-amplitude, pulse of CO_2 in the analytic flow, which is passed to a non-dispersive infrared (NDIR) CO_2 detector. The background level of CO_2 in the ambient air is determined before and after the heating cycle, providing the baselines against which the combustion pulse is measured. The CO_2 concentration over the baseline is integrated to give the TC content of the sample. The chamber and combustion elements are cooled after analysis.

3.3.3. Combining the TCA and AE33 (CASS)

The CASS is a combination of the TCA08 and AE33 instruments, which measure TC and equivalent BC, respectively. Given the following equation:

$$\mathrm{TC} = \mathrm{OC} + \mathrm{EC} \qquad \text{Eq. 1}$$

it follows that OC = TC – EC. In the CASS, the TCA and AE33 are connected and the data from the two instruments are automatically combined to provide a characterization of OC in near-real-time.

4. MONITORING OBJECTIVES AND RELATIONSHIP TO SITES AND NETWORKS

4.1. Monitoring Objectives

Carbonaceous aerosol measurements in high time resolution can assist a wide variety of monitoring objectives to support air quality management goals. Air quality monitoring agencies should review their Data Quality Objectives (DQOs) Plan to determine the specific goals they aim to achieve with carbon monitoring. Objectives supporting air quality management could include:

- Providing particle speciation information at air quality monitoring sites that enhance the network's ability to support decision makers on $PM_{2.5}$ NAAQS compliance.
- Providing emissions source information, such as the portion attributed to traffic and wildfires, to inform PM attainment goals, exceptional event documentation, and emissions reductions strategies.
- Exploring potential reductions in health-based risks related to BC inhalation exposure.
- Monitoring reductions in climate-forcing BC particles.
- Tracking long-term trends.
- Performing geospatial comparisons to other monitoring locations in the national air monitoring network. The ability to evaluate trends against other sites in the national network requires data collection and analysis methods to be performed in a standardized way, which is described in this TAD.

While many of these objectives could also be assisted by discrete, filter-based, longer time averaged carbonaceous aerosol measurements, the continuous measurements covered in this TAD enable the capability of high-resolution data that can (1) reveal diurnal profiles, (2) elucidate start and end periods for high-impact but infrequent events (e.g., industrial plumes or wildfire exceptional events), and (3) enable comparison with wind speed and direction data to assist in determining or confirming source direction.

4.2. Network Design Considerations

The specific elements of a network design, including the appropriate number of monitors, would be determined through analysis and subsequent discussion with EPA, and following its guidance documents available on the Ambient Monitoring Technology Information Center (AMTIC) website.[5] For example, the Ambient Air Monitoring Network Assessment Guide walks through network considerations, and a chapter is available in the EPA QA Handbook Vol II, section 6.0 on network design.[6] Ideally, the carbonaceous aerosol monitor would be collocated with a $PM_{2.5}$ mass monitor and a meteorological monitor providing wind speed and direction, as summarized in **Table *4***. A carbonaceous aerosol monitoring network can also be designed to:

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[5] https://www.epa.gov/amtic/ambient-air-monitoring-network-assessment-guidance-documents

[6] https://www.epa.gov/sites/default/files/2020-10/documents/final_handbook_document_1_17.pdf

- **Complement existing programs.** The continuous carbon measurements can be integrated with existing programs such as criteria pollutant monitoring, Photochemical Assessment Monitoring Stations (PAMS), National Core (NCore), CSN, etc., and take advantage of the efficiencies of scale of these programs to the extent that methodologies and operations are compatible. Near-road NO_2 measurements in particular can be informed by collocated measurements of BC as described in the Near-Road NO_2 measurements TAD (Watkins & Baldauf, 2012). Establishing continuous carbonaceous aerosol measurements at existing sites leverages the existing resources of experienced operators and infrastructure to achieve program objectives.
- **Reflect community-oriented population exposure.** For population exposure, stationary monitors are sited to be representative of average concentrations within a 0.5- to 4-kilometer area (i.e., neighborhood scale). These neighborhood-scale measurements are reflective of typical population exposure and can be incorporated in the estimation of long-term population risk. Consistent and long-term monitoring can provide information on new near-field sources impacting the measured concentrations.
- **Represent geographic variability.** A monitoring network should represent the variety of conditions (topography, altitude, proximity to large bodies of water, etc.) and environments in the airshed that will allow characterization of different emissions sources and meteorological conditions. Continuous carbonaceous aerosol measurements support population risk characterization, the determination of relationships between emissions and air quality under different circumstances, and tracking emissions changes.

Table 4. Potential Benefits of Collocated Monitors and/or Networks

Priority	Measurement	Potential Benefit
Primary	$PM_{2.5}$	Correlation and percent of total $PM_{2.5}$.
Primary	Wind speed and direction	Pollution roses and polar plots for source identification.
Secondary	Near-road NO_2 measurements	Identification of traffic related trends. Support multipollutant monitoring recommended by the Clean Air Scientific Advisory Committee (CASAC) – see the near-road NO_2 monitoring TAD. (Watkins & Baldauf, 2012)
Secondary	Collocation of multiple BC/EC monitors	Inform instrument precision and accuracy. Although many SLTs may not have resources to collocate monitors continually, they may benefit from an initial collocation study period.
Secondary	CSN or IMPROVE	Inform instrument precision and accuracy and comparison of BC/EC measurements. CSN or IMPROVE data have been considered a reference measurement in some studies.

4.3. Siting

Two of the instruments covered in this document—the AE33 and the TCA08—require installation in a temperature-controlled shelter, while the BC 1060 has no special shelter needs. The continuous carbonaceous aerosol instruments share the typical siting requirements as other instruments that sample and analyze PM. For example, although these instruments do not measure criteria pollutants, EPA recommends that all monitors are sited in accordance with EPA Title 40, Code of Federal Regulations Part 58, Appendix E. The inlet should be in the "breathing zone" between 2 and 15 meters above the ground. The inlet should also be a minimum of 1 meter, and preferably 2 meters, from any immediate obstructions and other sampler inlets. Large obstructions should be twice the height of the obstruction from the inlet.

Note that the AE33 manual states that the warranty may be void if there is "exposure to weather or rain, or the passage of water through the Product's air sampling and handling systems, exposure to excessive dust, transportation in improper packaging and damage due to internal condensation of water, if the Product is sampling outdoor air with a very high humidity, and the Product is in a room with excessively cold air-conditioning with a temperature below the condensation point of the outdoor sample air, leading to condensing of water inside the Product." Thus, following typical practices to ensure no condensation in the inlet line is important for both instrument operations and for acquiring valid data.

For the instruments covered in the TAD, data should be reviewed on a daily-to-weekly basis, so an internet connection or datalogger to routinely acquire the data is needed, as is site access to conduct maintenance or troubleshoot instrument issues. Wind speed, direction, and relative humidity are optional meteorological sensor accessories for the BC 1060, AE33, and TCA. The BC 1060 includes an ambient temperature and barometric pressure sensor.

5. DATA QUALITY PLANNING AND QUALITY ASSURANCE

5.1. Overview

Data quality planning and quality assurance are described in detail in the EPA Best Practices for Review and Validation of Ambient Air Monitoring Data (U.S. Environmental Protection Agency, 2021). This section briefly reviews data quality objectives (DQOs), data quality indicators (DQIs), and monitoring quality objectives (MQOs). These terms are defined in the following bullets and Figure 6 provides a comparison of DQOs, DQIs, and MQOs:

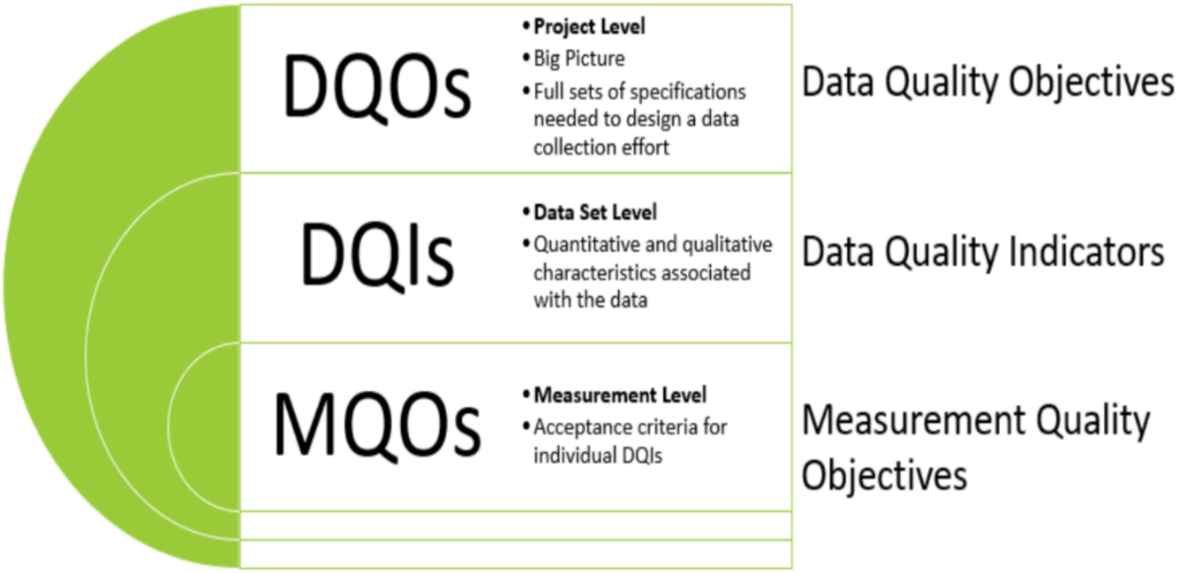

Figure 6. Comparison of DQOs, DQIs, and MQOs. Figure from U.S. Environmental Protection Agency (2021).

- **Data Quality Objectives (DQO)s.** DQOs are the guiding set of goals on which to build a quality system. They are qualitative and quantitative statements derived from the systematic planning process that: clarify the purpose of the study, define the most appropriate type of information to collect, determine the most appropriate conditions from which to collect that information, and specify tolerable levels of potential decision errors (U.S. Environmental Protection Agency, 2017). Qualitative DQOs for the Ambient Air Quality Monitoring Program are identified in 40 CFR Part 58. The quantitative DQOs for ambient monitoring of the criteria pollutants are specified in 40 CFR Part 58, Appendix A, Section 2.3.1.
- **Data Quality Indicators (DQIs)** are quantitative and qualitative attributes associated with data. The principal DQIs include representativeness, comparability, sensitivity (i.e., detection limit), precision, bias, and completeness.
- **Measurement Quality Objectives (MQOs).** MQOs serve as control limits in the data review process, and are often defined in terms of the DQIs. MQOs are designed to evaluate and control various phases (e.g., sampling, transportation, preparation, and

analysis) of the measurement process to ensure that total measurement uncertainty is within the range prescribed by the DQOs.

5.2. Data Quality Objectives

Setting quality objectives for data collection is imperative to ensure data will meet specific project needs. The EPA has established policy which states that before information or data are collected on Agency-funded or regulated environmental programs and projects, a systematic planning process must occur during which performance or acceptance criteria are developed for the collection, evaluation, or use of these data (U.S. Environmental Protection Agency, 2006).

Air quality managers should refer to the Guidance on Systematic Planning Using the Data Quality Objectives Process (U.S. Environmental Protection Agency, 2006), which provides information on how to apply the systematic planning processes to generate performance and acceptance criteria for collecting environmental data. In short, the DQO Process should identify:

- What question(s) will the data resolve?
- Why is a specific type, quantity, and quality of data needed?
- How will the data be used to make a defensible decision?
- How much data are required?
- What resources are needed?

The DQO process encourages efficient planning by generating clearly stated objectives, providing a framework for organizing complex issues, limiting the chances of decision errors, and resulting in efficient resource expenditure.

5.3. Data Quality Indicators

DQIs are quantitative and qualitative attributes associated with data designed to evaluate and control various phases (e.g., sampling, transportation, preparation, and analysis) of the measurement process to ensure that total measurement uncertainty is within the desired range (U.S. Environmental Protection Agency, 2017). EPA has not specified required DQIs for carbonaceous aerosol measurements, but these can include the principal DQIs such as precision, bias, completeness, and detectability. Definitions of these DQIs are included below (Camalier et al., 2007). Specific diagnostic data in the instrument data feed may also be useful, including status codes, flow rates, and loading factor parameters.

- **Representativeness** - the degree in which data accurately and precisely represents a characteristic of a population, parameter variation at a sampling point, a process condition, or an environmental condition.

- **Precision** - a measure of agreement among repeated measurements of the same property under identical, or substantially similar, conditions; expressed generally in terms of the standard deviation. This is the random component of error. Precision is estimated by various statistical techniques using some derivation of the standard deviation.

- **Bias** - the systematic or persistent distortion of a measurement process that causes errors in one direction (i.e., the expected sample measurement is different from the sample's true value). Bias is determined by estimating the positive and negative deviation from the true value as a percentage of the true value.

- **Detectability** - the determination of the low range critical value of a characteristic that a method specific procedure can reliably discern.

- **Completeness**- a measure of the amount of valid data obtained from a measurement system compared to the amount that was expected to be obtained under correct, normal conditions.

- **Comparability** - a measure of confidence with which one data set can be compared to another.

5.4. Measurement Quality Objectives for Associated Data Quality Objectives

MQOs are acceptance criteria for DQIs. EPA has not specified DQIs for carbonaceous aerosol measurements, and thus has not specified associated MQOs. For the purposes of the instruments covered here, manufacturer defined values could be used as MQOs. This section includes examples that have been used in the literature, and the end of this section includes a general example of an MQO check list (Table 5) and a specific example from an SLT monitoring agency (Table 6).

5.4.1. Representativeness

Potential sites should be chosen based on their representativeness of estimated or potential carbonaceous aerosol emissions. The unique characteristics of a location that could be considered in representativeness include proximity to a substantial stationary source or mobile sources. The EPA recognizes that state and local air agencies will likely have a good understanding of whether candidate monitoring sites have unique characteristics that do or do not represent the CBSA that those sites are within. The EPA encourages state and local air agencies to use their local knowledge in site selection and to engage the EPA Regional staff for assistance in evaluating such a situation as necessary.

5.4.2. Precision

For the carbonaceous instruments described here, precision can be assessed by collocating identical samplers and comparing reported concentrations. This could be accomplished by collocating two or more instruments temporarily when they are first acquired to ensure precision is established. However, many agencies may not have the infrastructure and instrumentation to perform collocated sampling. If feasible to run collocated instruments, a goal of a coefficient of variation (CV) ≤15% for 24-hr averaged data may be appropriate. Previous work has used this value for continuous carbonaceous aerosol measurements using a different instrument (Sunset OC/EC measurement) and is likely applicable to these instruments (Brown et al., 2018; Brown et al., 2019).

5.4.3. Bias

Measurement system bias is typically quantified by introducing standard reference material into a measurement phase and evaluating the results. However, there is currently no accurate reference standard or way of introducing a known concentration of carbonaceous aerosol into a sampler for these instruments. Total measurement system bias may be characterized by comparison to a collocated measurement from a filter-based method which can act as the reference standard. For example, bias has been estimated by collocating and comparing reported concentrations at a CSN site (Brown et al., 2019). This study used an MQO of 15% for bias, and observed bias was between 5-7% for similar continuous carbon aerosol instruments (Sunset OC/EC).

Instrument flow rate drift and comparison against flow standards have also been used as an approximation of bias (California Air Resources Board, 2019). Similarly, leak checks and temperature and barometric pressure sensor checks with a standard are bias measurements. For reference, MQOs for $PM_{2.5}$ on these diagnostics are flow ± 4%, temperature ± 2 °C, pressure ± 10 mm Hg. Users should refer to the specific instrument manual to evaluate appropriate ranges of these diagnostics.

5.4.4. Detectability

The manufacturer of each instrument provides target detection limits in the instrument manuals, which may vary by model. As an example, the AE33 reports a detection limit of 0.005 $\mu g/m^3$ for hourly BC measurements. The BC 1060 reports lowest detection limit (LDL 2σ) of < 0.008 $\mu g/m^3$ at 1-minute measurement intervals and < 0.001 $\mu g/m^3$ at 1-hour measurement intervals. The TCA08 lists a range of 0.3 $\mu g/m^3$ to 300 $\mu g/m^3$ of total carbon on a 1-hour measurement interval.

5.4.5. Completeness

Completeness is calculated as the percent of valid data out of the number of possible samples, and typically has a goal of 75% or greater (California Air Resources Board, 2019). Acceptable completeness would be contingent on the data representativeness chosen for the given purpose (how many sampling events completed per time period) based on the determined DQOs.

5.4.6. Filter loading correction

The AE33 reports loading factor parameter (k) values, which indicate the loading correction parameter being used on a given data point. If the k values reach and stay at a maximum or minimum for multiple hours or days (e.g., 12 hours or more), this may indicate an error in the correction and thus detectability of BC, and data should likely be invalidated.

Typical k values for Channel 1 are 0.002 to 0.003. With the most recent change to the type of tape that is included with the AE33 to correct for issues such as lateral leakages, from Part No. 8050 to Part No. 8060, k values are reported to be less consistent for higher wavelength channels and more consistent for lower wavelengths.

A similar metric is not available on the BC 1060, as the filter loading effect is mitigated by setting the automatic tape advance set point to 0.1 - 0.3 (or 10-30%),

5.4.7. Status Codes

The instruments covered in this document report status codes associated with each data point. These codes include errors, alarms, and status changes, and thus do not automatically indicate that the data are invalid. Descriptions of the status codes are available in the user manuals. Recommendations on review of these status codes are included in Section 8.2 in this document.

5.4.8. Examples

Example MQO checks are given in Table 5.

Table 5: Example MQO checks

DQI	MQO	Additional test needed to obtain
Representativeness	Site suitability discussed in Section 5.1	--
Precision	15%	Collocated instruments
Bias	15%	Collocated filter-based instrument
Flow	~4% (check specific user manual)	Check against reference standard
Temperature	~2 °C (check specific user manual)	Check against reference standard
Pressure	10 mm Hg (check specific user manual)	Check against reference standard
Detectability	See user manual for specific instrument and time base	--
Completeness	> 75%	--
Mass loading correction	K1 between 0.002-0.003 (for AE33 only)	--

An example of how these criteria have been applied at an SLT monitoring agency using a BC 1060 for BC measurements is shown in Table 6.

Table 6. Example of QA/QC checks applied at an SLT using a BC 1060. Table adapted from the San Diego Air Pollution Control District (SDAPCD).[7]

QA/QC Criteria	Frequency	Acceptance Criterion
Field Calibrations and Routine Checks		
One-point flow rate check at design flow rate	Monthly	±5% of transfer standard; and ±5% of design flow rate
External leak check	Conducted with monthly flow check	≤ 0.1 L/min
One-point temperature check	Monthly	±2 °C of standard
Pressure verification	Monthly	±10 mmHg
Clock/timer verification	Monthly	1 min/month
Other calibrations as specified by manufacturer	Per manufacturer's SOP	Per manufacturer's SOP
Quarterly Checks and Audits		
External leak check	Semi-annual unless failed audit then at least quarterly until passes for 2 quarters	≤ 0.1 L/min
Temperature audit	Semi-annual unless failed audit then at least quarterly until test passes for 2 consecutive quarters	±2 °C
Pressure audit	Semi-annual unless failed audit then at least quarterly until passes for 2 consecutive quarters	±10 mmHg
Flow rate audit	Semi-annual unless failed audit then at least quarterly until passes for 2 consecutive quarters	±5% of audit standard ±5% of design flow rate
Initial Installation Calibration and Recalibrations Thereafter		
Temperature calibration	On installation, annually, or if verification/audit indicates drift or failure	±2 °C of standard
Pressure calibration	On installation, then annually, or if verification/audit indicates drift or failure	±10 mmHg
Flow rate calibration	On installation, annually, or if verification/audit indicates drift or failure	±2% of transfer standard at each flow rate
Design flow rate adjustment	As needed	±2% of design flow rate

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[7] https://www.sdapcd.org/content/dam/sdapcd/documents/capp/meetings/int--border/03-15-23/CAMP%20Supplemental%20Information%20Document.docx

5.5. Incorporating into a Quality Assurance Project Plan

MQOs should be included in a QAPP following standard EPA guidance as to the level of the QAPP needed; see the EPA's Office of Air Quality Planning and Standards' (OAQPS) QAPP category descriptions for more information (U.S. Environmental Protection Agency, 2020). Continuous carbonaceous aerosol measurements are not a regulatory requirement, so a lower-level QAPP (i.e., higher number category) or a supplementary data QAPP may be more appropriate. The QAPP graded categories are summarized in brief here:

- **Category I** projects produce results that are autonomous. These projects are of sufficient scope and substance that their results could be used to directly support rulemaking, enforcement, regulatory, policy decisions, compliance, or other litigation. These projects require the most rigorous and detailed QA, as the resulting data must be both legally and scientifically defensible.
- **Category II** projects are those that complement other projects in support of regulatory or policy decisions. Such projects are of sufficient scope and substance that their results could be combined with those from other projects of similar scope to provide the necessary information for making decisions.
- **Category III** projects are those that are interim steps in a larger group of steps or projects. Such projects include those producing results that are used to evaluate and select options for interim decisions, or to perform feasibility studies or preliminary assessments of unexplored areas for possible future work.
- **Category IV** projects are those involved in studying basic issues, including proof of concepts, screening for particular analytical species, etc. These projects are non-regulatory and are typically limited in their scope.

6. INSTALLATION – RECOMMENDATIONS AND BEST PRACTICES

This section provides recommendations and best practices for the installation of a continuous carbonaceous aerosol instrument, including (1) acceptable shelters for the instruments, (2) temperature control systems, (3) inlet and separators, (4) sample stream dryers, (5) external or internal temperature and pressure control systems, and (6) options for connecting the instruments to data acquisition systems.

In general, installation of a continuous carbonaceous aerosol instrument will include the inlet, a size-selection cyclone, an insect screen, a water trap, and potentially a sample dryer. The inlet line should be kept as short as practical (less than 3 to 4 meters), avoid bends, and be a static-dissipative material to reduce wall loss of particles. The instrument and inlet line should be kept out of the airflow of air conditioners, as detailed in Section 6.4, and the rear area of the instrument should be kept accessible for maintenance.

Specific instructions for the instruments can be found in their respective SOPs, as well as the following sections of the user manuals (note these sections may be user manual revision or version specific):

- AE33 – Section 7: Instrument installation (Aerosol Mageee Scientific, 2021)
- BC 1060 – Section 3: Setup and deployment (Met One Instruments, 2020)
- TCA08 – Section 7: Instrument installation (Aerosol Mageee Scientific, 2022)

6.1. Acceptable Shelters

The BC 1060 has no special shelter needs. It can be mounted on its included stand and deployed outdoors when connected to a weatherproof outdoor electrical outlet. It can also be fitted with the optional Met One BCX-801 roof top extension kit and placed indoors on a table or other elevated, even surface. The AE33 and TCA08 are designed for indoor or sheltered use only and are not weatherproof. These instruments should preferably be installed indoors on an even surface and operated at ambient temperatures from 10 to 35°C. The instruments are intended for use in rack-mount installations or placement on top of a bench.

If the instruments are installed in a small enclosure, the enclosure must be ventilated by a fan. Users should additionally consider space for an air conditioning system and sample stream dryer if the ambient RH is expected to be an issue. Table 7 provides a summary of operating conditions for each instrument.

Table 7. Environmental operating conditions.

Parameter	AE33	BC 1060	TCA08
Weather-proof shelter	Required	Not required	Required
Altitude	Up to 3,000 m, or extended to 5,000 m with external pump	Not evaluated by manufacturer	Up to 3,000 m

Parameter	AE33	BC 1060	TCA08
Temperature range	10 – 40°C	-20 – 50°C	10 – 35°C
RH range	5-95%, non-condensing	0-95%, non-condensing	30% - 80%, non-condensing
Power supply	Can be supplied with 100 to 240 VAC	Can be supplied with 100 to 240 VAC	Can be supplied with 100 to 240 VAC
Power consumption	25 W average, 90 W max	102 W max	1,500 W
Flow	Typically, 5 LPM. Adjustable from 2-5 LPM.	2 LPM total. Can be modified via a dilution flow system for higher concentrations.	16.7 LPM
Unit dimensions	Standard 19”/6U, rack mount (note that a potential sample dryer will need additional space)	12 in (h) × 14 in (w) × 14.5 in (d)	Standard 19”/6U, rack mount
Unit weight	~45 lbs	~35 lbs	~77 lbs

6.2. Inlet and Separators

Although EPA probe and siting criteria (Appendix E to 40 CFR Part 58) are not required for continuous carbonaceous aerosol measurements, they are useful to reference. Generally continuous carbonaceous aerosol inlet heights should be 2 – 15 meters above the ground. Carbon measurements at smaller spatial scales including micro- and middle-scale should have inlet height of 2-7 meters off the ground. The inlet should be unobstructed, securely fixed, and placed at a distance of at least 0.5 meters from any roof or walls. EPA’s guidance in 40CFR part 58, Appendix E recommends that the sampling inlets be located within 1 meter, and preferably 2 meters, from other sampler inlets or any immediate obstructions, and that the inlet should be at twice the height of any large obstructions.

An inlet cyclone for size selection should be used, typically selecting for $PM_{2.5}$. The cyclones should be cleaned routinely via the procedure listed in the individual manuals. Although the cyclone can also serve as an insect trap, it is recommended that at least a screen is maintained on the cyclone inlet to keep the cyclone clean. If insects are able to enter the cyclone, webs can affect the particle filtration, and heavy rain in windy conditions can enter the cyclone, resulting in inaccurate measurements and damage to the flow meters. Additionally or alternatively, a water trap is recommended on the inlet line at a point close to the instrument and clearly visible.

Inlet cyclones should also be appropriately selected for the instrument flow rate. The AE33 has an adjustable flow rate from 2-5 LPM. The BC 1060 has a set total flow rate into the cyclone of 2 LPM because the sharp cut cyclone requires a total 2 LPM flow rate to perform correctly. At higher carbonaceous aerosol concentrations, BC 1060 users can use the dilution flow system, which can dilute the sample by 50 to 80%. This system is described in detail in Sections 5.1 and 5.2 of the BC 1060 user manual. Current instrument users report using a TSP inlet to prevent intrusion of unwanted items (such as insects or rain) placed before the dilution air flow adaptor, followed by the size selection cyclone.

The initial downtube after the cyclone on the BC 1060 is metal. There is an adapter to conductive tubing at the bottom of the downtube. Conductive tubing must be used to provide air flow from the sampling system to the inlet of the instruments. It is recommended to use black conductive tubing or similar antistatic black tubing to reduce wall loss of particles. It is recommended to avoid using Tygon®, Teflon™, or stainless-steel tubing, which all risk the loss of sample material on the tubing walls from static. It is also important to kept the inlet tubing at a minimal length and avoid bends and long horizontal stretches of tubing to minimize particle losses.

6.3. Sample Stream Dryers (Aethalometer®)

Humidity is a major consideration in a continuous carbonaceous aerosol sampling system. The operational humidity range is described in Table 7. If the instrument is sampling outdoor air with very high relative humidity or is in a room with air conditioning set to a temperature below the condensation point of the outdoor sample air, water can condense inside the instrument, which may result in significant measurement noise, system damage, or bias in the measurements. In high humidity conditions, the use of the sample stream dryer (Nafion®) accessory is recommended for the AE33 to remove water vapor from the sample air stream. The use of a dryer does add a significant space consideration of approximately 3 feet (82 cm length and 11 cm diameter).

6.4. Recommendations for Shelter Temperature Control

The operating temperature range of each instrument is described in Table 7. If an air conditioning system is required for optimal sampling conditions, it is important to not install the instrument directly in front of or under a heating, ventilating, and air conditioning (HVAC) unit. For rack mounted instruments in general, do place the HVAC unit on the opposite side of the shelter (if possible), do not direct the air flow of the HVAC unit toward the instruments, and do use a properly sized HVAC unit. A physical barrier is not always necessary, but a physical barrier (e.g., insulating pipe foam) may be placed between the HVAC unit and the instrument if issues arise, because small amounts of condensation and temperature changes may affect measurements. It is additionally recommended that any sample inlet tubing be insulated from air conditioning cold air discharge. Common symptoms of inadequate temperature and humidity control include large swings of concentration at times of rapid outdoor temperature changes (e.g., sunrise or sunset) which affect the temperature-sensitive optical equipment.

6.5. External or Internal Temperature and Pressure Sensors

Mass calculations for BC require a known volumetric flow rate. Note that this setting will affect how data are reported in AQS (see Section 8.4). The AE33 is equipped with a built-in mass flow meter, and measurements are converted to volumetric units using either:

1. **Recommended: Local or ambient temperature and pressure readings (LC) from an external probe connected to one of the AE33 serial ports.**

   Volumetric flow is recommended to be calculated and reported at local (or ambient) conditions of temperature and pressure. EPA prefers this option because it aligns with the regulatory $PM_{2.5}$ measurements and will improve the accuracy of cut points on size selection devices. Temperature and pressure may either be provided in real-time by a meteorological sensor connected to the instrument or input manually through post-processing.

2. **Not recommended: Standard preset temperature and pressure (STP), or a set temperature and pressure of the user's choosing:**

   The AE33 also offers the option to choose from different flow reporting standards. These flow reporting standards are the pressure and temperature that the instrument uses to calculate volumetric flow, based on the mass flow measured by the flow sensors. A variety of reporting standards are offered, such as STP (temperature set to 0 °C and standard pressure to 101325 Pa). Using STP can enable standardization of concentrations across varied sites but is not necessarily true to the actual conditions and not consistent with the EPA's recommendation to report air quality data at local conditions.

The TCA and BC 1060 should also be set up to report data at local conditions. The BC 1060 has its own temperature and pressure sensor, and the TCA can use its own or the AE33 temperature and pressure sensor.

The flow reporting standard selection influences the way the data are reported to AQS, which will be detailed in Section 8.4.

- AQS code 88313: Black Carbon $PM_{2.5}$ at 880 nm (LC)
- AQS code 84313: Black carbon $PM_{2.5}$ STP (STP)
- AQS code 88314: UV Carbon $PM_{2.5}$ at 370 nm (LC)
- AQS code 84314: UV Carbon $PM_{2.5}$ STP (STP)

EPA recommends only using the STP option if also reporting data in LC.

6.6. Connection to a Data Acquisition System

Data can be exported from any of the instruments onto a USB memory stick and then uploaded and stored. A data acquisition system is an easier way to acquire, QA, and store data, and can be accomplished with systems described in this section.

6.6.1. AE33

The instrument can be connected to a data acquisition system in one of two ways:

1. Through the RS-232 serial cable port using a DB9 crossover cable (or a standard serial cable, in which the transmit and receive lines are swapped, with a null modem adaptor) connecting to, for example, a datalogger.
2. Through the Ethernet port on the instrument, allowing the Aethalometer® network access for remote batch or streaming data acquisition, retrieval of instrument status, and control of instrument operations.

The instrument supports data acquisition using multiple protocols, including Bayern-Hessen (BH) and Qair. For more details, including a list of currently supported devices, see the AE33 user manual, Section 10 – Serial Data Port Connections.

The two most frequently used data loggers, Agilaire AirVision and DR DAS Envidas Ultimate, both have the capabilities to log additional data streams of interest, such as k values for both relevant channels, flow rates, and status codes. Additionally, both programs are capable of monitoring the status channel and automatically invalidating data points where the status code is equal to certain values.

6.6.2. BC 1060

The unit can be connected to a local computer, digital data logger, or a remote network connection using the serial data output. The serial data output can be routed through the RS-232 data port or the USB serial converter port. Access to the data through the serial ports is available using a terminal emulation program. See Section 7 – Data Retrieval and Communications of the BC 1060 user manual for more details.

The BC 1060 can also be paired with the Comet Cloud Services Modem 2 (CCS 2), an optional accessory, to upload data to the cloud. The data will be displayed as charts and in tabular format, and can be viewed by any web-enabled device (computer, smart-phone, etc.). The data are stored in the JSON format in the Comet Cloud, and data can therefore be ingested into a datalogger environment or data warehouse of the user’s choosing. Data can also be retrieved via a USB flash drive. Note that instrument data can be overwritten if the storage threshold is exceeded.

6.6.3. TCA08

The TCA08 can be connected with a DB9 crossover cable (or standard DB9 serial cable with null modem adapter) from the serial port on the rear panel of the instrument to a computer or datalogger. The instrument supports data acquisition using multiple protocols, including the BH protocol. The data acquisition system used must be capable (have a predefined protocol) to receive the data from the instrument. Details are available in the TCA08 user manual, Section 8.2 – Connecting to External Datalogger or PC.

7. OPERATION AND MAINTENANCE BEST PRACTICES

This section covers operation and maintenance best practices, including:

1. Expendables and spare parts
2. Preventative maintenance schedules
3. Recommended QC checks
4. Troubleshooting

7.1. Expendables and Spare Parts

7.1.1. AE33

The AE33 requires regular replacement of the filter tape rolls, which can be ordered from Aerosol Magee Scientific. The instrument comes with one roll installed. The AE33 user manual states that "Use of any other filter tape may damage the instrument, void the warranty or lead to incorrect data." The percent tape remaining is also a field that is recorded by the instrument.

7.1.2. BC 1060

Similar to the AE33, the BC 1060 requires regular replacement of the filter tape rolls. The BC 1060 uses treated glass fiber filter tape rolls, which are available from Met One Instruments. Note that this tape is different than the Met One Beta Attenuation Monitor (BAM) tape and therefore not interchangeable between instruments. The BC 1060 user manual states that "it is essential to use this particular tape to maintain proper instrument calibration and reproducibility." One filter tape roll is expected to last 2-12 months, depending on sampling conditions (such as concentrations and dilution settings; higher concentrations will use tape more quickly). The percent tape remaining is also a field that is recorded with the BC 1060. Installation instructions can be found in the BC 1060 user manual, Section 3.7.1 – 'Filter Tape Installation, Loading, and Filter Material Notes.'

Other accessories and parts for the BC 1060, such as fuses, tubing, and fittings, are described in detail in Section 8 ('Accessories and Parts') of the manual. Other monitoring agencies that are current BC 1060 users have recommended having spare pump parts available for potential pump rebuilds or replacements.

7.1.3. TCA08

The TCA08 collects samples on quartz fiber filters, which the manufacturer recommends be replaced twice per month. Users will need two fresh 47 mm quartz fiber filters and a pair of tweezers for the replacement. The user manual states to only use TCA08 5 01 006 quartz fiber filters, and always use the "Quartz filter change procedure" when changing the filter. The procedure ensures that appropriate instrument checks and pre-conditioning are conducted before the first heating cycle to prevent filter damage during the first heating cycle. Instructions for replacement of the filters can be found in the TCA08 user manual, Section 9.1 – Quartz filter change procedure.

7.2. Preventive Maintenance Schedules

The preventative maintenance schedules for each instrument are provided in their respective user manuals; users should check the most recent version for up-to-date information. The following examples of preventative maintenance schedules are available from the most recently available version at the time of this publication. Some items will need to be performed more or less often depending on local conditions.

7.2.1. AE33

The following example preventative maintenance schedule (Table 8) is from Magee Scientific Aethalometer® AE33 user's manual, version 1.60 (Dec. 2021), Section 9 – Maintenance. The AE33 user interface has automatic programming that can provide step-by-step instructions for many of the tests listed in this table. Step-by-step instructions with photographs and screenshots are also available in the user manual.

Table 8. Instrument maintenance actions and frequency – AE33.

Maintenance Item	Minimum Period	Manual Section
Check the sample inlet flow	Monthly	--
Inspect the sample line tubing	Monthly	--
Inspect and clean the size selective inlet (if present)	Monthly	--
Inspect and clean the insect screen assembly (if present)	Monthly	--
Verify time and date (if not set to update automatically)	Monthly	--
Inspect optical chamber, clean if necessary	Once every 6 months (site dependent, use educated judgment).	9.1
Flow check (flow verification, flow calibration)	Once every 6 months	9.9, 9.3
Leakage test	Once every 6 months	9.4, 9.11
Clean air test	Once every 6 months	9.6, 9.7
Stability test	Once every 6 months	9.5
Neutral density (ND) filter test	Annually	9.10
Lubricate optical chamber sliders	Annually	9.12
Install a new filter tape roll	As needed; the instrument issues a warning.	9.2
Change by-pass cartridge filter	As needed. Annually.	9.13

7.2.2. BC 1060

The following example preventative maintenance schedule (Table 9) is from BC 1060 operation manual, version BC1 1060-9800 Rev H (2020), Section 6.3. Similar to the AE33, the instrument manual includes step-by-step instructions with photographs and screenshots.

Table 9. Instrument maintenance actions and frequency – BC 1060.

Maintenance Item	Minimum Period	Manual Section
Replace filter tape	As required (typically 2-12 months)	3.7
Temperature, pressure, and flow audits (see the following note from users)	1 month	6.4.1, 6.4.2, 6.4.3, 6.4.4
Span check	3 months	6.4.6
Clean inlet particle traps (cyclone)	3 months	6.7
Leak test	3 months	6.5
Flow, temperature, and pressure full calibrations	3 months	6.4.1, 6.4.2, 6.4.3, 6.4.4
Clean cyclone	3 months	6.7
Replace cyclone O-rings	As required	6.7
Clean the debris filter	1 year	6.6
Replace dilution system cartridge filter	3 years	See the BC 1060 Service Manual
Replace main pump	As required	See the BC 1060 Service Manual
Replace dilution system pump	As required	See the BC 1060 Service Manual
Replace dilution system flow sensor	As required	See the BC 1060 Service Manual
Factory service	As required	0

Current users note that when using the dilution air system in the BC 1060, auditing/calibrating the dilution flow should be done both at the port on the front and at the adapter (while removed) that is on the downtube. This is because of the solenoid switching that occurs when determining the dilution flow at the port vs. the dilution flow adapter, one must perform this to ensure no leaks are occurring and the solenoid is actually switching, etc. This is not in the manual.

7.2.3. TCA08

The following example preventative maintenance schedule (Table 10) is from Magee Scientific/Aerosol TCA08 user’s manual, version 1.1.1.1 (April 2022), in Section 9 – Maintenance and Service.

Table 10. Instrument maintenance actions and frequency – TCA08.

Maintenance Item	Minimum Period	Manual Section
Cleaning with dry cloth	As needed	--
Verify sample inlet flow	Once a month	--
Inspect the sample line tubing	Once a month	--
Inspect and clean the size selective ($PM_{2.5}$) inlet	Once a month	--
Verify date/time	Once a month	--
Quartz filter change procedure	Twice a month	9.1
Zero verification and Denuder efficiency test	Once a month	9.6, 9.9
Flow verification (analytic /sample flow), calibrate if necessary	Twice a year	9.3
Change analytic air filter	Twice a year	9.12
Change cartridge filter	Once a year	9.12

Maintenance Item	Minimum Period	Manual Section
Verification of TCA08 with ambient filter punches, calibrate if necessary	Once a year, or after any major maintenance or modification of the system	9.8
Leakage test	Each time a chamber is opened	9.2
Replacement of CO_2 sensor	Every 20,000 operation hours	9.13

7.3. Recommended QC Checks for Leaks and Flow

All three instrument user manuals provide guidance on checks for leak and flow issues. See the following user manual sections or the individual instrument SOPs for additional details.

7.3.1. AE33

The AE33 user manual includes details on automated tests for:

- Flow calibration (Section 9.3)
- Flow verification (Section 9.9)
- Leakage tests (Section 9.4)
- Inlet leakage tests (Section 9.11)

The passing QC threshold for the flow verification and leakage tests is 10%, and typical leakage values are 1-2%.

7.3.2. BC 1060

The BC 1060 manual includes a table in Section 6.2 (Maintenance and Troubleshooting – Basic Problem Causes/Solutions Table) that outlines basic problem causes and solutions. The following suggestions are made for leaks and flows.

1. Flow failures or low flow:
    - Make sure that the tape is properly advancing the dirty spots. See user manual Section 4.5 (User Interface and Menu Systems - Load Tape) or 4.10.2 (‘The TAPE TEST Screen’).
    - DEFAULT the flow sensor calibrations and re-calibrate the flow. If corrupted flow calibration parameters are entered into the flow calibration, it may appear that the flow system is not working. See user manual Section 6.4 (Maintenance and troubleshooting - Temperature, Pressure, and Flow Audits and Calibrations) .
    - Verify the ambient temperature (AT) and barometric pressure (BP) sensor function. Failed ambient sensors will affect the flow. See user manual Section 6.4.
    - Check the internal debris filter. If it is clogged, remove and clean (or replace) the filter element. See user manual Section 6.6 (Maintenance and Troubleshooting – Debris Filter Changes).

  - The sample pump itself will eventually wear out and need to be replaced. It should last at least two years under normal conditions. Check the above listed possibilities first. See user manual Section 8 (Accessories and Parts) for replacement parts and the BC 1060 Service Manual for instructions.

2. Leak check failures:
   - There is always a small amount of leakage at the filter tape interface.
   - Make sure the upper and lower nozzles are completely clean.
   - Check the push-to-connect tubing fittings inside the instrument.
   - The filter tape can be replaced with a small rubber sheet with a small hole positioned under the nozzle. This will eliminate the tape as the leak point to help isolate the leak source.
   - Note: nothing down-stream of the flow sensor is leak-tested during the standard leak-test procedure.

7.3.3. TCA08

The TCA08 user manual includes a table in Section 9 – Maintenance and Service, that outlines basic problem causes and solutions. This includes details on automated tests for:

- Leakage tests (Section 9.2)
- Flow calibration (Section 9.3)
- Flow verification (Section 9.4)

The leakage test is fully automated on this system, and leakage values must be below 0.5% to be acceptable.

7.4. Troubleshooting

The user manuals for the AE33 and BC 1060 instruments provide guidance on troubleshooting issues. See the following user manual sections or the individual instrument SOPs for additional details.

1. AE33 – Section 13: Troubleshooting
2. BC 1060 – Section 6: Maintenance and troubleshooting

The TCA08 does not currently have a troubleshooting section in the user manual. Current SLT users note that a helpful tool in TCA08 troubleshooting is to download the database log onto a flash drive. A common example was in receiving ball valve errors on the status bar, in which case the downloaded database log spreadsheet was helpful as it identifies which valve is having an issue.

8. DATA STORAGE, REVIEW, AND REPORTING

The AE33 and BC 1060 measure BC in PM samples using multiple wavelengths of light concurrently, and report concentrations measured by these wavelengths separately. The two most useful wavelengths are 370 nm and 880 nm. The 370 nm channel indicates the presence of UVPM, while the 880 nm channel is associated with BC.

8.1. Data Storage and Time Resolution Within a Monitoring Agency Data System

Averaging time or time base is the amount of time over which the data will be averaged and logged. While AQS recommends reporting data with a 1-hour averaging time, individual agencies may choose to analyze their own data at a different averaging time, and the time that they choose should depend on the local conditions.

If a user is measuring BC at a site that is known to have relatively high BC concentration levels, like a near-road location, the instrument’s ability to detect concentrations accurately at shorter averaging times is greater. Therefore, a user measuring at this type of location could choose to use a 5-minute averaging time. At lower concentrations, short averaging time data is often very noisy and unreliable. Users with instruments sited at low concentration locations should consider analyzing their data with an hourly or multi-hourly average basis. AirVision, Envidas Ultimate, and CAAT (carbonaceous aerosol analysis tool, software available from Aerosol Magee Scientific) are capable of applying custom averaging times to datasets.

8.2. Data Review and Validation

Internal and external factors can cause data from a carbonaceous aerosol instrument to be inaccurate or ultimately invalid, such as exposure to high humidity or unstable temperatures. Rain and insects can also obstruct the inlet filter leading to skewed data. It is recommended that agencies regularly review their data for obvious errors. These errors can include, but are not limited to, negative concentrations, multiple “zero” data points in a row, unusual high or low swings in concentration, data points that swing very high and remain high for an irregularly long period, and unusually high or low concentrations when the instrument is just starting up. If agencies notice any of these issues, they should invalidate the data and perform routine maintenance and calibration to attempt to resolve the issue.

The AE33 outputs both raw and corrected data after k value manipulation for loading effect compensation (see **Figure 5** in Section 3.1.3). Agencies should regularly plot their corrected data overlayed with their raw data using simple graphing software, such as Microsoft Excel, and compare data curves. The shape and slope of the curves should follow similar trends. Often, major divergences occur at the end of a filter spot, just before a tape advance. Additionally, the shape of the corrected data curve should follow general trends measured by collocated instruments relating to BC, such as PM or NO_2.

The instruments covered in this document report error and alarm codes associated with each data point. The presence of a non-zero status code does not automatically mean that the data are invalid. Note that for all three instruments, if multiple alarms are generated for a single data record, the sum of the alarm codes is reported as a single value. Users can use a sum of values binary decoder in a programming language such as python or R to decode the sum as part of their regular data analysis. Users can also manually deconvolute these codes into their individual numbers manually by identifying the largest possible error code that is less than the displayed error code, and then subtracting that value from the displayed code and continuing until the final value is 0.

8.2.1. AE33

During operation, the AE33 instrument reports status using colored icons on the 'Home' screen. The colored icon includes:

- Green check: normal operation
- Yellow exclamation point: Warning; instrument is still collecting measurements, but there is/was an issue that needs to be checked
- Red X: instrument stopped. Immediate response needed.

The instrument also shows a real time status code that is causing the color of the colored icon. The specific meaning of most codes can be found by pressing on the colored icon in the instrument's interface.

During data processing, the status code should be used to assess for invalid or suspect data. The status code descriptions are available in Section 8.2 ('User Interface Settings and Operation - Instrument Status') of the AE33 user manual, and potential solutions to common status codes are described in Section 14.2 ('Troubleshooting - Instrument Status') of the AE33 user manual. Note that if multiple status codes are present at the same time, the overall status code reported is a sum of the individual codes (e.g., if Status = 289, 289 = 256 + 32 + 1. The instrument is performing a Tape Advance; there was a calibration error in one LED channel of the optical source; and the tape sensors show that only 5 tape advances remain.). Examples of R and Python scripts that have been used to deconvolute the summed status codes for automated data validation are included in Appendix A.

Table 11. Common AE33 status code descriptions and actions. Note that final status codes will be a sum of all individual codes triggered during the measurement.

Status Code	Description	Proposed Data Review Action
1	Tape advance	Invalidate
2	First measurement	Check Data
3	Stopped	Invalidate
4	Flow low/high or F1 < 0 or F2/F1 outside range	Invalidate
8	Check flow status history	Check Data
12	Flow low/high & check flow status history	Invalidate
16	Calibrating LED	Invalidate
32	Calibration error	Invalidate
48	LED error	Invalidate
64	Chamber error	Invalidate

Status Code	Description	Proposed Data Review Action
128	Tape warning (less than 30 spots left)	Valid
256	Tape last warning	Valid
384	Tape error	Invalidate
1024	Stability test	Invalidate
2048	Clean air test	Invalidate
3072	Change tape procedure	Invalidate
4096	Optical test	Invalidate
6144	Leakage test	Invalidate
8192	Connection Error	Invalidate
16384	Clear air test not acceptable.	Invalidate
32768	Problem while saving or retrieving files	Valid
65536	Database reaching limit warning	Valid

Data reported while these status codes are active may either have a “zero” value or a significantly inaccurate value. Besides Tape Advance, which is a necessary step in the AE33 functions, these status codes either occur because of user prompted tests or device malfunctions. Status code 4 concerns flow rate, and is triggered if (1) the total flow rate is higher or lower than the user-set flow rate by more than 0.5 liters/minute, (2) if F1 (Flow Rate 1) < 0, or (3) if F2/F1 is outside the 0.2-0.75 range.

Two of the problem status codes in Table 11— First measurement and Check flow status history—do not automatically render data invalid but instead imply that a manual check of the data should be performed. First measurement is the status code of the first measurement that the instrument takes when it is initially started, and this measurement can be unusually high or low compared to the rest of the measurements. Check flow status history shows that there may be a problem with the flow rate, which is another reason that logging flow rate is helpful.

8.2.2. BC 1060

The BC 1060 contains a system of error and alarm codes (Table 12) that are mainly used to alert the operator to problems with the unit, but they can also be used to inform data quality. The ‘Status’ field is reported in the data files by a numeric code. These codes are described in BC 1060 user manual Section 6.1 (‘Maintenance and Troubleshooting – BC 1060 Error & Alarm Event Descriptions’). Note that similarly to the AE33, if multiple status codes are present, the final status code will be recorded as the sum of the status codes. For example, a power failure (1) and a sensor link failure (2) would be recorded as a 3.

Table 12. BC 1060 status code descriptions and actions.

Status Code	Description	Proposed Data Review Action
0	No Alarm	Valid
1	Power Failure	Invalidate

Status Code	**Description**	**Proposed Data Review Action**
2	Digital Sensor Link Failure	Check data
4	Tape Move Failure	Invalidate
8	Maintenance	Invalidate
16	Flow Failure	Invalidate
32	Automatic Tape Advance	Check data
64	Detector Failure	Invalidate
128	N/A	Valid
256	Sensor Range	Check data
512	Nozzle Move Failure	Invalidate
1024	N/A	Valid
2048	Calibration Audit	Check data
4096	N/A	Valid
65536	Tape Move	Check data

8.2.3. TCA08

The general status of the instrument is shown by the color of the top line of the screen display and the LED indicator next to it:

- Green: OK
- Yellow: warning, check status
- Red: error

When the status signals an error, the instrument stops. When the status signals a warning, the instrument continues running but needs technical attention.

A detailed status code is also available and is discussed in the user manual Section 8.4 (‘User Interface, Settings, and Operation – Instrument Status’). In short, the status code is a concatenated code with seven groups, displayed as G0_G1_G2_G3_G4_G5_G6. Each group code is a sum of the codes present, similar to the process used by the BC 1060 and AE33. Pressing the colored check icon on the top left of the screen will also provide descriptions of most errors.

8.3. AirNow-Tech Data Reporting

The 1-hr averaged carbonaceous aerosol data can be automatically submitted to AirNow-Tech on an hourly basis. To create a new site or add parameters to an existing site, users should follow the “Site Management” document available on the AirNow-Tech website.[8]

The data format required for submission to AirNow-Tech is the AirNow Air Quality Comma Separated Values (AQCSV) format, which is a simple text file with comma delimiters between each field. Each record contains one data value for a given site, time, and parameter. Other supporting fields in an AQCSV file describe the time zone, parameter units, location, and other

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[8] https://www.airnowtech.org/Resources/airnow_site-management.pdf

information for that data value. The formatting requirements for data to be uploaded into AirNow-Tech can be found on the AirNow-Tech website.[9]

When an observation file is received from an agency, each hourly measurement is compared against a set of QC criteria. These criteria help identify potentially erroneous measurements for other users. Data flagged as suspect (QC code 5) or invalid (QC code 9) by the automatic QC checks need to be manually reviewed. Suspect or invalid observations may become valid or remain invalid after manual review, which considers local meteorological conditions and/or current air quality events (e.g., wildfires, dust storms, etc.), as well as the site's history, location, and observations from nearby monitors. More information on the QC metrics used by AirNow-Tech, which can be customized by agency staff for the network of monitoring sites and parameters, can be found on the AirNow-Tech website.[10]

Additional assistance for AirNow-Tech data reporting is available by contacting the AirNow Data Management Center (dmc@airnowtech.org or info@airnowtech.org) or John White of the U.S. Environmental Protection Agency (white.johne@epa.gov).

8.4. Air Quality System (AQS) Data Reporting

It is suggested that carbonaceous aerosol data be primarily reported for measurements of ambient air. Using these instruments to directly measure combustion source emissions, where BC levels are very high, has resulted in inaccurate data. As BC itself is not a criteria pollutant and is not required to be reported under any NAAQS, agencies may report data to AQS in their preferred format. However, for consistency, and to improve the ability to analyze data across agencies and regions, the following parameters are suggested for reporting:

- 370 nm concentrations (AE33 Channel 1)
- 880 nm concentrations (AE33 Channel 6)
- Sample duration
- Reporting units
- Null codes
- Qualifiers
- QA codes
- Method of measurement

The EPA prefers that data be reported in hourly values, and that data are reported in LC instead of being converted to STP. Agencies can also report data in both LC and STP. The EPA also recommends that concentration data be reported in micrograms/cubic meter (µg/m^3) units.

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[9] https://www.airnowtech.org/Resources/AirNow%20AQCSV%20File%20Format%20Quick-Start%20Guide.pdf; https://www.airnowtech.org/Resources/AIRNow-I_AQCSV-Final.pdf

[10] https://www.airnowtech.org/Resources/airnow_quality-control.pdf

8.4.1. Reporting Data to AQS

After data verification and validation activities are complete, it is recommended that data be reported to AQS following the same time frame as criteria pollutant data. Criteria pollutant data are to be reported to AQS within 180 days of the end of the calendar quarter in which the measurements were made. During data verification and validation, data that are valid, but that may not have met QC criteria or are otherwise compromised, will have appropriate qualifier codes added to the data so that users querying data in AQS are informed of any data quality issues. Monitoring agencies should have staff responsible for coding the air monitoring data for AQS and uploading the coded data.

8.4.2. Coding Ambient and Quality Assurance Data for AQS

AQS accepts data transactions, or inputs, from monitoring agencies for air monitoring data in a pipe-delimited format. These transactions must be programmed in a specific way for AQS to accept the information. The information contained in each data string consists of codes, dates, numeric data, and alphanumeric data. Definitions of these information types are detailed in the AQS Data Coding Manual, Version 3.6 (U.S. Environmental Protection Agency, 2015).

Each data string, or transaction, consists of a series of fields, each separated by a pipe, “|”, to indicate the end of a field and the start of the next field. Depending on the transaction type, some fields may be required, and the information in the field must meet specific criteria as defined in the AQS Data Coding Manual.

The EPA has developed an AQS Transaction Generator program that runs in the Windows operating system. This tool facilitates the creation of the AQS transactions and verifies compliance with the AQS data and business rules to ensure the coded transaction will successfully upload to AQS. Note that users will need to have administrator rights on their computer to install the program, which is available to download from the EPA website.[11]

Additional assistance is available by calling the AQS help line at (866) 411-4372, or through your regional EPA representative.

8.4.3. Reporting Carbonaceous Aerosol Parameters and Units to AQS

Careful attention must be paid to the coding of the data uploaded to AQS to ensure that the five-digit parameter code is accurate and that the associated units comply with those units that AQS accepts. Monitoring agencies are highly encouraged to employ software (e.g., from a data acquisition system [DAS], laboratory information management system [LIMS], or similar) or spreadsheet programs in which the various AQS codes and the data outputs have been validated. Prior to submitting the data to AQS, the monitoring agency should have completed data validation and performed a spot check of the dataset to ensure that the parameter code, parameter occurrence code (POC), unit code, method code, and any associated qualifier or null codes are properly assigned. Data that are miscoded may not be identified properly, which may result in underestimation of data completeness or data being rejected by AQS. AQS instructions for data

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[11] https://19january2017snapshot.epa.gov/aqs/aqs-transaction-generator_.html

upload are described in the AQS User Guide, and additional AQS manuals and guides are available on the EPA website.[12]

Data may be coded for AQS upload with any appropriate unit accepted for that parameter by AQS. Recommended units for reporting data to AQS for each parameter are shown in Table 13.

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[12] https://www.epa.gov/aqs/aqs-manuals-and-guides

Table 13. AQS parameters and recommended reporting units. Parameters in bold are preferred by EPA.

Parameter	AQS Parameter Code	Duration	AQS Duration Code	Recommended Reported Unit	AQS Unit Code	Digits	Round (R) or Truncate (T)?
Black Carbon $PM_{2.5}$ at 880 nm (LC)	88313	hourly average	1	Micrograms/cubic meter (LC)	105	2	R
Black carbon $PM_{2.5}$ STP (STP)	84313	hourly average	1	Micrograms/cubic meter (25 C)	001	2	R
UV Carbon $PM_{2.5}$ at 370 nm (LC)	88314	hourly average	1	Micrograms/cubic meter (LC)	105	2	R
UV Carbon $PM_{2.5}$ STP (STP)	84314	hourly average	1	Micrograms/cubic meter (25 C)	001	2	R
$PM_{2.5}$ Carbon at 470 nm	88360	hourly average	1	Micrograms/cubic meter (LC)	105	2	R
$PM_{2.5}$ Carbon at 520 nm	88361	hourly average	1	Micrograms/cubic meter (LC)	105	2	R
$PM_{2.5}$ Carbon at 590 nm	88362	hourly average	1	Micrograms/cubic meter (LC)	105	2	R
$PM_{2.5}$ Carbon at 660 nm	88363	hourly average	1	Micrograms/cubic meter (LC)	105	2	R

It is recommended that monitoring agencies report data in LC instead of converting data to STP.

8.4.4. AQS Qualifiers

The monitoring agency should identify compromised data within AQS by the addition of a qualifier or combination of qualifiers. Compromised data should either be flagged or invalidated using EPA-established qualifier codes in AQS. Note that EPA periodically updates the AQS qualifier list, which is published on the EPA's website.[13]

Data should be qualified and estimated with descriptive QA and INFORM flags where the data are compromised but remain valid, and NULL codes for invalid data.

Flagging Data in AQS: Compromised monitoring data will be flagged in AQS only if the data are considered valid for most purposes and uses. AQS permits users to label each data point with up to 10 QA qualifiers and/or informational (INFORM) qualifiers. Low concentration data should be qualified according to whether they are above or below the sample quantitation limit (SQL) or method detection limit (MDL) thresholds. Concentration data less than the determined MDL are to be flagged with the QA qualifier code MD, while values greater than or equal to the MDL but less than the SQL (3.18 × the MDL) are to be flagged using the QA qualifier code SQ. All concentration values for qualitatively (positively) identified analytes, even those less than MDL, are to be reported to AQS and should not be censored by substitution of one half the MDL, by replacement with 0, or by any other substitution method. Negative concentrations should not be translated to zero for reporting purposes. Where qualitative identification acceptance criteria are not met for a given parameter, its concentration must be reported as zero and flagged as ND.

Invalidating Data in AQS: Data of uncertain origin, data with unacceptable levels of uncertainty, or data which are known to not be an ambient measurement will not have an associated measurement value included in AQS. Such data may be the result of instrument failure, known instrument contamination issues, irrecoverable data corruption, measurements associated with failed routine QC checks, calibration processes, determination of MDLs, or instrument troubleshooting. Invalid data are reported to AQS with a Null (NULL) Code Qualifier, which eliminates the associated measurement value and indicates the reason for the invalidation. AQS accepts a single NULL qualifier and does not permit the addition of other qualifiers to the transaction string. Incorrect use of NULL codes in the AQS transaction string eliminates the measurement value.

Based on the hourly AE33 data reported to AQS in 2021, around 3.5% of data were reported as a NULL code, meaning that these data were either manually or automatically invalidated by agencies before being reported. This shows that some agencies are diligently performing data validation, but it also shows that data issues with Aethalometers® are not uncommon. The most common NULL codes in the 2021 data were machine malfunction (code AN), collection error (code AQ), and maintenance/routine repairs (code BA). Additionally, any negative values for BC concentration should be invalidated or NULL-coded. Data points with unusually high or low swings in concentrations may not be inaccurate, but should at least be checked for accuracy. This is also true when there are several "zero" value data points in a row.

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[13] https://aqs.epa.gov/aqsweb/documents/codetables/qualifiers.html

8.4.5. Corrections to Data Uploaded to AQS

If erroneous data have been reported to AQS, whether through data validation, as a result of corrective action, or through other means, the data should be corrected and the updated data uploaded to AQS. Situations where this may occur could result in previously acceptable data being invalidated as a result of an audit, or data that were initially incorrectly invalidated could be deemed valid. Monitoring agencies should notify EPA Region staff when a significant amount (as determined by the monitoring agency) of erroneous data are discovered and require updating in AQS. Monitoring agencies should coordinate with their EPA Region to correct the records in AQS, as it is important to ensure that data end users are notified of data that may have been updated due to the potential impact on decision-making processes.

9. DATA USES

Continuous carbonaceous aerosol measurements can provide air monitoring agencies with important PM speciation information relevant to federal regulatory requirements, such as targeting specific emissions reductions for $PM_{2.5}$ NAAQS attainment and providing evidence of exceptional events such as wildfire smoke. This measurement data can also be used to target community-level air quality improvements, as carbonaceous aerosols have important impacts on human health. This section provides a brief summary of potential data analysis and data uses that may be informative to air quality agencies beginning to make carbonaceous aerosol measurements.

9.1. Typical Data Products

The following data products are foundational for carbonaceous aerosol measurement analysis.

9.1.1. Time Series

An example time series is shown in Figure 7. As part of continuous operations, carbonaceous aerosol time series data should be inspected regularly (daily to weekly) to ensure instruments are working as expected and to take action if not. This initial evaluation should include steps discussed in the data review Section 8.2, including:

- Evaluating the instrument status codes, which can indicate invalid data.
- Inspecting very high concentration spikes during inclement weather, particularly during rain events. If rain is able to enter the inlet, it may carry debris from the inlet opening along with it and deposit the debris on the sample. For example, if a very high concentration is observed during a rain event and there is a visible splatter pattern on the filter tape, the sample can be considered invalid.
- Logging any known meteorological or event activity that may contribute to concentrations being higher or lower than expected.

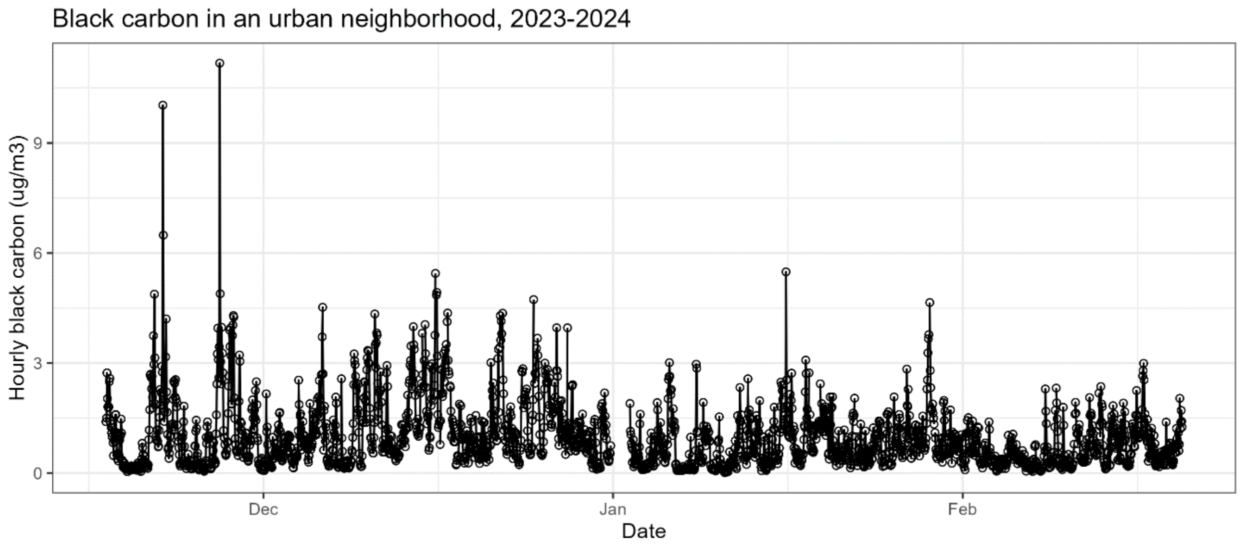


Figure 7. An example time series of BC data, produced using the ggplot package in R.

9.1.2. Meteorological Data Analysis

It is also recommended that wind speed and direction data are collected at or nearby deployment of continuous carbonaceous aerosol instruments. These data will typically be used to generate wind roses, pollution roses, and/or polar plots of the data as a function of wind speed and wind direction, as shown in Figure 8. Wind roses summarize how wind speed and directions can vary by season or year. A pollution rose is an extension of the wind rose and plots the percentage of time a pollution concentration is in a particular range of wind direction (Henry et al., 2009). Polar plots are similar but are enhanced by showing a continuous surface calculated through modeling using smoothing techniques. These techniques can be helpful in identifying and distinguishing the impact of possible source regions of carbonaceous aerosols in varying wind direction sectors.

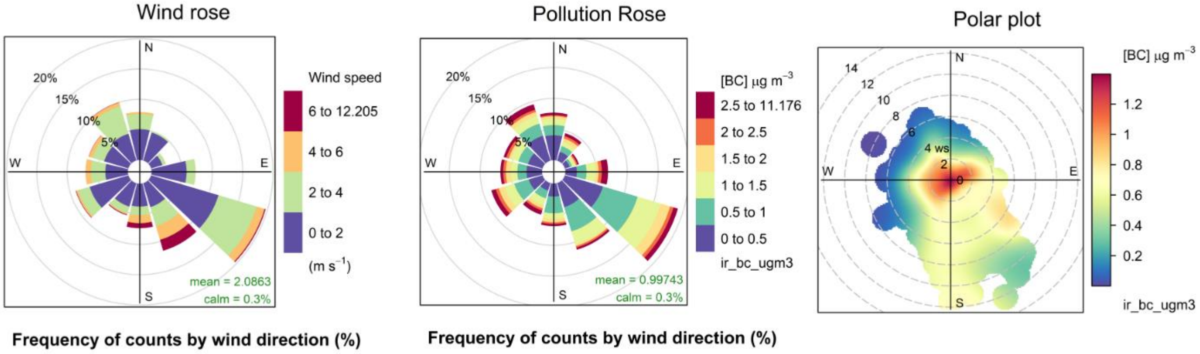


Figure 8. A wind rose, pollution rose, and polar plot of BC concentrations, wind speed, and wind direction data from an example urban neighborhood, produced using the openair package in R.

9.1.3. Diurnal and Seasonal Variation Plots

Diurnal, weekly, and seasonal variations in concentrations should be evaluated. The variation of carbonaceous aerosols by time of day and day of week can reveal useful information concerning likely sources. In the example shown in Figure 9, typical diurnal patterns of BC concentrations increasing during morning commuting traffic are observed in the hourly variation (bottom left). Typical seasonal patterns of increases of BC in winter months are observed in the monthly variation (bottom center).

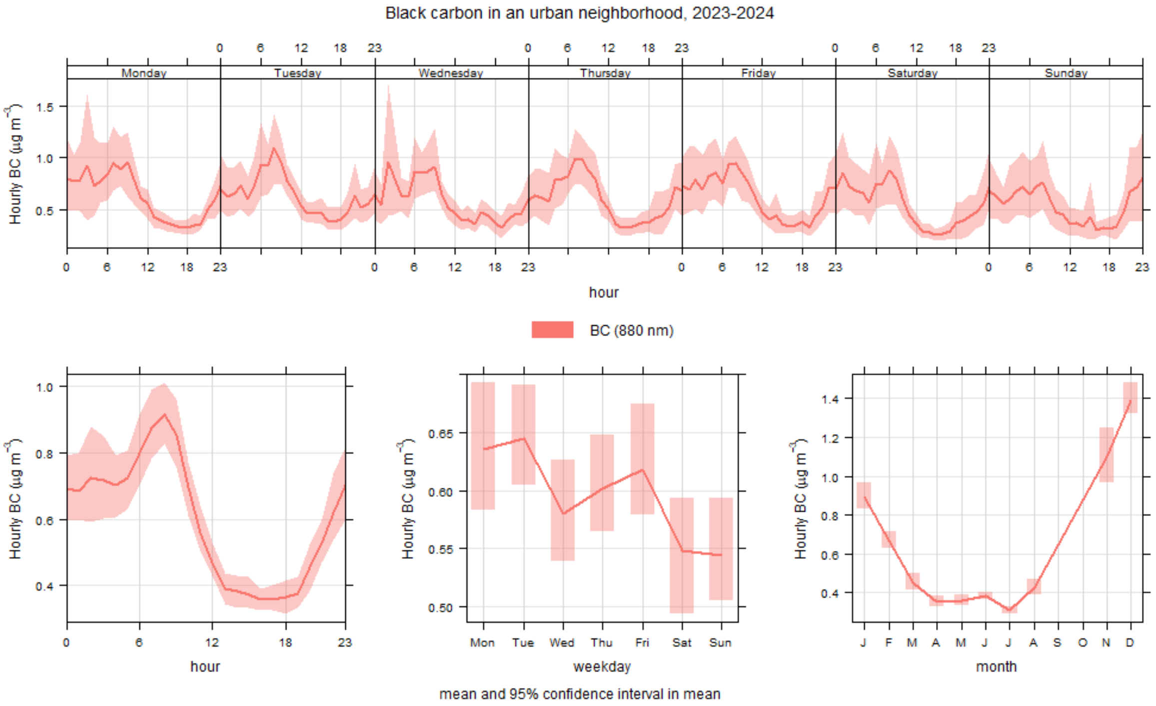
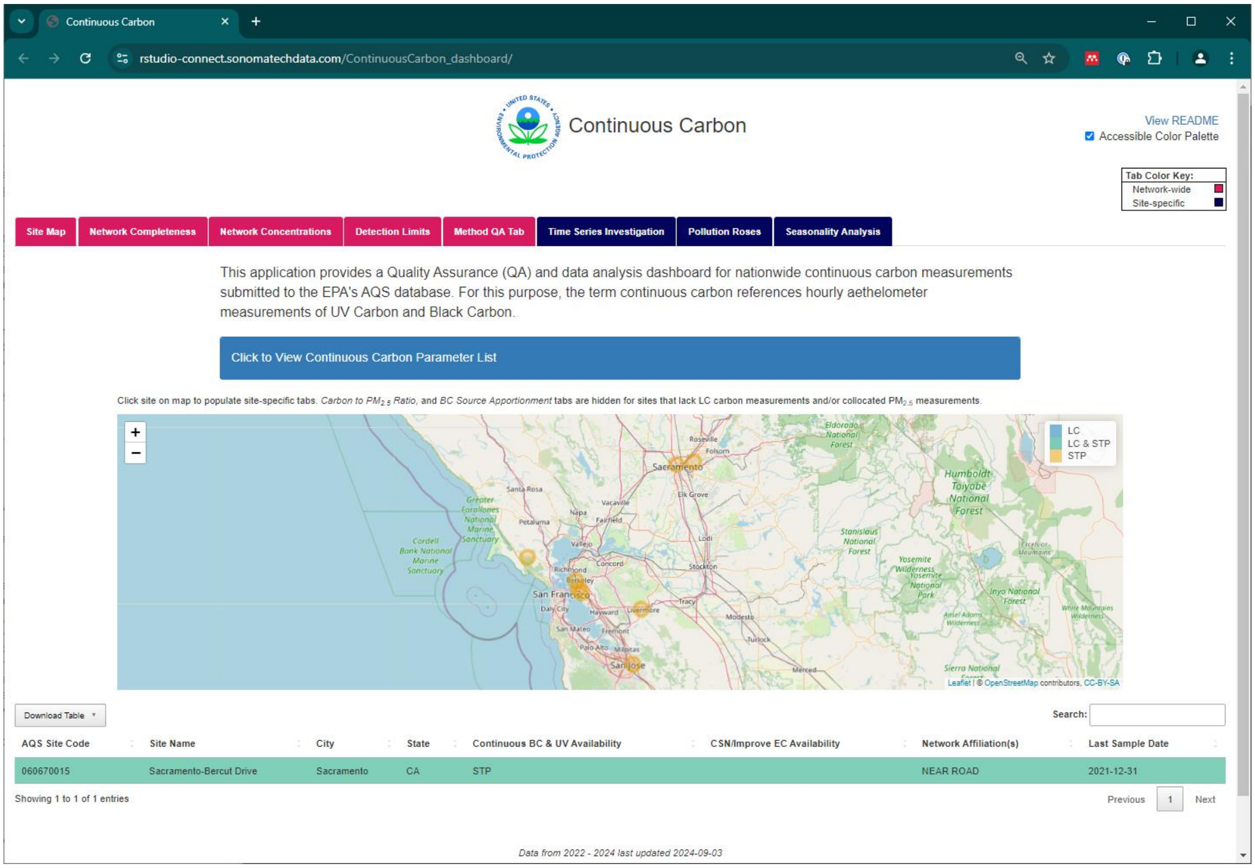

Black carbon in an urban neighborhood, 2023-2024

Figure 9. Time variation plot of BC data from an example urban neighborhood, produced using the openair package in R.

9.1.4. Continuous Carbon Interactive Dashboards

EPA has developed an interactive dashboard to display and explore existing AQS data streams of black and UV carbon parameters, the homepage of which is shown in Figure 10. This dashboard can be useful to explore existing carbonaceous aerosol data trends in the area of interest. The dashboards are currently located at:

https://rstudio-connect.sonomatechdata.com/ContinuousCarbon_dashboard/.



This application provides a Quality Assurance (QA) and data analysis dashboard for nationwide continuous carbon measurements submitted to the EPA's AQS database. For this purpose, the term continuous carbon references hourly aethelometer measurements of UV Carbon and Black Carbon.

Click site on map to populate site-specific tabs. *Carbon to $PM_{2.5}$ Ratio*, and *BC Source Apportionment* tabs are hidden for sites that lack LC carbon measurements and/or collocated $PM_{2.5}$ measurements.

AQS Site Code	Site Name	City	State	Continuous BC & UV Availability	CSN/Improve EC Availability	Network Affiliation(s)	Last Sample Date
060670015	Sacramento-Bercut Drive	Sacramento	CA	STP		NEAR ROAD	2021-12-31

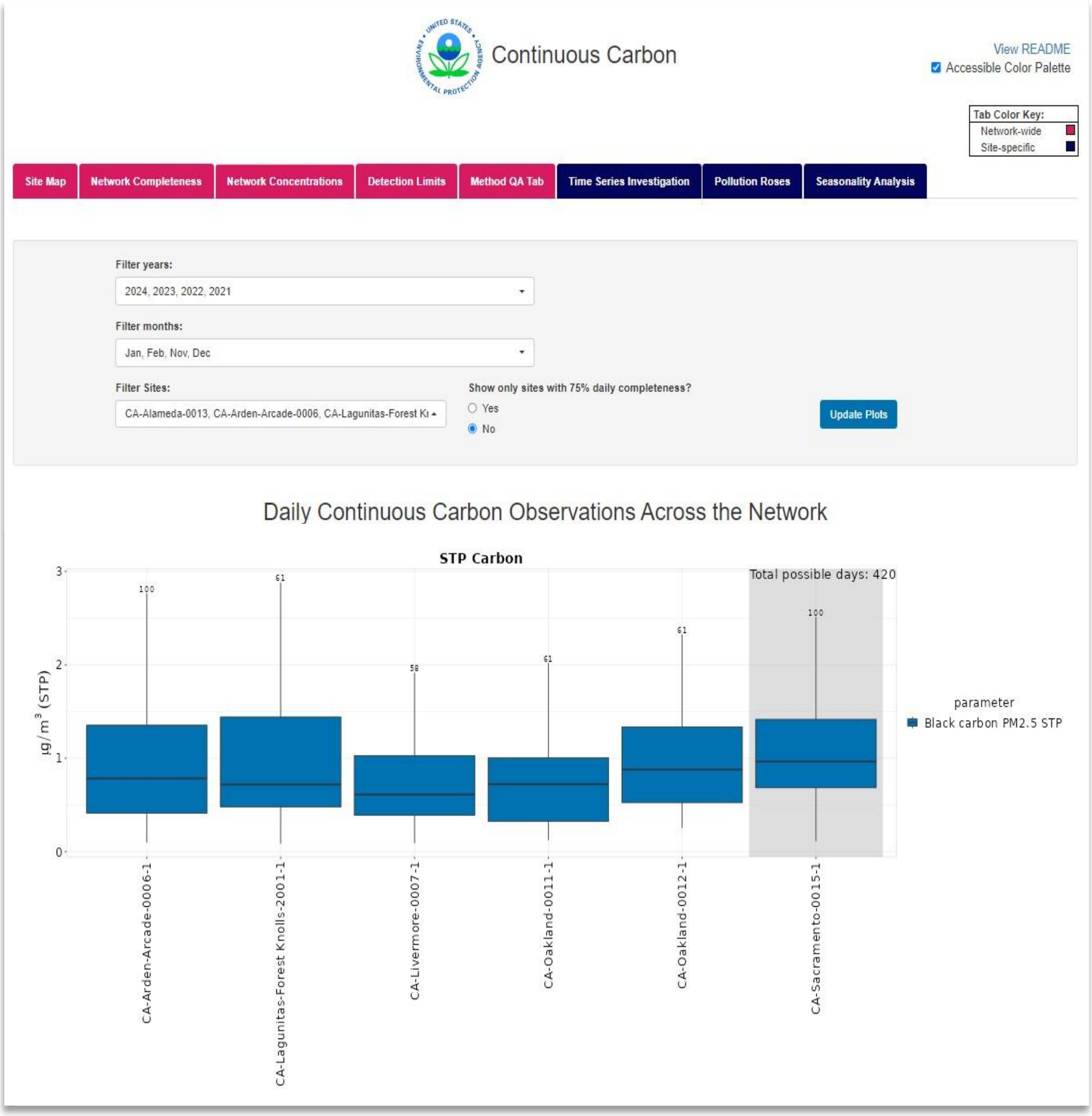
Showing 1 to 1 of 1 entries

Data from 2022 - 2024 last updated 2024-09-03

Figure 10. EPA continuous carbon interactive dashboard home page, where users can view a map to find existing AQS carbonaceous aerosol data to explore in their area of interest.

The dashboard has site-specific tabs (purple tabs in Figure 10), where a user can select a single site, and then quickly and easily generate the three data products discussed in Section 9.1 in the (1) time series investigation, (2) pollution roses, and (3) seasonality analysis tabs.

The dashboard also has network-wide tabs (pink tabs in Figure 10), which include the ability to compare measurements across different sites or instruments. For example, a comparison of measurements across different locations in California is available in the ‘Network Concentrations’ tab, Figure 11. Additionally, a comparison of continuous measurements to collocated CSN and IMPROVE network monitors is available in the ‘Method QA’ tab, Figure 12, which offers insights on the bias of specific instruments.



Filter years: 2024, 2023, 2022, 2021

Filter months: Jan, Feb, Nov, Dec

Filter Sites: CA-Alameda-0013, CA-Arden-Arcade-0006, CA-Lagunitas-Forest Kı

Show only sites with 75% daily completeness?
○ Yes
● No

Figure 11. EPA continuous carbon interactive dashboard home page, network wide comparisons in the 'Network Concentration' tab. Users can evaluate concentrations across sites with existing AQS carbonaceous aerosol data.

Displays on this tab evaluate continuous carbon methods against CSN/Improve methods. Comparisons are made between 24-hour observations of (1) continuous BC and CSN/IMPROVE EC, and (2) continuous UV and CSN/IMPROVE OC. Percent Difference is calculated with CSN/IMPROVE measurements as the "true" value.

Filter parameters: Black Carbon PM2.5 Correcte

Filter years: 2016, 2017, 2018, 2019, 2

Filter sites: CT-Cornwall-0005, CT-New Haven-0027, MI

Figure 12. EPA continuous carbon interactive dashboard home page, network wide comparisons in the 'Method QA' tab. Users can evaluate concentrations across continuous instruments and sites compared to CSN and IMPROVE network data.

9.2. Typical Trends

9.2.1. Long-Term Trends

BC concentrations trended upwards globally between 1960 to 2007 (Wang et al., 2014). In the U.S., however, BC concentrations have been trending downward in line with reductions in mobile source emissions (Ahmed et al., 2013; McDonald et al., 2015). For example, in New York, Ahmed et al. (2013) reductions in ambient BC concentrations from about 0.5 µg/m^3 in 1984 to 0.3 µg/m^3 in 2011 were observed (Figure 13). Monitoring in California has similarly shown that ambient BC concentrations had peaked by 1990 to near 4 µg/m^3 in the Los Angeles, CA, area and 2 µg/m^3 in the San Francisco Bay Area, CA, before dropping rapidly by 1995 and continuing to decline to near 1 µg/m^3 in 2010 (Figure 14). EC concentrations measured at rural sites by the IMPROVE network have decreased to the point that many sites now have concentrations that are below the lower quantifiable limits, as discussed by Schichtel et al. (2021) and Hand (2023).

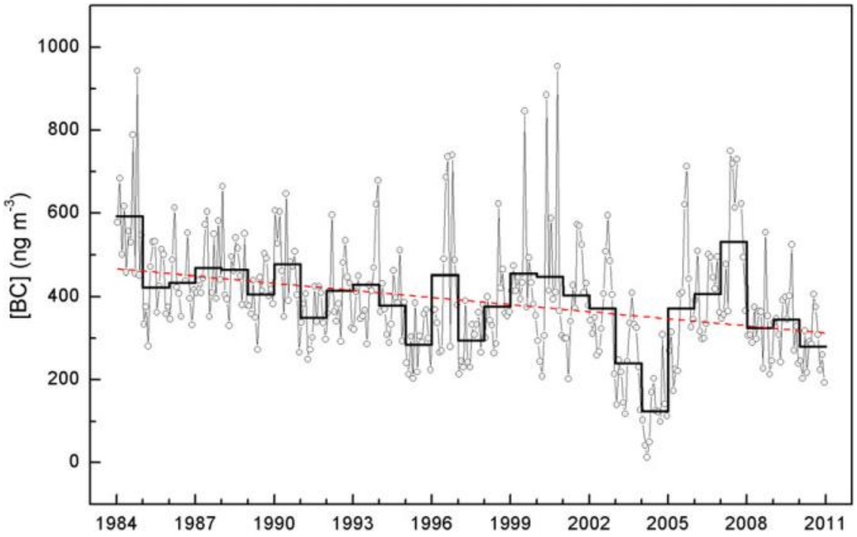


Figure 13. Monthly BC concentrations in Mayville, New York, from 1984-2010. Measurements made using thermal optical measurements until April 2008, and using an Aethalometer® from May 2008-December 2010. Heavy bars are annual means, and the dashed line is a linear regression fit to the monthly data. Figure from Ahmed et al. (2013).

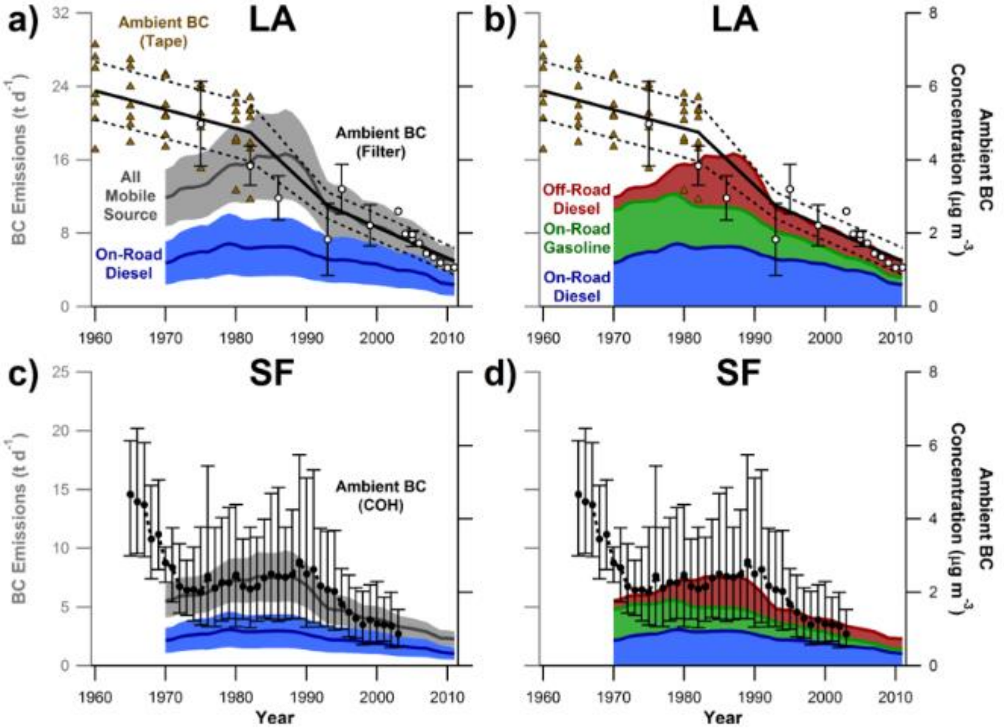


Figure 14. Trends in ambient BC concentration (right axis) compared with fuel-based inventory trends for BC emissions (left axis) for the Los Angeles area (top) and San Francisco Bay area (bottom) in California. Error bars on the ambient data show 95% confidence intervals. Panels (b) and (d) show the trends in mobile source emissions of BC broken down by major source categories. Figure from McDonald et al. (2015).

9.2.2. Temporal Trends

Carbonaceous aerosol time series data should be evaluated for diurnal, weekday, and seasonal trends, which can indicate source types. At the seasonal scale, carbonaceous aerosol measurements are often highest in the winter due to shallower mixing heights and potentially increased residential burning. Because of the association between carbonaceous aerosol and traffic patterns, day-of-week and diurnal concentration trends are also present. Mobile source related pollutant concentrations are often lower on weekends than weekdays. At the diurnal scale, peaks during the morning commute are common, and peaks during afternoon commute hours are often less pronounced. Example data for both of these trends, as observed in Southern California by an AE33, are shown in Figure 15 and Figure 16.

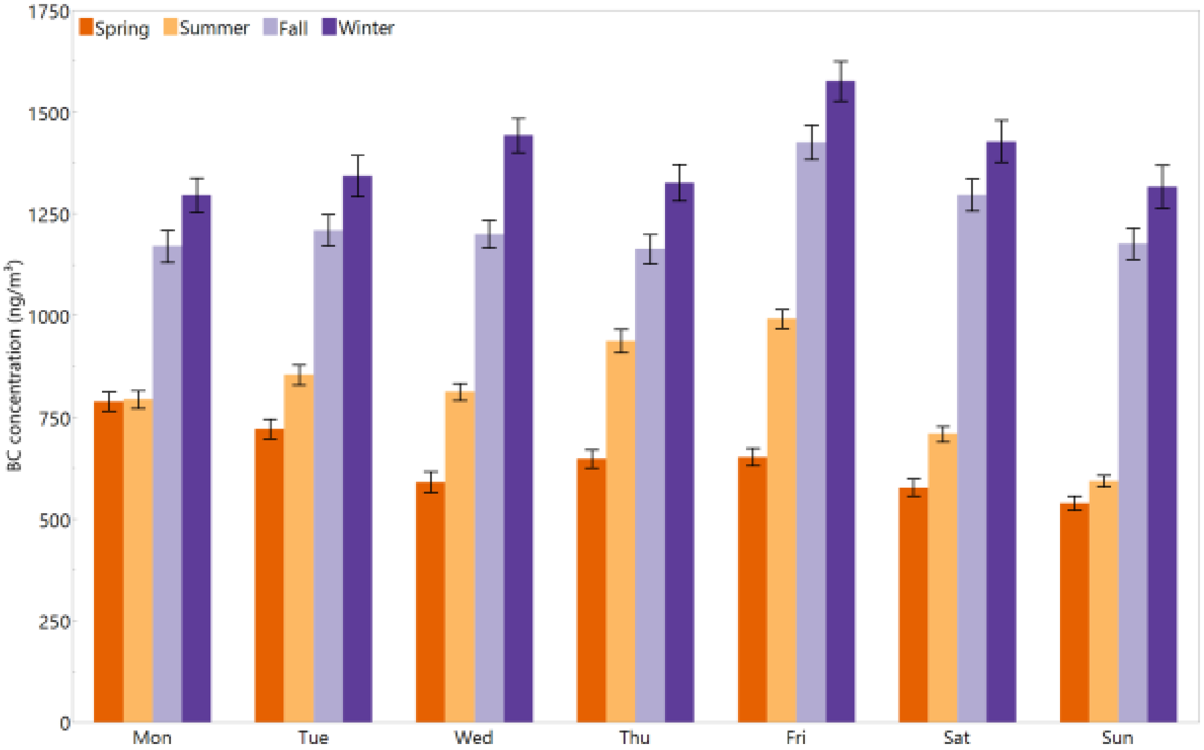


Figure 15. Seasonal day-of-week comparison of BC concentrations in the South Coast Air Basin during MATES V. Figure from Nastri et al. (2021).

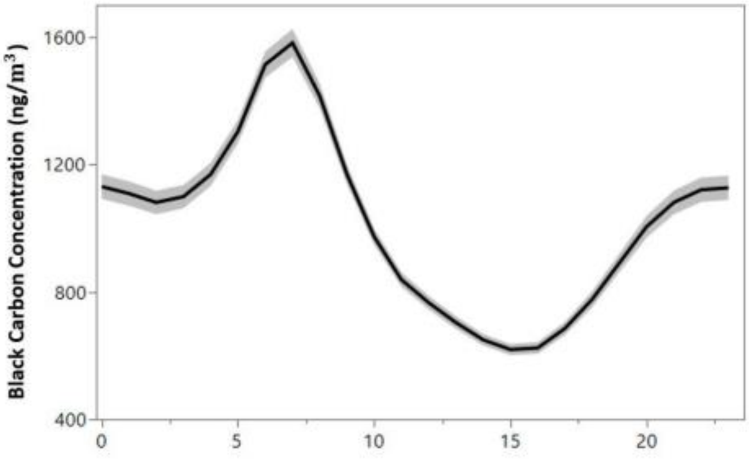


Figure 16. Diurnal variation of BC concentrations in the South Coast Air Basin during MATES V. Shaded area represents the 95% confidence level of the measurement. Figure from Nastri et al. (2021).

9.2.3. Source-Apportionment Trends

Diurnal-to-seasonal trends are also observed in other species measured or calculated from continuous carbonaceous aerosol measurements. An example from a measurement campaign in California from 2018 to 2020 is shown in Figure 17. In this example, BC measurements from the AE33 were divided into BC_{ff} (shown in grey) and BC_{bb} (shown in brown). Across the four seasons, the highest BC_{ff} values are observed during the early morning due to a combination of peak traffic and a low mixing layer, while the highest BC_{bb} values were observed overnight in winter, likely in connection with increased residential heating. OC values obtained from TCA08 measurements make up the remainder of the species, including POA (shown in blue shades) and SOA (shown in orange shades). The diurnal peaks for OC are shown to vary from the early morning for POA in all seasons to midday for SOA. Primary organic aerosol classified as BrC (POA_{BrC}) was shown to peak at night during winter, similar to BC_{bb}.

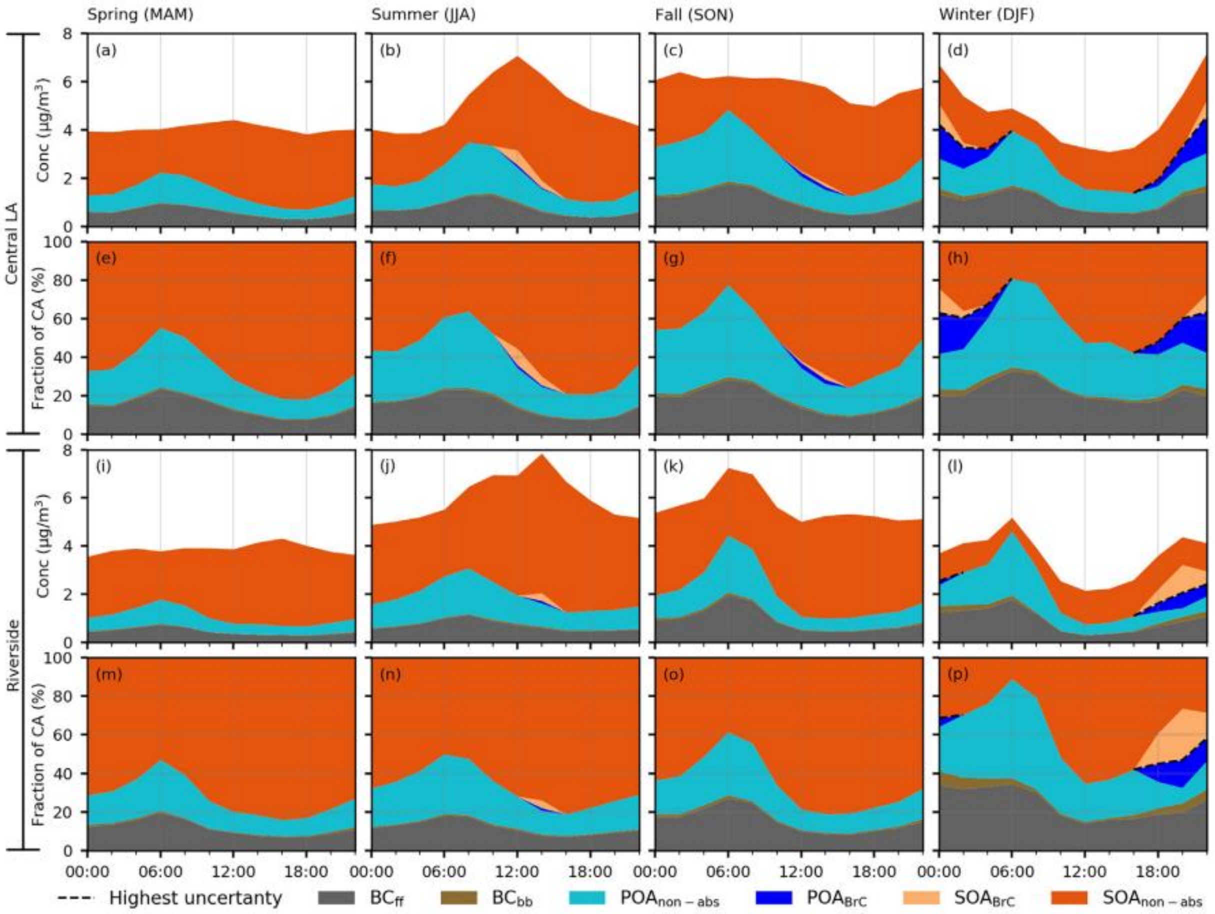


Figure 17. Diurnal profiles of carbonaceous aerosol apportioned BC measured using a AE33 and OC calculated from using a TCA08. Built-in apportionment techniques were used to report the BC data as from BC_{ff} and BC_{bb}, and the OC data as from POA or SOA, that are either POA_{BrC} or $POA_{non\text{-}abs}$. Results are separated into seasons. The black dashed line represents the split between POA_{BrC} and SOA_{BrC} during winter nights, when the highest uncertainty is expected to appear. Figure from Ivančič et al. (2022).

9.2.4. Spatial Trends

Fossil fuels and mobile sources are a major component of carbonaceous aerosol pollution, which can be observed by comparing near-road measurements to neighborhood or rural sites. BC concentrations are typically most elevated during morning commuting hours and decrease as distance from the road increases. Examples of this trend are shown in Figure 18, which highlights near-road air quality measurements in Raleigh, NC, using an Aethalometer®, and Figure 19, which shows higher BC values at near-road sites in the South Coast Air Basin measured using an AE33 Aethalometer® from 2018-2019 (Nastri et al., 2021).

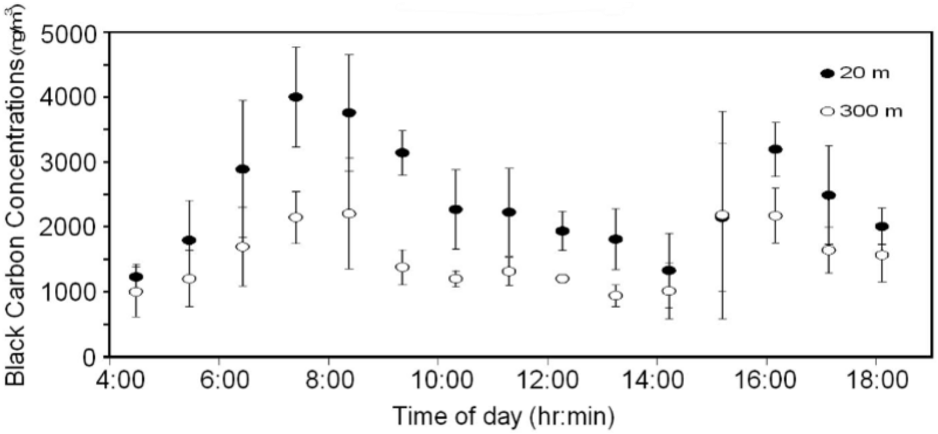


Figure 18. BC concentration (ng m^{-3}) diurnal pattern at 20 m from the road (filled circles) and 300 m from the road (open circles) measured in Raleigh, NC, using an Aethalometer®. Figure from Baldauf et al. (2012).

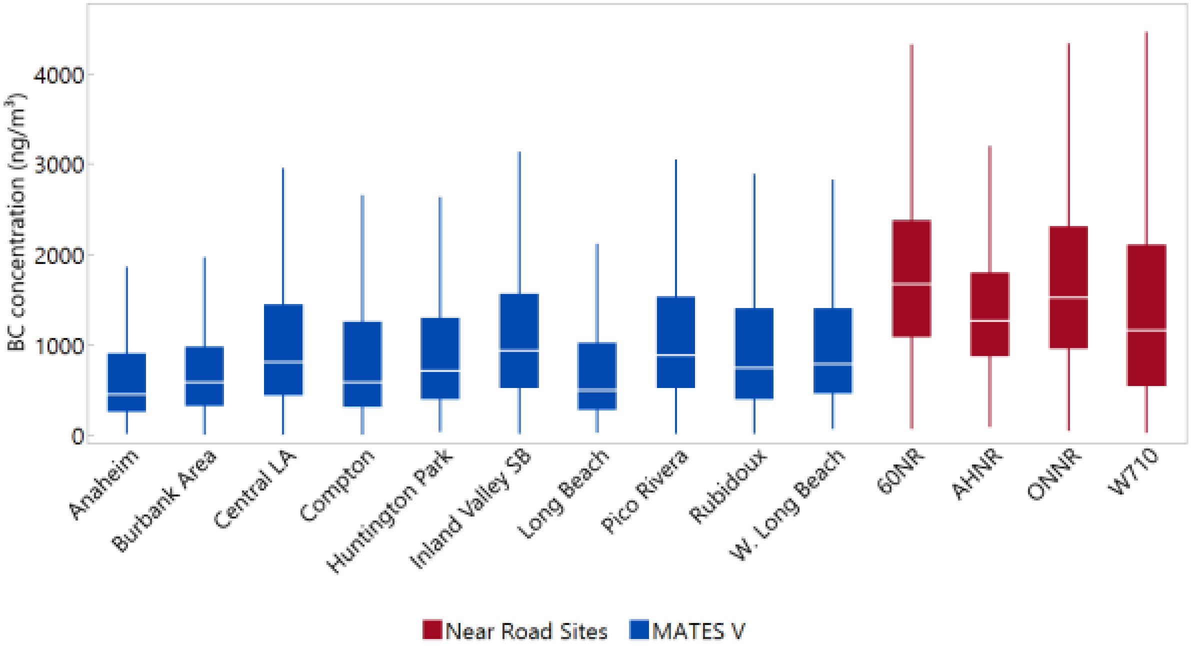


Figure 19. Boxplot comparison of BC concentration between MATES V (2018-2019) sites (blue) and near-road sites (red), in the South Coast Air Basin in California. Figure from Nastri et al. (2021).

9.3. Important Cases of Carbonaceous Aerosol Data

While graphics in Section 9.2.1 showed that BC concentrations have trended downward across the U.S. in general, several important cases result in important hotspots of carbonaceous aerosol concentrations to note. Figure 20 from Wei et al. (2023) shows national average BC concentrations from 2000 to 2020 (left image) as well as the concentration trend (increasing or decreasing, right image). Hotspots in the trends are observed in (1) wildfire prone areas and (2) areas sensitive to residential wood burning as discussed next.

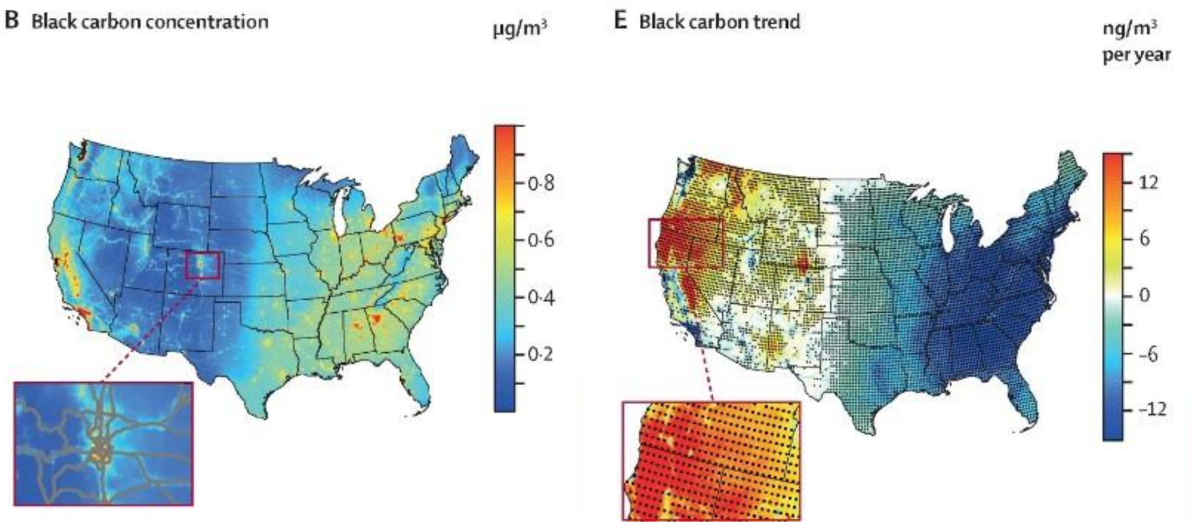


Figure 20. (B, left) Multiyear means for BC concentrations averaged over the period from 2000 to 2020 at each 1-km^2 grid across the continental USA. (E, right) Annual trends for BC concentrations. Each black dot in E denotes a 30-km^2 area where the trend is significant at the 95% ($p < 0.05$) confidence level. The magnified sections show Denver, Colorado, with grey lines representing major roads (B), and fire-prone areas encompassing California, Oregon, and Nevada (E). Figure from Wei et al. (2023).

9.3.1. Wildfire Impacts

Wildfires are a key factor impacting air quality, with wildfire severity and size increasing substantially in the past decade. Fire episodes are a major disruption to long-term air quality improvements over the past decade. Wildfires have potentially offset decreases in anthropogenic emissions in some areas (McClure & Jaffe, 2018), and potentially increased the toxicity of ambient $PM_{2.5}$ concentrations, exacerbating the health impacts of $PM_{2.5}$ (Wei et al., 2023).

Wildfires have been shown to impact nearby and downwind criteria air pollutant concentrations such as PM_{10}, $PM_{2.5}$, CO, NO_x, and ozone. Wildfires are also influencing carbonaceous aerosol concentrations in the western U.S. The right magnified section of Figure 20 shows the trend in increased BC concentrations in fire-prone areas encompassing California, Oregon, and Nevada. Fire episodes can have a widely varying level of influence on pollutant measurements, depending on the distance and time of smoke transport, fuel source, and extent of vertical mixing. Key indicators of wildfire smoke influence in air quality include increases in PM concentrations, reductions in visibility, and the presence of NOAA Hazard Mapping System (HMS) smoke polygons[14] over the area (although note that the HMS data product does not necessarily reflect ground-level conditions of pollutants).

Carbonaceous aerosol measurements can also provide air quality networks with specific evidence of and insight into fire influence in their local air quality. These measurements can aid identification of smoke-impacted air masses by revealing changing trends in BC, OC, and BrC aerosols, and particularly increases in the OC-to-BC ratio. For example, Ivančič et al. (2023)

---

[14] https://www.ospo.noaa.gov/Products/land/hms.html

used the AE33 and TCA08 to measure concentrations of these species downwind of the 2018 Camp Fire, the deadliest and most destructive fire in California (Figure 21). Key trends included:

- Increases in BC and TC throughout the fire period.
- Increases in OC throughout the fire period, and a further increase in OC in the smoldering phase of the fire compared to the flaming phase.
- Increases in the fraction of light absorbed by BrC.

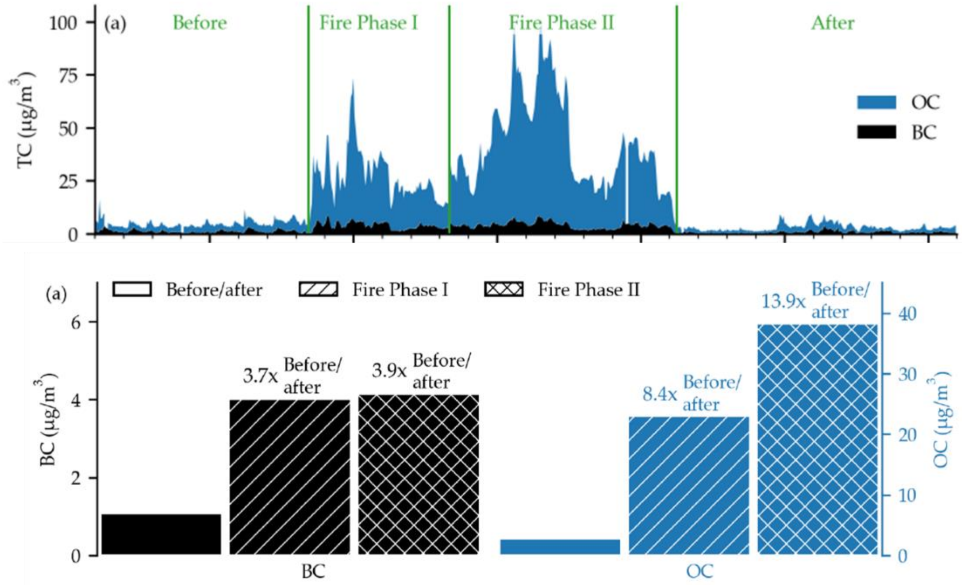


Figure 21. Concentrations of BC (black) and OC (blue) downwind of the 2018 Camp Fire in California measured using AE33 and TCA08 instruments. Fire Phase 1 was characterized as a flaming period with high fuel loading, while smoldering and spot fires were more typical in Fire Phase II. Figure modified from Ivančič et al. (2023).

9.3.2. Residential Wood Burning

Hotspots in urban areas are also visible in Figure 20; for example, Denver is shown in the left magnified section. In addition to mobile source pollution, residential heating and burning also contributes to community BC pollution in urban areas. In communities where wood is burned for home heating, wood smoke can, at times, contribute the majority of the atmospheric fine-particle burden and have impacts on both ambient and indoor air pollution. In these communities, continuous carbonaceous aerosol data and analysis may provide insight into and support for targeted pollution reduction programs, such as wood burning stove replacement programs.

Residential heating and burning impacts are most often seen on a seasonal basis, peaking during winter nights. Example episodes of winter wood burning aerosol enhancements have been documented by (Brown et al., 2020; Cappa et al., 2019; Olson et al., 2024; Skiles et al., 2018; Watson & Chow, 2002). These works have identified that wintertime enhancements in BrC caused by residential wood burning occur primarily at night, while daytime winter enhancements are more strongly associated with secondary aerosol formation. An example from Brown et al. (2020) is shown in Figure 22, where the contributions of BC_{bb} and BC_{ff} are compared across environmental justice (EJ) and non-EJ communities. These results demonstrated higher percentages of wintertime BC were attributed to BC_{bb} in non-EJ communities.

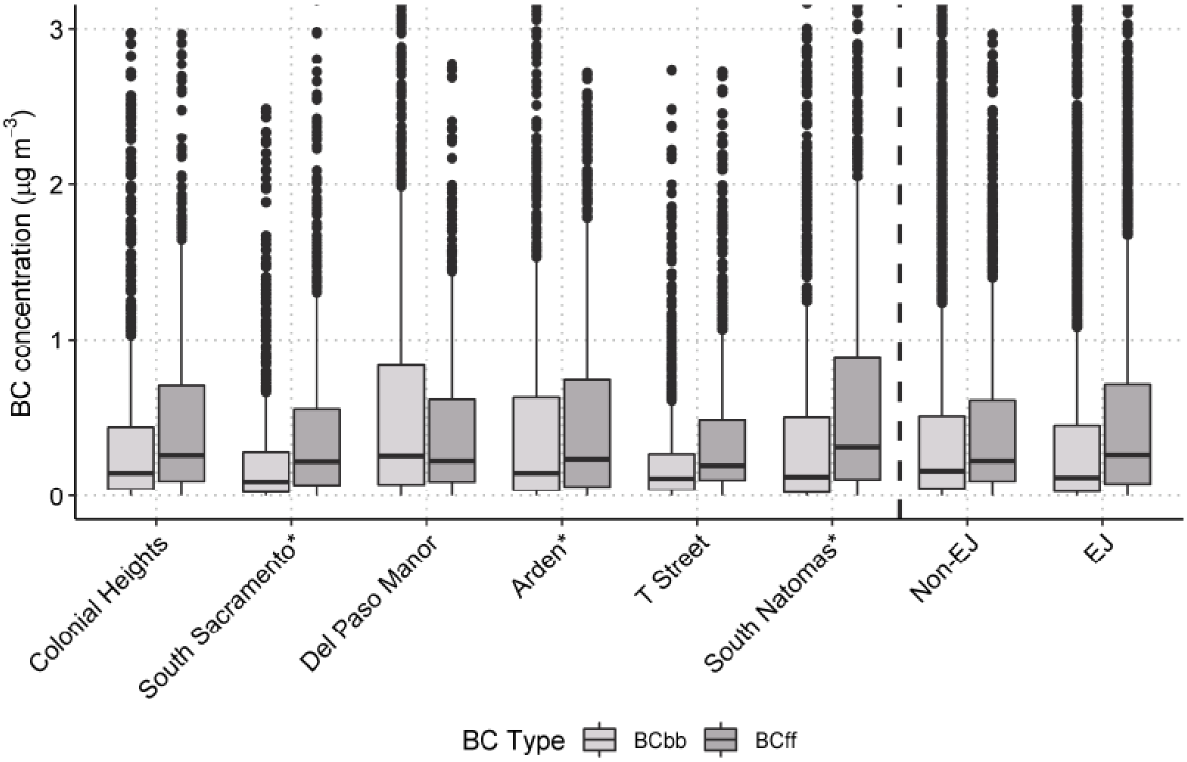


Figure 22. Box plot of concentrations of BC from BC_{bb} and BC_{ff} at EJ and non-EJ sites in December 2016-January 2017. Data values above 3.1 µg/m^3 are not shown for trend clarity. Figure from Brown et al. (2020).

10. APPENDIX A: ERROR CODE DECONVOLUTION SCRIPTS

Status codes for the AE33 and BC 1060 are output as the sum of all codes triggered during a measurement. During data review, it may be helpful to automatically process these values as valid or invalid, in which case it is necessary to deconvolute the sum of the codes into the individual codes. The following are three generic R and Python scripts for instruments that sum error codes together in this manner that have been used to output a list of the individual codes for automated data validation.

The first script (R example) applies the following logic steps:

1. Set the potential status code values to check for (n). All potential status codes for these instruments are generated from a 16-bit binary system, so the list of all values is a set of 2^n.
2. Find the highest potential status code that can be in the final summed code (e.g., for a final code of 135,170, no individual status code can be greater than 135,170, and the highest 2^n value is 2^17 = 131,072).
3. Subtract that highest potential status code from the final summed code. (e.g., 135,170-131,072 = 4,098).
4. Repeat steps 2 and 3 in descending order of all potential status codes.

R example:

This script (1) creates a function ‘decoder’ to decode the summed error codes, (2) summarizes the raw data by error codes, and (3) summarizes how much of the data is valid or suspect. A screenshot of the code and output is below, followed by the plain-text of the code that can be copy and pasted into R or R Studio.

```
#> Deconvolute error codes ----

  decoder <- function(code){
    nmax = 20 # Can adjust this if values greater than 2^n
    nlist = list.reverse(1:nmax)
    output = c()

      for(n in nlist){
        if(code %/% 2^n == 1){
          code = code-2^n
          output = paste(output, 2^n, sep = ",")
        }
      }
      return(output)
  }

qc_summary <- raw_data %>%
  group_by(Status) %>%
  summarize(count = n()) %>% ungroup() %>%
  mutate(percent = round(100*count/sum(count),2),
         decoded = 0)

for(n in 1:nrow(qc_summary)){
  qc_summary$decoded[n] <- decoder(qc_summary$Status[n])
  }


qc_summary_deconvoluted <- qc_summary %>%
  arrange(-percent) %>%
  mutate(validity = ifelse(grepl(",16",decoded) | grepl(",128",decoded) | grepl(",256",decoded) | grepl(",8192",decoded),
                           "suspect", "Valid")) %>%
  mutate(status_code_notes = "",
         status_code_notes = ifelse(grepl(",128",decoded),
                                    paste(status_code_notes, "Caution! 128 = Flow Unstable."), status_code_notes),
         status_code_notes = ifelse(grepl(",16",decoded),
                                    paste(status_code_notes, "Caution! 16 = Optical saturation."), status_code_notes)
         ) %>%
  relocate(decoded, .after = "validity")

  qc_summary_deconvoluted
```

```
## # A tibble: 11 × 6
##    Status  count percent validity decoded      status_code_notes
##     <int>  <int>   <dbl> <chr>    <chr>        <chr>
##  1     64 236553   65.0  Valid    ,64          ""
##  2     80 126582   34.8  suspect  ,64,16       " Caution! 16 = Optical saturati…
##  3     88    318    0.09 suspect  ,64,16,8     " Caution! 16 = Optical saturati…
##  4     68    220    0.06 Valid    ,64,4        ""
##  5     72    209    0.06 Valid    ,64,8        ""
##  6     66     66    0.02 Valid    ,64,2        ""
##  7     82     49    0.01 suspect  ,64,16,2     " Caution! 16 = Optical saturati…
##  8     84     44    0.01 suspect  ,64,16,4     " Caution! 16 = Optical saturati…
##  9    192      6    0    suspect  ,128,64      " Caution! 128 = Flow Unstable."
## 10    208      2    0    suspect  ,128,64,16   " Caution! 128 = Flow Unstable. …
## 11    210      1    0    suspect  ,128,64,16,2 " Caution! 128 = Flow Unstable. …
```

```
#> Deconvolute error codes ----

    decoder <- function(code){
      nmax = 20 # Can adjust this if values greater than 2^n
      nlist = list.reverse(1:nmax)
      output = c()

        for(n in nlist){
          if(code %/% 2^n == 1){
            code = code-2^n
            output = paste(output, 2^n, sep = ",")
          }
        }
        return(output)
    }


  qc_summary <- raw_data %>%
    group_by(Status) %>%
    summarize(count = n()) %>% ungroup() %>%
    mutate(percent = round(100*count/sum(count),2),
           decoded = 0)

  for(n in 1:nrow(qcsumm)){
      qcsumm$decoded[n] <- decoder(qcsumm$Status[n])
    }


  qc_summary_deconvoluted <- qc_summary %>%
    arrange(-percent) %>%
```

```
  mutate(validity = ifelse(grepl(",16",decoded) | grepl(",128",decoded) | grepl(",256",decoded) |
grepl(",8192",decoded),
                    "suspect", "Valid")) %>%
  mutate(status_code_notes = "",
        status_code_notes = ifelse(grepl(",128",decoded),
                               paste(status_code_notes, "Caution! 128 = Flow Unstable."),
status_code_notes),
        status_code_notes = ifelse(grepl(",16",decoded),
                               paste(status_code_notes, "Caution! 16 = Optical saturation."),
status_code_notes)
        ) %>%
  relocate(decoded, .after = "validity")

  qc_summary_deconvoluted
```

Python example:

```
# The following functions can be used to read in the AE33's status code
# and output a plain-language description of the status.
# Requires converting from decimal to binary and pairing with table of
# key bit positions (as described in Section 8.2 of Magee's AE33 User
# Manual V1.58).

# Code developed and tested on an Aethalometer(R) Model AE33-7 firmware
# version 518, Software version 1.4.1.1 using Python 3.12.0. Code should
# be used with caution with different AE33 models and firmware.

##### ##### ##### ##### ##### ##### ##### ##### ##### ##### ##### #####

# Convert decimal to 16-bit binary; used in fcn ae33_status_description
def decimal_to_binary(decimal):
    '''
    Function converts decimal values to 16-bit binary

    Arguments:
    decimal = (int or float) the decimal value to be converted. Floating
        values are rounded down to nearest integer. String or other
        datatypes return '0000000000000000'.

    Output: (string) 16-bit binary value.
    '''
    try:
        binary = format(int(decimal), '016b')
    except:
        binary = format(0,'016b')
    return binary
```

```
##### ##### ##### ##### ##### ##### ##### ##### ##### ##### ##### #####

# Convert decimal status code to plain-language description.
def ae33_status_describe(decimal_value=0, returned_message=False):
    '''
    Function provides a plain language description of the AE33 status
        code.

    Arguments:
    decimal_value = (int or float) the status code output by the AE33.
    returned_message = (binary) If False (default) will only output when
        error or non-normal status is reported. If True will provide all
        status values.

    Output: (string) Plain-language description of AE33 status code.
    '''

    # Convert the decimal to binary
    binary_value = decimal_to_binary(decimal_value)

    # Make a dictionary holding the bit position combinations and
    # meaning.
    bit_key = [
        # Operation: bits 1 and 0 (code[14:])
        {'00': 'Measurement',
         '01': 'Tape advance (tape advance, fast calibration, warm-up)',
         '10': 'First measurement - obtaining ATN0',
         '11': 'Stopped'},
        # Flow: bits 3 and 2 (code[12:14])
        {'00': 'Flow OK',
         '01': 'Flow low/high by more than 0.5 LPM or F1 < 0 or F2/F1 outside 0.2 - 0.75 range',
         '10': 'Check flow status history',
         '11': 'Flow low/high & check flow status history'},
```

```
# Optical Source: bits 5 and 4 (code[10:12])
{'00': 'LEDs OK',
 '01': 'Calibrating LED',
 '10': 'Calibration error (at least one channel OK)',
 '11': 'LED error (all channels calibration error, COM error'},
# Chamber: bit 6 (code[9])
{'0': 'Chamber OK',
 '1': 'Chamber error'},
# Filter tape: bits 8 and 7 (code[7:9])
{'00': 'Filter tape OK',
 '01': 'Tape warning (less than 30 spots left)',
 '10': 'Tape last warning (less than 5 spots left)',
 '11': 'Tape error (tape not moving, end of tape)'},
# Setup file: bit 9 (code[6])
{'0': 'Setup file OK',
 '1': 'Setup warning'},
# Tests & procedures: bits 12, 11, and 10 (code[3:6])
{'000': 'No test',
 '001': 'Stability test',
 '010': 'Clean air test',
 '011': 'Change tape procedure',
 '100': 'Optical test',
 '110': 'Leakage test'},
# External device: bit 13 (code[2])
{'0': 'Connection OK',
 '1': 'Connection Error'},
# Auto clean air test status: bit 14 (code[1])
{'0': 'Status OK or test not run yet',
 '1': 'Result of clean air test is not acceptable. Service of instrument is recommended'},
# CF card failure: bit 15 (code[0])
{'0': 'CF card OK???',
 '1': 'Problem while saving or retrieving files to/from CF card'},
# # Database status: bit 16 (code[:]????)
```

```
    # {#'0': 'Database status OK',
    #  '1111111111111111': 'Database bigger than 6x10^6 data lines'},
]

bit_link = {
    0:binary_value[14:], # Operation: bits 1 and 0
    1:binary_value[12:14], # Flow: bits 3 and 2
    2:binary_value[10:12], # Optical Source: bits 5 and 4
    3:binary_value[9], # Chamber: bit 6
    4:binary_value[7:9], # Filter tape: bits 8 and 7
    5:binary_value[6], # Setup file: bit 9
    6:binary_value[3:6], # Tests & procedures: bits 12, 11, and 10
    7:binary_value[2], # External device: bit 13
    8:binary_value[1], # Auto clean air test status: bit 14
    9:binary_value[0], # CF card failure: bit 15
    #10:binary_value[:] # Database status: bit 16
}

full_message = ''
if binary_value == '1111111111111111':
    full_message = 'Database bigger than 6x10^6 data lines; '
else:
    for key, value in bit_link.items():
        full_message = full_message + bit_key[key][value] + '; '

# Create an alternative output, only showing error messages
error_only_message = full_message
remove_str = ['Measurement; ','Flow OK; ','LEDs OK; ','Chamber OK; ',
              'Filter tape OK; ', 'Setup file OK; ','No test; ',
              'Connection OK; ','Status OK or test not run yet; ',
              'CF card OK???; ']

for remove in remove_str:
```

```
        error_only_message = error_only_message.replace(remove, ")

    if returned_message:
        return full_message[:-2]
    else:
        return error_only_message[:-2]
```

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