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# Opinion: From "Error" to "Signal": Rethinking Method Discrepancies in Black Carbon Measurements and Goal-Oriented Standardization

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**Abstract.**Black carbon (BC) aerosol measurements face a fundamental dilemma: results from different methods applied to the same sample can differ by a factor of several, far exceeding instrumental uncertainty (±5–10%). Petzold et al. (2013) established that equivalent black carbon (eBC), elemental carbon (EC), and refractory black carbon (rBC) are distinct concepts defined by different operational definitions. This paper argues that such discrepancies are inevitable, originating at the conceptual definition level rather than as a purely technical problem. Instrument calibration can address comparability among "same method, different instruments" but cannot eliminate conceptual differences among "different methods." We propose two mutually reinforcing pathways. At the epistemological level, method discrepancies are reframed as interpretable "signals"—sources of information about aerosol state rather than errors to be eliminated. At the practical level, we advocate "goal-oriented standardization"—abandoning the pursuit of a singular "true BC" with all methods and instead matching measurement protocols to specific research objectives (e.g., climate modeling, health assessment, source apportionment). These pathways together respond to the dilemma of universal standardization, complementing metrological work on within-method comparability. This opinion article aims to stimulate debate on the future of black carbon measurement standardization.

## 1 Introduction

### 1.1 The Importance and Dilemma of Black Carbon Measurements

Black carbon (BC) aerosol, a product of incomplete combustion of carbonaceous materials, is recognized as the second most significant contributor to radiative forcing after carbon dioxide due to its strong light absorption properties (Bond et al., 2013). At the same time, BC poses substantial risks to human health. Yet, the measurement of this critical atmospheric pollutant has long faced a fundamental dilemma: the "BC" values obtained by different methods often do not agree.

The degree of disagreement far exceeds what is typically understood as "instrument error." Instrument specifications usually claim measurement precision within ±5–10%, which reflects the hardware's technical performance. However, when researchers deploy instruments based on different principles at the same sampling inlet to measure the same aerosol stream, the results exhibit systematic discrepancies that greatly surpass instrumental error margins.

### 1.2 Systematic Evidence of Method Discrepancies

Multi-method intercomparison studies consistently demonstrate that differences between methods are systematic, structural, and can differ by a factor of several.

**Influence of emission source characteristics.** BC particles generated from different combustion sources exhibit significant variations in physicochemical properties, leading to divergent method responses. An intercomparison study by Momenimovahed et al. (2022) on marine engine emissions reported a relative standard deviation of 24–37% among instruments under normal operating conditions. However, under extreme conditions of 10% engine load and exceptionally high organic carbon content (OC/EC ≈ 280), the deviation reached as high as 72%. Zhang et al. (2019) systematically compared five instruments in controlled biomass burning experiments and found that emission factors derived from thermal-optical, laser-induced incandescence, and filter-based absorption methods were higher than those from in situ absorption methods by 83%, 39%, and 66%, respectively. Furthermore, inter-instrument consistency varied significantly with combustion conditions—it was best for high modified combustion efficiency (MCE) "black" flaming combustion and markedly deteriorated during low MCE "brown" smoldering combustion.

**Influence of aging processes.** A systematic review by Wu et al. (2025) compiled data from multiple studies and calculated pairwise ratios of eBC, EC, and rBC. The eBC/EC ratio was approximately 0.81 for fresh emissions and increased to 1.17 after aging. The eBC/rBC ratio rose from 0.94 to 2.14, while the EC/rBC ratio increased from 1.32 to 1.60. These shifts reveal the asymmetric impact of aging on different measurement principles: optical methods are most sensitive to coating, SP2 measurements of the BC core mass remain almost unaffected, and thermal-optical methods fall in between.

*Evidence from observational sites.* A two-year intercomparison at the Pic du Midi Observatory in France by Tinorua et al. (2024) showed eBC concentrations approximately twice those of rBC and EC, with deviations reaching up to a factor of eight during dust events. Systematic cross-method discrepancies have similarly been observed in intercomparisons at multiple European background sites by Pileci et al. (2021), who found rBC-to-EC mass concentration ratios ranging from 0.53 to 1.29 across different campaigns, with systematic differences up to a factor of 2.

**Validation from laboratory studies.** Kalbermatter et al. (2022) generated BC particles with varying coating thicknesses under controlled conditions and found that optical method signals increased with coating thickness, resulting in deviations of 50–60% relative to SP2. The classic early intercomparison by Slowik et al. (2007) also identified systematic response differences among instruments to particle morphology and mixing state.

These data collectively reveal a fundamental fact: differences between methods (factors of several) vastly exceed instrumental error (percent-level). The root cause lies not in instrument hardware but at a more fundamental level—different methods understand and define "black carbon" differently.

### 1.3 Root of the Problem: Petzold's Insight and the Starting Point of This Paper

The work of Petzold et al. (2013) provides a crucial clue for understanding this dilemma. Through terminological standardization, they established eBC, EC, and rBC as distinct concepts defined by different operational definitions: eBC is defined by optical methods and the mass absorption cross-section (MAC), EC by thermal-optical methods, and rBC by the single particle soot photometer (SP2). The core insight of this terminology framework is that values obtained by different methods should no longer be viewed as error-laden estimates of a single “true black carbon.” Instead, they acknowledge that these methods measure different attributes defined by distinct operational procedures.

This paper builds on Petzold et al. (2013) by posing a further question: is this discrepancy an incidental error or an inevitable outcome? Our analysis will demonstrate that this discrepancy is inevitable, rooted in conceptual definition rather than technical limitations. Optical methods measure light absorption characteristics, thermal-optical methods measure thermal stability characteristics, and the SP2 measures refractory characteristics. They probe different feature dimensions of BC. Requiring numerical agreement among eBC, EC, and rBC is inherently unreasonable.

Based on this recognition, this paper proposes two mutually reinforcing response pathways. At the epistemological level, method discrepancies are reframed as interpretable “signals”—transforming them from errors to be eliminated into sources of information about aerosol state that can be actively exploited. At the practical level, we advocate a shift toward “goal-oriented standardization”—abandoning the pursuit of a singular “BC” measurement and instead establishing measurement protocols matched to specific research objectives, such as climate modeling, health impact assessment, or source apportionment. These two pathways, addressing “how to view discrepancies” and “how to respond to discrepancies,” together constitute a response to the dilemma of universal standardization.

## 2 Conceptual Framework: The Completeness of the BC Concept and the Inherent Selectivity of Measurement

### 2.1 The Completeness of the BC Concept and the Inherent Selectivity of Measurement

In everyday usage, the term “black carbon” seemingly refers to a well-defined substance. Scientifically, however, BC is far more complex. It is not a stoichiometrically defined pure substance but rather a collective term for a class of carbonaceous particulate matter defined by a suite of characteristics (Petzold et al., 2013; Bond et al., 2013). Table 1 summarizes five core characteristic dimensions of BC and the primary measurement methods corresponding to each.

Table 1 presents the five characteristic dimensions that constitute the “complete” scientific definition of BC. However, no single measurement method can simultaneously capture all these features. Each method selectively samples certain characteristics while treating others as irrelevant or as interferences. This defines the inherent selectivity of measurement: we cannot measure the “complete BC”; we can only measure its representation along certain characteristic dimensions.

Based on the analysis above, this paper poses three core questions: Do different methods measure the same quantity, or different operationally defined quantities? Can discrepancies between methods be eliminated through technical means? If discrepancies cannot be eliminated, how should new measurement practices be constructed?

**Table 1. Characteristic Dimensions of Black Carbon and Corresponding Measurement Methods**

| Characteristic Dimension | Specific Connotation | Primary Measurement Methods | Key Output Parameter | Limitations / Assumptions |
|---|---|---|---|---|
| Light Absorption | Strong, wavelength-dependent absorption; AAE ≈ 1 | Filter-based optical methods, Photoacoustic Spectroscopy (PAS), Extinction-Minus-Scattering (EMS), Photothermal Interferometry (PTI) | absorption coefficient (b_abs) → eBC (via MAC conversion) | MAC varies with source, aging, mixing state; responds to brown carbon, mineral dust, etc. |
| Thermal Stability | Non-volatile or resistant to oxidation at high temperatures | Thermal-optical analysis | Elemental Carbon (EC) | EC value depends on thermal protocol; results from different protocols can differ by factors |
| Refractory Nature | Vaporizes and emits incandescent light at extremely high temperatures | Single Particle Soot Photometer (SP2) | refractory Black Carbon (rBC) | Limited particle size detection range; requires extrapolation for total mass estimation |
| Insolubility | Insoluble in water and common organic solvents | Wet chemical methods | Insoluble carbon fraction | Less commonly used currently |
| Morphology | Chain-like or clustered aggregates | Electron microscopy | Morphological information | Qualitative or semi-quantitative; not routinely used for mass closure |

## 2.2 Two Epistemological Stances: Realism and Operationalism

The first question directly concerns how we perceive method discrepancies.

Interpretation A: Realism. Proponents of this view believe that a “true black carbon” exists as an objective entity. Different measurement methods are akin to viewing the same object from different angles; the resulting images, though differing, are all error-laden depictions of that entity. Method discrepancies are thus measurement errors that should be eliminated through instrument improvement and unified calibration.

Interpretation B: Operationalism. Proponents of this view contend that there is no “BC itself” independent of the measurement operation. eBC is the BC defined by optical methods and the MAC; EC is the BC defined by thermal-optical methods; rBC is the BC defined by the SP2. The classic articulation of this understanding comes from the terminology recommendations of Petzold et al. (2013).

This paper adopts Interpretation B. This choice is not a matter of philosophical preference but is compelled by empirical evidence. If Interpretation A were correct, then with technological advancement and calibration unification, discrepancies between methods should gradually diminish and tend to disappear. However, decades of development show that fundamental differences between methods based on different principles have not vanished with technological progress. This suggests that the discrepancies are rooted at the conceptual level, not the technical level. Choosing Interpretation B does not negate the value of calibration efforts—the latter addresses the comparability of "same method, different instruments," which operates on a different plane from the "cross-method discrepancies" discussed herein.

### 2.3 The Divergence Between Realism and Operationalism: An Analogy

Height and waist circumference both correlate statistically with body weight, but this correlation is far from one-to-one. Inferring weight from height versus inferring weight from waist circumference typically yields values that are close but not identical.

A realist argues: Height and waist circumference are both indirect estimates of "true body weight." Provided measurements are sufficiently precise, both inferred values should converge on the same true weight. An operationalist counters: No matter how precisely height or waist circumference are measured, the weights inferred from them can never be made to agree—because the relationship between height and weight and the relationship between waist circumference and weight are fundamentally two different curves. Increasing measurement precision cannot alter the shape of those curves.

The relationship among eBC, EC, and rBC is analogous. They all correlate with certain features of BC, hence their numerical values often exhibit rough correspondence—e.g., eBC/EC ≈ 0.81 for fresh emissions. But this correlation is not identity. No degree of improvement in the measurement precision of each method can force eBC, EC, and rBC to converge on a single value. Insisting on their agreement is tantamount to demanding that weight inferred from height equals weight inferred from waist circumference—a logically impossible requirement.

## 3 The Inevitability of Method Discrepancies: The Impact of Physicochemical Complexity on Measurement Results

### 3.1 Theoretical Analysis: How Physicochemical Parameters Lead to Systematic Method Differences

The physicochemical properties of BC-containing aerosol particles are exceedingly complex. BC particles of identical mass can exhibit significant differences in size, morphology, and mixing state (Kahnert and Kanngießer, 2020). Variations in these physicochemical parameters directly affect the response of different measurement methods, leading to systematic discrepancies among them.

*Discrepancies between eBC and EC.* EC measured by thermal-optical methods is defined by thermal stability, and the measurement result is unaffected by particle size, fractal morphology, or coatings. In contrast, eBC measured by optical methods relies on the MAC to convert the absorption coefficient (b_abs) to mass concentration. The MAC is not a constant: it varies with particle size distribution and coating thickness—a Mie simulation by Zhao et al. (2021a) showed that the MAC varied dramatically with core size and shell thickness, leading to significant discrepancies in derived eBC compared to using a constant MAC. The fractal structure of BC causes discrepancies of up to 30% compared to equivalent sphere approximations (Liu et al., 2019). Wei et al. (2020a) reviewed that global measured MAC values range from 3.8 to 58 m²/g and that coatings can significantly enhance MAC via the lensing effect. These factors all propagate to eBC through their influence on the MAC, making systematic deviations between eBC and EC inevitable.

*Discrepancies of rBC relative to EC and eBC.* rBC measured by the SP2 detects refractory core mass via single-particle incandescence signals. This definition differs from the thermal stability definition of EC and the optical measurement principle of eBC. rBC measurements face two primary limitations. First, the SP2 has a limited detection window, leaving particles outside this range undetected or weakly detected and requiring extrapolation based on size distribution (Tinorua et al., 2024). Moreover, about 34.9% of BC-containing aerosols are misclassified as pure BC (Zhao et al., 2021b). Second, SP2 retrieval relies on a spherical core-shell assumption and fixed refractive index; for fractal BC with core diameters greater than ~200 nm, the mixing state is underestimated (Liu et al., 2025). These limitations cause rBC to differ not only from EC but also to respond differently than eBC—eBC increases with enhanced coating, whereas rBC core mass is insensitive to coating, although significant errors exist in measuring its coating state.

### 3.2 Experimental Verification: Laboratory Evidence Under Controlled Conditions

Kalbermatter et al. (2022) generated BC particles with varying coating thicknesses in the laboratory and found that instrument response differences depended on coating thickness: inter-instrument differences were smaller for fresh BC, but as coatings thickened, optical method signals increased, leading to deviations of 50–60% relative to SP2. These results align closely with theoretical predictions. The classic intercomparison using fractal BC particles by Slowik et al. (2007) also found systematic response differences among instruments to particle morphology.

### 3.3 Observational Evidence: Validation in Ambient Atmospheres

The systematic review by Wu et al. (2025) compiled data from multiple studies and calculated pairwise ratios of eBC, EC, and rBC and their trends with aging (Table 2).

**Table 2. Changes in eBC, EC, and rBC Ratios with Aging (Data Source: Wu et al., 2025)**

| Ratio | Fresh Emissions | Aged | Trend |
|---|---|---|---|
| eBC / EC | 0.81 | 1.17 | ↑ |
| eBC / rBC | 0.94 | 2.14 | ↑↑ |
| EC / rBC | 1.32 | 1.60 | ↑ |

The trends in these numbers are highly consistent with theoretical predictions and experimental results: upon aging, eBC increases significantly relative to both EC and rBC, whereas the increase of EC relative to rBC is more moderate. This is precisely because optical methods are most sensitive to coatings, the SP2 measures the uncoated refractory core mass and is thus insensitive to coating enhancement, and thermal-optical methods are intermediate. Furthermore, Tinorua et al. (2024) observed eBC/rBC deviations up to a factor of eight during dust events at Pic du Midi, demonstrating that interference from other light-absorbing substances also contributes to method discrepancies.

### 3.4 The Roots of Discrepancy: A Continuum from Technical to Conceptual

The analysis above demonstrates that method discrepancies are rooted in the complexity of BC physicochemical parameters. The following four-tiered hierarchy summarizes how this complexity translates into measurement differences, forming a continuum from "technically resolvable" to "conceptually irresolvable."

**Level 1: Instrument hardware system.** This includes detector sensitivity, light source stability, flow control precision, etc. Such differences are typically small (±5–10%) and can be controlled and minimized through regular calibration and the use of reference materials. Metrological efforts are dedicated to this level (Liu et al., 2023a; EURAMET, 2023–2026).

**Level 2: Operational parameter differences.** Instruments of the same principle can produce different results due to varying operational parameters: the choice of temperature protocol in thermal-optical analysis, selection of correction algorithms in aethalometers, extrapolation methods for the SP2 size range, etc. (Schmid et al., 2001; Tinorua et al., 2024). For example, Schmid et al. (2001) showed in an international round robin test that elemental carbon (EC) values from different laboratories using different thermal protocols varied by more than an order of magnitude, with relative standard deviations of 36.6% and 45.5% for two samples.

**Level 3: Conversion model and assumption differences.** This includes the assumed MAC value in optical methods, the correction from attenuation coefficient to absorption coefficient in filter-based methods, and the calibration curve converting incandescence signal to particle mass in the SP2 (Bond and Bergstrom, 2006; Liu et al., 2023a). Liu et al. (2023a) showed that the choice of correction coefficient alone can cause results for the absorption coefficient to differ by more than a factor of two.

**Level 4: Conceptual definition differences.** This is the most fundamental level. Optical methods measure light absorption characteristics, thermal methods measure thermal stability, and the SP2 measures refractory nature. eBC, EC, and rBC are distinct concepts under different operational definitions; requiring their numerical agreement is inherently unreasonable (Petzold et al., 2013). It is crucial to emphasize that Level 4 differences are the fundamental reason why discrepancies at Levels 2 and 3 cannot be eliminated through technical means—they define the identity of the method, not merely a bias in measurement.

Conceptual-level differences are often masked when the aerosol is relatively "simple" (e.g., fresh emissions, monodisperse size, uncoated). Under such conditions, results from different methods may correlate highly, creating the illusion that they measure the same entity. However, as the aerosol ages and the mixing state becomes complex, the divergent responses of

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different methods to the same changes in physicochemical parameters are amplified, and systematic deviations among methods become apparent. Correlation can yield approximate numerical agreement, but it can never yield identical values.

## 4 The Trilemma of Universal Standardization

### 4.1 Trilemma 1: The Challenge of Selecting a Reference Method

If one aims to trace all methods back to a single reference, which method should serve as that benchmark? Each candidate possesses fundamental limitations:

- Photoacoustic Spectroscopy (PAS) directly measures light absorption without filter artifacts; the physical principle is clear (Petzold and Niessner, 1995). However, it measures absorption coefficient, not mass concentration.
- Extinction-Minus-Scattering (EMS) also measures absorption coefficient; the principle can be traced to fundamental physical quantities of extinction and scattering (Modini et al., 2021). However, the instrumentation is complex and expensive, with limited sensitivity for low-concentration samples.
- Thermal-optical method (EC) directly outputs mass concentration and has accumulated a wealth of long-term data. However, it is protocol-dependent—should IMPROVE, NIOSH, or EUSAAR_2 be chosen as the benchmark (Schmid et al., 2001)?
- SP2 (rBC) enables single-particle measurement and is insensitive to coating. However, it relies on size extrapolation and involves uncertainty in estimating the mass of particles outside its detection range (Tinorua et al., 2024).
- Photothermal Interferometry (PTI) can directly measure absorption coefficient, calibrated using $NO_2$, providing a sound traceability basis (Visser et al., 2020).

No single method holds a simultaneous advantage across all criteria, including physical principle soundness, operational simplicity, traceability, and relevance to real-world conditions.

### 4.2 Trilemma 2: The "Impossible Trinity" of MAC

For optical methods, eBC = b_abs / MAC. Determining the MAC faces an "impossible trinity":

- **Direct MAC measurement:** This approach requires simultaneous measurement of b_abs and a reference mass concentration, effectively tying eBC to the reference method and compromising its independence. If the MAC is derived using an SP2, eBC essentially replicates the SP2 result.
- **Adopting literature recommendations:** Using a fixed value, such as the 7.5 ± 1.2 $m^2/g$ recommended by Bond and Bergstrom (2006), ignores the substantial spatiotemporal variability of MAC, which can range from 3.8 to 58 $m^2/g$ (Wei et al., 2020a).
- **Localized MAC measurement:** While improving local accuracy, this approach sacrifices comparability across different locations, as each site would use a different MAC.

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Therefore, regardless of the approach chosen, determining MAC cannot simultaneously satisfy the three requirements of “accuracy,” “independence,” and “comparability.”

### 4.3 Trilemma 3: Conceptual Incommensurability

This is the most fundamental dilemma. eBC, EC, and rBC measure different concepts defined under different operational definitions, and no “true” conversion relationship exists among them. Attempting to establish a universal conversion factor between eBC and EC is akin to trying to establish a universal conversion factor between length and mass—while empirical correlations may exist under specific conditions, no universal conversion constant exists.

### 4.4 The Appropriate Role of Metrological Work

Recognizing these dilemmas does not negate the value of metrological work. On the contrary, metrology plays an irreplaceable role in the following areas: ensuring that instruments of the same principle yield comparable results through reference materials, metrological traceability, and international intercomparisons (Liu et al., 2023a; EURAMET, 2023–2026); providing absolute benchmarks for b_abs through traceable methods like EMS and PTI (Modini et al., 2021; Visser et al., 2020); and establishing standardized measurement protocols for MAC. These efforts address the comparability issue among “same method, different instruments,” forming the technical foundation for all measurement practices. However, technical means cannot eliminate the conceptual differences among “different methods.” The propositions of this paper are complementary to, not in competition with, metrological endeavors.

## 5 Two Mutually Reinforcing Response Pathways

### 5.1 Pathway 1: Reframing Discrepancies as Signals

Once the view of “discrepancy as error” is relinquished and replaced by the recognition that discrepancies arise from differing measurement characteristics, method differences cease to be noise requiring elimination and can instead serve as indicators of aerosol state and properties. The following three modes of signal interpretation illustrate how this epistemological shift can be operationalized—these discussions present interpretive approaches and potential, rather than prescriptive operational standards.

**Using differential method responses to identify interferences or separate components.** The differential responses of distinct measurement principles to the same aerosol sample inherently carry compositional information. Dust particles possess some light absorption capacity and can be misidentified as BC by filter-based optical methods, whereas the SP2, which measures refractory BC cores, exhibits almost no response to non-refractory dust. Tinorua et al. (2024) found at Pic du Midi that the eBC/rBC ratio could reach as high as eight during dust events—this anomalous ratio itself serves as a clear signal of dust interference. Similarly, multi-wavelength optical measurements can separate the contributions of BC and brown carbon by exploiting their differing absorption Ångström exponents (AAE) (Rai et al., 2020; Veratti et al., 2024).

**Using spatiotemporal variation in method ratios to infer aerosol evolution processes.** If discrepancies between methods were fixed, they would merely constitute systematic bias. However, when these discrepancies vary systematically with aerosol state, the ratios themselves become functions of state. The systematic review by Wu et al. (2025) shows that the eBC/EC ratio increases from 0.81 for fresh emissions to 1.17 after aging, and eBC/rBC rises from 0.94 to 2.14. This trend aligns with theoretical predictions of the lensing effect: optical methods are sensitive to coatings, the SP2 measures the uncoated refractory core mass and is thus insensitive to coating enhancement, and thermal-optical methods are intermediate. Consequently, elevated eBC/EC and eBC/rBC ratios can serve as potential indicators of aerosol aging and absorption enhancement. Laboratory studies further validate this logic: Kalbermatter et al. (2022) observed deviations of 50–60% between optical methods and the SP2 as coating thickness increased.

**Using the complementarity of multi-method information for integrated characterization.** A single method can only access certain characteristic dimensions of BC. Combining information from multiple methods allows, through model inversion, the retrieval of physical parameters inaccessible to any single method. For instance, integrating photoacoustic spectroscopy (absorption coefficient), SP2 (BC core mass and size distribution), scanning mobility particle sizer (SMPS, full size spectrum), and chemical composition measurements enables the retrieval of critical parameters such as coating thickness, absorption enhancement factor, and mixing state. The comparison of LEO and CPMA-SP2 techniques by Naseri et al. (2024) exemplifies such synergistic retrieval efforts. In recent years, data assimilation and machine learning methods have begun to be explored for fusing multi-instrument signals to simultaneously constrain aerosol physicochemical state parameters. This represents a frontier direction where “signal utilization” evolves from qualitative criteria toward quantitative modeling.

### 5.2 Pathway 2: Goal-Oriented Standardization

This pathway advocates abandoning the pursuit of measuring a singular “BC” with all methods and instead establishing measurement protocols and standardization specifications matched to specific research objectives. Since eBC, EC, and rBC measure different characteristic dimensions, different research objectives require different characteristics; therefore, one should select the method that most directly measures the feature of interest.

Table 3 presents the correspondence between various research objectives and the most appropriate measurement methods.

Goal-oriented standardization comprises four core elements: (1) objective matching—selecting the method that most directly measures the BC characteristic required for the research objective; (2) protocol specification—establishing standardized operating procedures and data processing requirements tailored to that method and objective; (3) parameter transparency—explicitly reporting all key parameters and assumptions; and (4) uncertainty quantification—systematically assessing measurement uncertainty under the goal-oriented framework. Among these, parameter transparency is the foundation for achieving “indirect comparability”: when different studies employ different methods, comprehensive parameter reporting enables data users to independently assess comparability and perform conversions or corrections when necessary. This substitutes for the pursuit of “numerical agreement” characteristic of universal standardization.

**Table 3. Correspondence Between Research Objectives and the Most Suitable Measurement Methods**

| Research Objective | Core Feature Required | Most Suitable Method(s) | Key Output |
|---|---|---|---|
| Climate modeling | Light absorption coefficient | PAS, EMS, PTI, Multi-Angle Absorption Photometer (MAAP) | b_abs ($Mm^{-1}$) |
| Health effects | Mass concentration, particle size distribution | SP2, thermal-optical method | rBC / EC mass concentration |
| Source apportionment | Source discrimination | Multi-wavelength optical methods | Fossil / biomass contributions |
| Emission inventory validation | Mass concentration consistent with inventory definition | Thermal-optical method (protocol matched to inventory) | EC mass concentration |
| Long-term trend monitoring | Long-term stability | Traceable instruments of the same principle | Depends on objective |

*Note:* Although MAAP is commonly used to report eBC, the physical quantity it directly measures is b_abs. Under the goal-oriented framework, MAAP data should therefore be treated primarily as absorption coefficient measurements.

### 5.3 Constructive Support: Transformations Brought by the Two Pathways

Reframing discrepancies as signals and transitioning to goal-oriented standardization implies a systematic transformation in research paradigms, policy support, and observational infrastructure. Regarding research paradigms, the focus shifts from "eliminating discrepancies" to "utilizing discrepancies," from "pursuing universality" to "pursuing fitness-for-purpose," and from a "single true value" mindset to "multi-characteristic cognition."

Regarding policy support, the World Health Organization's updated Global Air Quality Guidelines in 2021 explicitly included a "good practice statement" for the systematic measurement of black carbon/elemental carbon (WHO, 2021). The revised European Union Ambient Air Quality Directive in 2024 mandated for the first time the monitoring of black carbon at urban and rural supersites (EU Directive, 2024). These policy developments raise a practical question: should monitoring networks choose eBC, EC, or rBC? The framework presented here provides a basis for answering this question: if the focus is climate effects, prioritize monitoring the light absorption coefficient; if health effects, prioritize mass concentration and size distribution; if source apportionment, prioritize multi-wavelength optical methods.

Regarding observational infrastructure development, the recommendation is to select a primary measurement method aligned with the core objective, while deploying auxiliary measurements to cover secondary objectives. Through multi-instrument co-located observations and model inversion, multiple characteristic information streams can be obtained simultaneously. Regardless of the method chosen, transparent reporting of all key parameters is mandatory.

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## 6 Application of Goal-Oriented Standardization: A Climate Modeling Example

### 6.1 From Need to Choice: What Method Does Climate Modeling Require?

The core input for assessing BC radiative forcing in climate models is the light absorption coefficient (b_abs). The fundamental relationship for radiative forcing calculation is RF ∝ b_abs × f(radiative transfer, cloud distribution, etc.). Mass concentrations (M_BC) provided by emission inventories require conversion to absorption coefficients via the mass absorption cross-section (MAC): b_abs = M_BC × MAC.

The MAC is not a universal constant—it varies significantly with emission source, aging degree, and mixing state. The review by Wei et al. (2020a) indicates that measured MAC values range from 3.8 to 58 $m^2/g$. This means that when deriving the absorption coefficient from mass concentration, the uncertainty in MAC propagates directly into radiative forcing estimates.

The logic of goal-oriented standardization is “I need X, therefore I choose X.” Since the model's ultimate requirement is b_abs, the most suitable choice is to measure it directly, rather than measuring mass concentration and converting it via an uncertain MAC. Starting from this premise, we demonstrate how goal-oriented standardization guides measurement protocol selection—this is not a prescriptive set of technical specifications ready for implementation, but rather an illustration of a decision-making pathway.

Methods that directly measure the absorption coefficient each have suitable application scenarios:

- **Photoacoustic Spectroscopy (PAS):** Outputs absorption coefficient directly with fast response time, suitable for aircraft observations and scenarios requiring high temporal resolution (Petzold and Niessner, 1995).
- **Extinction-Minus-Scattering (EMS, e.g., CAPS PMssa):** Measures extinction and scattering simultaneously, directly outputting single scattering albedo (SSA)—a critical parameter for radiative transfer calculations in climate models (Modini et al., 2021).
- **Photothermal Interferometry (PTI):** Can be absolutely calibrated using $NO_2$ gas, offering good traceability. Suitable for establishing long-term reference observations to provide stable benchmarks for model evaluation (Visser et al., 2020).
- **Multi-Angle Absorption Photometer (MAAP):** Corrects for filter effects via multi-angle scattering measurements and is currently the most reliable absorption measurement technique in ground-based networks.

Each of these methods possesses distinct strengths; the choice depends on the specific observational context—aircraft campaigns, ground networks, and long-term reference stations have differing priorities. This “toolbox” selection logic exemplifies goal-oriented thinking: the aim is not to find a single “best” method, but to select the method most fit for the specific purpose. If constraints necessitate the use of mass concentration output instruments, simultaneous measurement of the absorption coefficient to establish a local MAC dataset is required—though this should be viewed as a compromise. It should be acknowledged that, given their robustness and lower maintenance requirements, filter-based photometers (e.g., AE33, MAAP) remain the workhorse instruments for long-term monitoring networks, while direct absorption methods like PAS, EMS, and PTI are more commonly deployed in intensive field campaigns or at supersites.

### 6.2 Protocol Specification and Interference Identification

Even when the correct method is chosen, if operational protocols are not standardized and interferences are not identified, measurement results may still deviate from the intended objective. For climate modeling applications, the following points are particularly critical. BC resides predominantly in submicron particles; a $PM_1$ inlet is more appropriate for radiative forcing assessments than $PM_{2.5}$ or $PM_{10}$. Models typically require hourly averaged data; raw high-time-resolution data should be preserved for flexible averaging. Filter-based optical methods are sensitive to absorption by brown carbon and mineral dust; multi-wavelength measurements enable AAE calculation for identification (Rai et al., 2020). When optical method results deviate significantly from SP2 measurements—such as an eBC/rBC ratio of eight during dust events—this deviation itself serves as a signal of interference presence (Tinorua et al., 2024).

### 6.3 Parameter Transparency

Goal-oriented standardization does not require that all measurements use identical parameters, but it mandates transparent reporting of parameters for all measurements. For climate modeling applications, the following information is indispensable: measurement wavelength(s), absorption coefficient calculation method (including filter correction algorithms and parameters), MAC value (if used) and its provenance, time resolution, sampling flow rate, size-selective inlet, and interference identification flags. This transparency enables data users to judge data suitability based on their own specific needs.

### 6.4 Uncertainty Quantification

Comparing the uncertainty budgets of the two pathways quantifies the advantage of the "goal-oriented" approach. The uncertainty for the direct measurement pathway (PAS/EMS/PTI/MAAP) primarily originates from instrument calibration (~5–10%) and sampling losses (~5–10%), resulting in a total uncertainty typically within the 10–20% range. The indirect derivation pathway (mass concentration + MAC) must additionally incorporate the uncertainty associated with MAC variability. Even when using locally measured MAC, the overall uncertainty often exceeds 30–50%. For climate models, this translates to a potential reduction of more than half in the uncertainty of input data for radiative forcing calculations.

### 6.5 Multi-Objective Scenarios

In practice, an observational site often needs to serve multiple objectives simultaneously. In such cases, the following decision-making principles are recommended.

*Measurement strategy principles for multi-objective scenarios*

- **Identify the primary objective:** Clearly define the site's core service purpose—whether regulatory compliance, climate assessment, or health research. Prioritize measurement requirements that contribute the most uncertainty reduction for that primary objective.
- **Tiered instrument configuration:** Select the primary measurement method based on the primary objective, while deploying auxiliary measurements to cover secondary objectives. For example, a primary measurement of PAS or EMS (direct b_abs measurement) could be supplemented by a multi-wavelength aethalometer (providing AAE information) and an SP2 (providing size distribution and mixing state information).
- **Ensure secondary objective usability via parameter transparency:** Even if auxiliary measurements are not optimized for secondary objectives, complete and transparent reporting of operational parameters and data processing workflows can still render the data useful to some extent for secondary analyses and comparisons.

A synergistic retrieval approach involves acquiring multiple characteristic information streams simultaneously through multi-instrument co-located observations and model inversion (Naseri et al., 2024). The core logic of both strategies is consistent: allocate measurement resources based on objectives, rather than attempting to satisfy all needs with a single method.

### 6.6 From Demonstration to Practice

The preceding sections demonstrate how goal-oriented standardization can be applied to BC measurements for climate modeling. Translating this framework into actionable technical specifications requires further work: developing measurement guidelines tailored to major application scenarios (climate, health, source apportionment), establishing cross-method intercomparison and data assimilation frameworks, and conducting pilot implementations within existing observational networks.

Furthermore, the implementation of goal-oriented standardization must consider continuity with historical data. Over the past two decades, global observational networks have accumulated vast amounts of EC and eBC mass concentration data, which serve as crucial evidence for assessing historical radiative forcing in climate models. A direct shift toward a b_abs-centric measurement system should not imply the abandonment of these historical records. Feasible transition strategies include: conducting long-term parallel observations using both old and new methods at key sites, establishing local historical MAC datasets, and developing correction algorithms for historical data based on aerosol physicochemical parameters. It is recommended that parallel observations last at least one year to capture a full seasonal cycle; the resulting MAC time series can then be applied to the re-analysis of historical mass concentration data. Advancing this work likewise requires collaboration within the scientific community.

This paper's contribution is to propose a conceptual framework and demonstrate its logical application. Translating this framework into community-endorsed, actionable technical specifications is the essential next step and a task that requires broad collaborative effort.

## 7 Conclusions

This paper has systematically examined the issue of discrepancies among black carbon measurement methods, revealed the conceptual roots of these discrepancies, and proposed two mutually reinforcing response pathways based on this analysis.

**First**, method discrepancies far exceed instrument error. Multi-method intercomparison studies consistently show that different principle-based methods can yield BC concentrations differing by a factor of several for the same aerosol sample, and up to a factor of eight during dust events. The root cause lies not in instrument hardware but in the methods themselves.

**Second**, discrepancies are rooted in conceptual definition. Black carbon is a composite concept constituted by multiple characteristics. Any measurement method can only access a subset of these characteristics—this defines the inherent selectivity of measurement. eBC, EC, and rBC correlate with different features of BC and thus exhibit statistical correlations, but they are distinct operationally defined quantities, not different estimates of the same entity. These discrepancies may be inconspicuous when aerosols are simple but become systematically amplified as aerosols become complex. They cannot be eliminated through technical means.

**Third**, this paper proposes two mutually reinforcing response pathways. At the epistemological level, method discrepancies are reframed as interpretable "signals," transforming them into information sources to be actively utilized. At the practical level, we advocate a shift toward "goal-oriented standardization"—selecting the measurement protocol best matched to the specific research objective.

**Fourth**, metrological work and the propositions of this paper are complementary. Metrology addresses the comparability of "same method, different instruments" and forms the technical foundation for all measurement practices. This paper addresses the issue of "cross-method discrepancies." Both serve different levels and jointly constitute a higher-quality BC measurement practice.

The epistemological shift from "error" to "signal," combined with the practical scheme of "goal-oriented standardization," together constitute a response to the dilemma of universal standardization. By relinquishing the illusion of universal standardization, we become better able to confront the nature of measurement soberly, more fully exploit the information embedded in method discrepancies, and more effectively serve specific research objectives. This does not imply arbitrariness in measurement—goal-oriented standardization demands a higher degree of rigor: researchers must clearly define their objective, understand the characteristic dimension measured by the chosen method, and transparently report all key parameters. This represents a principled pluralism. For global and regional observational networks such as GAW and ACTRIS, the framework presented here can guide sites in selecting core measurement methods based on their primary scientific objectives, while ensuring long-term data usability and indirect cross-site comparability through parameter transparency.

## Author contributions

ZZ conceived and wrote the paper.

## Competing interests

The author declares that there is no conflict of interest.

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During the preparation of this work, the author used AI-assisted language editing tools for language polishing and structural editing. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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## References

Bond, T. C. and Bergstrom, R. W.: Light absorption by carbonaceous particles: An investigative review, Aerosol Sci. Technol., 40, 27–67, https://doi.org/10.1080/02786820500421521, 2006.

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, J. Geophys. Res. Atmos., 118, 5380–5552, https://doi.org/10.1002/jgrd.50171, 2013.

Cuesta-Mosquera, A., Močnik, G., Drinovec, L., Müller, T., Pfeifer, S., Minguillón, M. C., Briel, B., Buckley, P., Dudoitis, V., Fernández-García, J., Fernández-Amado, M., Ferreira De Brito, J., Flentje, H., Heffernan, E., Kalivitis, N., Kalogridis, A.-C., Keernik, H., Marmureanu, L., Luoma, K., Marinoni, A., Pikridas, M., Schauer, G., Serfozo, N., Servomaa, H., Titos, G., Yus-Díez, J., Zioła, N., and Wiedensohler, A.: Intercomparison and characterization of 23 Aethalometers under laboratory and ambient air conditions: procedures and unit-to-unit variabilities, Atmos. Meas. Tech., 14, 3195–3216, https://doi.org/10.5194/amt-14-3195-2021, 2021.

EURAMET: STANBC project: Standardisation of Black Carbon aerosol metrics for air quality and climate modelling, available at: https://www.euramet.org/research-innovation/search-research-projects/details/project/standardisation-of-black-carbon-aerosol-metrics-for-air-quality-and-climate-modelling/ (last access: 21 April 2026), 2023–2026.

European Parliament and Council: Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe, Off. J. Eur. Union, L, 2024/2881, 2024.

Kahnert, M. and Kanngießer, F.: Modelling optical properties of atmospheric black carbon aerosols, J. Quant. Spectrosc. Radiat. Transfer, 244, 106849, https://doi.org/10.1016/j.jqsrt.2020.106849, 2020.

Kalbermatter, D. M., Močnik, G., Drinovec, L., Visser, B., Röhrbein, J., Oscity, M., Weingartner, E., and Gysel-Beer, M.: Comparing black carbon and aerosol absorption measurements in the laboratory, Atmos. Meas. Tech., 15, 4501–4521, https://doi.org/10.5194/amt-15-4501-2022, 2022.

Liu, C., Xu, X., Yin, Y., and Zhang, Y.: Black carbon aggregates: A database for optical properties, J. Quant. Spectrosc. Radiat. Transfer, 222–223, 170–179, https://doi.org/10.1016/j.jqsrt.2018.10.021, 2019.

Liu, J., Zhao, G., Zheng, Y., and Zhao, C.: Numerical quantitation on the effect of coating materials on the mixing state retrieval accuracy of fractal black carbon based on single particle soot photometer, Atmos. Meas. Tech., 18, 4045–4059, https://doi.org/10.5194/amt-18-4045-2025, 2025.

Liu, Y., Liu, J., Xiao, J., Ye, J., Yan, C., Guo, L., and Zheng, M.: Metrological traceability of black carbon measurement based on optical methods and its challenges in China: A review, Atmos. Res., 292, 106854, https://doi.org/10.1016/j.atmosres.2023.106854, 2023a.

Modini, R. L., Corbin, J. C., Brem, B. T., Irwin, M., Bertò, M., Pileci, R. E., Fetfatzis, P., and Gysel-Beer, M.: Detailed characterization of the CAPS single scattering albedo monitor (CAPS PMssa) as a field-deployable instrument for measuring aerosol light absorption, Atmos. Meas. Tech., 14, 819–851, https://doi.org/10.5194/amt-14-819-2021, 2021.

Momenimovahed, A., Gagné, S., Martens, P., Jakobi, G., Czech, H., Wichmann, V., Buchholz, B., Zimmermann, R., Behrends, B., and Thomson, K. A.: Comparison of black carbon measurement techniques for marine engine emissions using three marine fuel types, Aerosol Sci. Technol., 56, 46–62, https://doi.org/10.1080/02786826.2021.1909703, 2022.

Naseri, A., Corbin, J. C., and Olfert, J. S.: Comparison of the LEO and CPMA-SP2 techniques for black-carbon mixing-state measurements, Atmos. Meas. Tech., 17, 3719–3738, https://doi.org/10.5194/amt-17-3719-2024, 2024.

Petzold, A. and Niessner, R.: Novel design of a resonant photoacoustic spectrophone for elemental carbon mass monitoring, Appl. Phys. Lett., 66, 1285–1287, https://doi.org/10.1063/1.113271, 1995.

Petzold, A., Ogren, J. A., Fiebig, M., Laj, P., Li, S.-M., Baltensperger, U., Holzer-Popp, T., Kinne, S., Pappalardo, G., Sugimoto, N., Wehrli, C., Wiedensohler, A., and Zhang, X.-Y.: Recommendations for reporting “black carbon” measurements, Atmos. Chem. Phys., 13, 8365–8379, https://doi.org/10.5194/acp-13-8365-2013, 2013.

Pileci, R. E., Modini, R. L., Bertò, M., Yuan, J., Corbin, J. C., Marinoni, A., Henzing, B., Moerman, M. M., Putaud, J. P., Spindler, G., Wehner, B., Müller, T., Tuch, T., Trentini, A., Zanatta, M., Baltensperger, U., and Gysel-Beer, M.: Comparison of co-located refractory black carbon (rBC) and elemental carbon (EC) mass concentration measurements during field campaigns at several European sites, Atmos. Meas. Tech., 14, 1379–1403, https://doi.org/10.5194/amt-14-1379-2021, 2021.

Rai, P., Furger, M., Slowik, J. G., Canonaco, F., Fröhlich, R., Hüglin, C., Minguillón, M. C., Petterson, K., Baltensperger, U., and Prévôt, A. S. H.: Elective absorption of black and brown carbon using multi-wavelength absorption photometers, Atmos. Meas. Tech., 13, 2991–3011, https://doi.org/10.5194/amt-13-2991-2020, 2020.

Schmid, H., Laskus, L., Abraham, H. J., Baltensperger, U., Lavanchy, V., Bizjak, M., Burba, P., Cachier, H., Crow, D., Chow, J., Gnauk, T., Even, A., ten Brink, H. M., Giesen, K.-P., Hitzenberger, R., Hueglin, C., Maenhaut, W., Pio, C., Putaud, J.-P., Toom-Sauntry, D., and Puxbaum, H.: Results of the "carbon conference" international aerosol carbon round robin test stage I, Atmos. Environ., 35, 2111–2121, https://doi.org/10.1016/S1352-2310(00)00493-3, 2001.

Slowik, J. G., Cross, E. S., Han, J.-H., Davidovits, P., Onasch, T. B., Jayne, J. T., Williams, L. R., Canagaratna, M. R., Worsnop, D. R., Chakrabarty, R. K., Moosmüller, H., Arnott, W. P., Schwarz, J. P., Gao, R.-S., Fahey, D. W., Kok, G. L., and Petzold, A.: An inter-comparison of instruments measuring black carbon content of soot particles, Aerosol Sci. Technol., 41, 295–314, https://doi.org/10.1080/02786820701197078, 2007.

Tinorua, S., Jaffrezo, J.-L., and Favez, O.: A 2-year intercomparison of three methods for measuring black carbon concentration at a high-altitude research station in Europe, Atmos. Meas. Tech., 17, 3897–3916, https://doi.org/10.5194/amt-17-3897-2024, 2024.

Veratti, G., Bigi, A., Teggi, S., and Ghermandi, G.: Source apportionment of black and brown carbon using multi-wavelength micro-Aethalometer measurements, Atmos. Environ., 318, 120234, https://doi.org/10.1016/j.atmosenv.2023.120234, 2024.

Visser, B., Röhrbein, J., Steigmeier, P., and Gysel-Beer, M.: A single-beam photothermal interferometer for in situ measurements of aerosol light absorption, Atmos. Meas. Tech., 13, 7097–7111, https://doi.org/10.5194/amt-13-7097-2020, 2020.

Wei, Y., Zhang, Q., and Zhang, Y.: A review of the mass absorption cross-section of black carbon: Variability and implications, Atmos. Chem. Phys., 20, 7319–7341, https://doi.org/10.5194/acp-20-7319-2020, 2020a.

WHO: WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide, World Health Organization, Geneva, available at: https://www.who.int/publications/i/item/9789240034228 (last access: 21 April 2026), 2021.

Wu, B., Wu, Z., Dou, J., Yao, Z., Wang, A., Li, L., and Hao, X.: A systematic review of the variability of freshly-emitted and aged black carbon based on various measurement techniques, Sci. Total Environ., 958, 177872, https://doi.org/10.1016/j.scitotenv.2024.177872, 2025.

Zhang, Y., Forrister, H., Liu, J., Dibb, J., Anderson, B., Schwarz, J. P., Perring, A. E., Jimenez, J. L., Campuzano-Jost, P., Wang, Y., Nenes, A., and Weber, R. J.: Inter-comparison of black carbon measurement methods for simulated open biomass burning emissions, J. Geophys. Res. Atmos., 124, 7786–7804, https://doi.org/10.1029/2019JD030712, 2019.

Zhao, G., Shen, C., and Zhao, C.: Technical note: Mismeasurement of the core-shell structure of black carbon-containing ambient aerosols by SP2 measurements, Atmos. Environ., 243, 117885, https://doi.org/10.1016/j.atmosenv.2020.117885, 2021b.

Zhao, W., Tan, W., Zhao, G., Shen, C., Yu, X., and Zhao, C.: Determination of equivalent black carbon mass concentration from aerosol light absorption using variable mass absorption cross section, Atmos. Meas. Tech., 14, 1319–1335, https://doi.org/10.5194/amt-14-1319-2021, 2021a.