

Optical ~~properties~~ and Shape-Dependent Complex Refractive Index Retrievals ~~shape-dependent retrievals~~ of Freshly Emitted ~~the imaginary part of the refractive index of freshly emitted~~ Saharan Dust

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Abstract.

Mineral dust is a major contributor to atmospheric ~~aerosols~~ aerosol mass and plays a complex role in ~~the~~ Earth's radiation budget, ~~yet significant~~. However, large uncertainties remain in quantifying its direct radiative effects (~~DRE~~), ~~largely due to poor constraints on its absorption properties~~. ~~While most estimates rely on remote sensing or laboratory experiments, direct,~~ partly because dust absorption is poorly constrained and in situ measurements of freshly emitted dust ~~are rarer~~ remain scarce. Here, we present field high temporal resolution measurements of dust optical properties collected during active dust emission ~~in a source region of events in~~ the Moroccan Sahara (~~September 2019~~). ~~During high dust emission activity, optical properties were broadly consistent in September 2019. During dust emission periods, the optical properties aligned~~ with previous Saharan dust studies. Single scattering albedo (SSA) for PM_{2.5} (PM₁₀) was 0.95 (0.94) at 370 nm and 0.97 (0.96) at 660 nm. Coarse ~~dust particles~~ contributed to negative scattering and SSA Ångström exponents (SSAAE), ~~along with and~~ absorption Ångström exponents (AAE) ~~reaching~~ reached up to 2.5 (2.0), ~~indicating strong consistent with stronger~~ wavelength-dependent absorption ~~driven~~ by iron oxides. The asymmetry parameter (~~gg~~) was 0.7 (0.65) at 520 ~~, while nm, and~~ the backscatter fraction (BF) was 0.11 (0.13), ~~highlighting the influence of coarse mineral dust on scattering characteristics~~ showing coarse dust's impact on scattering. Mass absorption efficiency (MAE) decreased from ~~~~~ 0.30 to 0.15 m² g⁻¹ at 370 ~~with increasing effective particle~~

15 ~~radius, while mass nm with increasing particle size. Mass~~ scattering efficiency (MSE) ~~showed a shift shifted~~ towards longer wavelengths for ~~coarser particles. A key novelty of this work is the consistent retrieval of the larger particles. We further~~ retrieved the imaginary part of the complex refractive index (k) ~~across multiple wavelengths, accounting for different particle~~ shape assumptions constrained by measured aspect ratios. We demonstrate a clear linear increase in, for the PM2.5 dust-event period under prescribed assumptions for particle shape, particle density, and the real part of the refractive index. For the central density assumption, retrieved k ~~with particle asphericity, with values rising from 0.0011 for spherical particles to 0.0016 at 520 nm ranged from 0.00104 for spheres to 0.00145 for triaxial ellipsoids and irregular shapes at 520 nm—representing up to a 60% enhancement relative to spheres. Our results provide source-region-constrained dust optical properties and highlight the importance of realistic particle shapes for satellite retrievals and climate model representations of dust DRE, corresponding to a 40% increase. These results show that particle-shape assumptions can substantially affect retrieved k , and therefore need to~~ be considered when interpreting in situ, remote-sensing, and model estimates of dust optical properties.

1 Introduction

Mineral dust emitted from arid regions is one of the most abundant aerosol types by mass (Myhre et al., 2013) and influences the Earth’s climate through multiple mechanisms. It exerts a direct radiative effect (DRE) by absorbing and scattering solar and terrestrial radiation (Kok et al., 2017; Adebisi and Kok, 2020), a semi-direct effect by modifying ~~the atmospheric temperature~~ profile atmospheric temperature profiles and influencing cloud properties (e.g., Ackerman et al., 2000; Perlwitz and Miller, 2010), and an indirect effect by altering cloud microphysics and precipitation patterns (Karydis et al., 2017; McGraw et al., 2020). ~~Additionally, mineral dust has significant impacts on~~ Mineral dust also affects the cryosphere (Skiles et al., 2018) and atmospheric chemistry (Mahowald, 2011), contributing to climate and environmental ~~changes change~~ (Kok et al., 2023).

Despite its importance, the DRE of mineral dust remains highly uncertain, ~~primarily due to poorly constrained partly because~~ dust absorption properties are still poorly constrained (Samset et al., 2018). Current estimates place the short-wave DRE at a central value of $-0.40 \pm 0.30 \text{ Wm}^{-2}$ (90% confidence) based on model assessments that integrate dust optical depth, optical properties and particle size distributions (PSDs) consistent with limited experimental constraints (Kok et al., 2023). ~~Furthermore, Kok et al. (2023) found~~ Kok et al. (2023) further estimated a $55 \pm 30\%$ increase in global dust aerosol mass concentrations since pre-industrial times ~~and additional uncertainties on other dust interactions~~, with an associated global negative mean effective radiative forcing of approximately -0.07 Wm^{-2} , partially offsetting greenhouse warming. However, the uncertainty in this estimate remains substantial ($\pm 0.18 \text{ Wm}^{-2}$), leaving open the possibility that dust aerosols may have contributed to net warming since pre-industrial times (Kok et al., 2023).

~~Key dust characteristics influencing its optical properties—and consequently its direct DRE include variations in~~ Several dust properties influence its optical behaviour and, consequently, its DRE. These include mineralogical composition, PSD, particle shape and morphology, ~~and mixing state~~ mixing state, total atmospheric dust loading, and vertical distribution (e.g. Kok et al., 2017; Di Biagio et al., 2020; Adebisi and Kok, 2020; Li et al., 2021). Uncertainties in these properties ~~, along with uncertainties in the total atmospheric dust mass and its vertical distribution, significantly impact the accuracy of DRE quantification~~ propagate

into estimates of dust scattering, absorption, extinction, and angular scattering, thereby affecting radiative-transfer calculations and climate-model simulations.

- 50 Dust optical properties, particularly the complex refractive index ($\text{CRI} = n + ik$), play a critical role in determining the dust radiative impact. The real part ~~of the CRI (n) predominantly determines~~ primarily controls scattering, while the imaginary part (k) controls absorption. ~~However, the imaginary component also influences scattering because a higher absorption will, for a given extinction, diminish the scattering coefficient.~~ The intrinsic CRI of dust depends on its mineralogical composition and describes how a homogeneous material interacts with light ~~at on~~ a microscopic scale. For instance, the presence of
- 55 iron oxides ~~such in such minerals~~ as goethite and hematite, plays a dominant role in dust absorption (e.g., Di Biagio et al., 2019). Several studies have also found that the relative fraction of total iron in dust correlates with its absorption properties, influencing radiative forcing estimates (Sokolik and Toon, 1999; Lafon et al., 2006; Balkanski et al., 2007; Caponi et al., 2017). The imaginary part of the CRI for iron oxides exhibits increased absorption at short-wavelength UV compared to red and near-infrared wavelengths (e.g. Sokolik and Toon, 1999; Balkanski et al., 2007). However, particle size and shape influ-
- 60 ence how a given CRI translates into observable optical properties. It is important to note that in real-world measurements, the effective CRI retrieved from bulk optical observations depends not only on composition but also on the particle size and shape distribution of the dust particles. This is because dust is composed of irregularly shaped particles spanning a wide range of sizes, and retrievals from optical measurements inherently integrate these variations ~~(Gasteiger and Wiegner, 2018, e.g.,)~~ (e.g., Gasteiger and Wiegner, 2018).
- 65 The PSD of mineral dust exerts a strong influence on its optical properties ~~, as because~~ the size parameter ~~(ratio of particle circumference to wavelength), defined by the ratio between particle circumference and wavelength,~~ dictates the dominant scattering regime (Mishchenko et al., 2002). Smaller particles ~~often display more uniformly distributed scattering tend to scatter light more evenly across~~ angles, whereas larger particles ~~tend to scatter light~~ scatter more strongly in the forward direction, ~~thereby increasing total extinction but decreasing~~ increasing extinction and reducing backscattering (e.g., Sokolik
- 70 and Toon, 1999). Coarse-mode dust can dominate dust mass and exert substantial effects on direct radiative forcing, yet is often under-represented in models (Adebisi and Kok, 2020). ~~Since optical measurements are sensitive to both the particle size distribution and its interaction with light, retrievals of the CRI inherently reflect the size-dependent scattering and absorption behaviour of dust~~ Therefore, retrievals of dust optical properties from observations are sensitive not only to composition but also to the PSD used in the interpretation.
- 75 Particle shape further modulates optical properties. Several studies have reported that total extinction ~~from by~~ non-spherical dust particles ~~deviates from spherical models can differ from spherical particle calculations~~ by roughly 10–20% (e.g., Nousiainen, 2009; Bi et al., 2018), especially when averaged across a typical size distribution. ~~However, Kok et al. (2017) showed that shape effects on extinction could even be significantly larger, although larger effects have also been reported (Kok et al., 2017)~~ . Despite these potential differences in total extinction, the single scattering albedo (SSA) often remains relatively unchanged
- 80 or only modestly affected. Conversely, shape tends to have a more pronounced impact on the scattering phase function and asymmetry factor (g), influencing how light is directionally scattered. Retrievals of the effective CRI are impacted by shape assumptions, ~~as because~~ standard inversion algorithms often rely on ~~Mie theory, which assumes sphericity. The use of spherical~~

~~models can introduce systematic biases, particularly simplified particle geometries. As a result, differences in assumed particle shape can lead to systematic differences in the retrieved imaginary part of the CRI, which governs absorption refractive index.~~

85 Thus, ~~while the intrinsic CRI is composition-dependent, the effective CRI derived from measurements is shaped by the interplay of mineralogy, PSD, and non-sphericity.~~ It is therefore important to distinguish between intrinsic refractive indices, which are determined by particle composition, and effective or retrieved refractive indices, which depend on the assumptions used in the inversion. In atmospheric measurements, the retrieved k is conditional on the assumed PSD, particle shape, density, and real refractive index. Additional complexities ~~are originated~~ arise from internal mixing and physico-chemical ageing of
90 dust ~~with other aerosol species~~ during transport. This distinction is crucial for interpreting ~~observational data~~ observations, improving remote-sensing retrievals, and reducing uncertainties in climate models.

Climate models require accurate representations of dust optical properties, including the complex refractive index, single-scattering albedo, and asymmetry ~~factor~~ parameter. Some studies have examined how various mineralogical compositions and PSDs affect these parameters, often through laboratory experiments with resuspended soil samples (e.g., Di Biagio et al.,
95 2017; Di Biagio et al., 2019), ground-based or satellite remote-sensing, or in-situ observations in known dust outflow regions. ~~Indeed~~ However, direct in-situ measurements of freshly emitted dust within source regions remain relatively scarce. Most existing observations in deserts focus on campaigns that capture dust outflow rather than the exact point of emission (Kandler et al., 2009; Müller et al., 2009; Schladitz et al., 2009), leaving gaps in understanding how local soil characteristics and emission processes govern the initial PSD and optical properties of dust. Measurements from large networks such as AERONET also
100 provide valuable remote retrievals of total-column aerosol properties, though the presence of other particles can complicate dust-specific analyses (e.g., Obiso et al., 2024).

To address ~~the gap on the local emission processes and its relationships~~ these gaps, a field campaign was conducted in the Saharan desert (Morocco) in September 2019 under the framework of the FRAGMENT project. One major aim was to characterize the size-resolved mineralogical composition of freshly emitted dust and the emission mechanisms that inject these
105 particles into the lower troposphere (González-Romero et al., 2023, 2024a, b; Panta et al., 2023; González-Flórez et al., 2023). ~~Another goal~~ A complementary objective, and the focus of the present study, was to measure and interpret the multi-wavelength optical properties ~~—specifically, scattering and absorption, which is the focus in the present study of freshly emitted dust.~~

Here, we present high-temporal-resolution measurements of extensive properties (~~i.e.,~~ namely scattering and absorption coefficients), and derived intensive properties, including SSA, asymmetry parameter, backscatter fraction, and ~~Ångström~~
110 ~~exponents and mass~~ scattering, absorption and extinction efficiencies ~~at several wavelengths of freshly emitted dust at a key Saharan source region. We further link these observations. We relate these properties~~ to the size of the emitted particles and use aspect-ratio information derived from single-particle analyses (Panta et al., 2023) together with optical particle counter measurements (González-Flórez et al., 2023) to ~~then~~ retrieve the imaginary part of the CRI (~~complex refractive index, k~~). ~~The influence of different shape assumptions on the retrieval of~~. The retrieval is performed under prescribed assumptions
for particle shape, particle density, and the real part of the refractive index, n . We use campaign-specific particle density measurements, particle-shape information from single-particle analyses (Panta et al., 2023), optical particle counter measurements (González-Flórez et al., 2023), and additional literature-based shape assumptions to quantify how retrieved k ~~is also explored.~~

~~These high-resolution, source-region measurements provide crucial insights for improving remote-sensing algorithms and reducing uncertainties in climate models (e.g., Castellanos et al., 2024)~~depends on particle-shape representation.

In the following, Sect. 2 presents the measurement ~~area, the instruments used, and the key optical properties examined in this study, highlighting their relevance for mineral dust. It also provides a detailed explanation of the methodology employed to estimate site, instruments, optical properties, and k retrieval methodology.~~ Particular attention is given to the distinction between corrected scattering coefficients, used for the descriptive optical-property analysis, and truncated scattering coefficients, used in the retrieval. Sect. 3 ~~then presents the findings~~ presents the results in three parts: ~~(i) first, the temporal evolution of the measured optical properties, focusing on three representative scenarios that are particularly important for understanding dust emission into the atmosphere; (ii) the relationships between these;~~ second, the relationships between optical properties and the size of the measured aerosol particles; and (iii) the retrieved values ~~particle size; and third, the conditional retrievals of k based on the above measurements under different assumptions for particle shape, and n .~~ The implications and limitations of the retrieval are then discussed in the context of in situ observations, remote sensing, and climate-model applications.

2 Methodology

2.1 Measurement site

In-situ dust measurements were conducted in a mineral dust emission area in southeastern Morocco, at the transition between the southern foothills of the Atlas Mountains and the Saharan Desert. The study site is located in L'Bour (29° 49' 30" N, 5° 52' 25" W, 500 m a.s.l.), a small terminal depression near the Drâa dry riverbed, west of M'Hamid El Ghizlane. It is also ~~situated~~ located east of Lake Iriki, a seasonal dry lake, and adjacent to two major dune fields, Erg Cheggaga and Erg Smar (see Fig. 1).

The surface at L'Bour is predominantly hard-packed, ~~featuring with~~ crust formations resulting from wind and dust erosion, interspersed with shallow sand dunes ~~(height < less than 1 m)~~ high. These characteristics make ~~it a representative site~~ the site well suited for studying freshly emitted dust from natural Saharan sources. Further details on the sampling site and its environmental conditions can be found in González-Flórez et al. (2023); González-Romero et al. (2023); Panta et al. (2023).

2.2 Measurements of optical properties

Scattering coefficients (b_{scat}) were measured using an LED-based multi-angle integrating nephelometer (Aurora 4000, ECOTECH Pty Ltd, Knoxfield, Australia). The nephelometer operates at three wavelengths (450, 525 and 635 nm) and collects scattering measurements at eight angular positions (0°, 10°, 25°, 40°, 55°, 70°, 90°, and 170°). The forward (0°) and backward (170°) scattering measurements are affected by non-ideal illumination of the light source and by angular truncation (Müller et al., 2011; Teri et al., . For the descriptive analysis of the campaign optical properties, the scattering coefficients were corrected using the correction scheme of Teri et al. (2022). These corrected scattering coefficients are used throughout the manuscript when reporting scattering

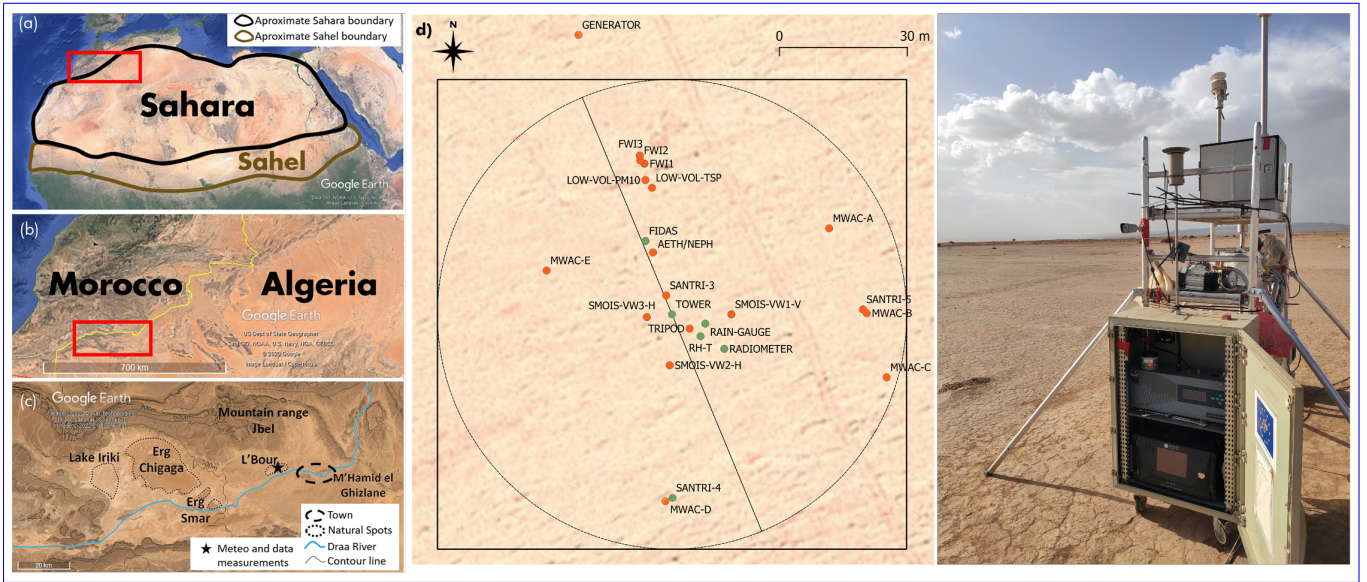


Figure 1. Location of the area of study over Northern Africa (a,b and c.), the instrument deployment over the L'Bour site, where the diagonal black line is perpendicular to the approximate predominant wind direction estimated based on prior data analysis (d), the green points correspond to the optical instruments (AE33 and nephelometer) and the Fidas, which are shown in (e), where the optical instruments are placed in cage in front of the scaffolding and the Fidas is located in the background behind the scaffolding. The integrating nephelometer is placed in the upper level and the Aethalometer AE33 in the lower one. [Satellite imagery in panels a, b, c and d were taken from base layer from world imagery of © Google Earth Pro v:7.3.6.9345. The photo in panel e\) was taken by one of the authors.](#)

[coefficients, SSA, asymmetry parameter, backscatter fraction, and mass scattering and extinction efficiencies, except in the retrieval of the imaginary part of the complex refractive index.](#)

150 [For the refractive-index retrieval, we use the uncorrected scattering coefficient measured by the nephelometer, hereafter referred to as the truncated scattering coefficient, \(*tsc*\). The corresponding truncated scattering is simulated explicitly in the retrieval observation operator, as described in Sect. 2.6. This distinction avoids applying a correction from truncated scattering to full-phase-function scattering in the retrieval itself, which would introduce additional assumptions about particle shape and the scattering phase function. The corrected multi-angle scattering measurements were also used to derive the asymmetry](#)

155 [parameter \(e.g., Horvath et al., 2018; Liou, 2002\).](#)

Multi-wavelength aerosol absorption coefficients (b_{abs}^{λ}) were derived using a multi-wavelength dual-spot aethalometer (AE33, Aerosol d.o.o.). The AE33 measures light attenuation at seven wavelengths spanning from the short-UV to the near-infrared range (370, 470, 520, 590, 660, 880, and 950 nm). Absorption coefficients are then computed using [equation \(Eq. 17\) in of Drinovec et al. \(2015\), with an-the AE33 online correction for filter loading effects applied by the AE33 software.](#)

160 [To obtain accurate absorption coefficients from AE33 measurements, an additional correction for multiple light scattering within the filter tape was applied. The The uncertainty of AE33-derived absorption coefficients, ranging between 10 and 30 %,](#)

depends strongly on measurement artefacts, particularly the cross-sensitivity of attenuation measurements to light scattering by particles on the filter (Drinovec et al., 2015; Yus-Díez et al., 2021). To correct for this effect, we used the scattering artefact parameter, m_s , and the multiple-scattering parameter, C , has been shown to be higher for aerosols with high single-scattering albedo, such as mineral dust, compared to typical values found in urban and regional background sites (e.g. Di Biagio et al., 2017; Yus-Díez et al., 2021). Since measurements were performed in an environment dominated by dust particles, we used a C value obtained by optimizing SSA and C as recommended in Yus-Díez et al. (2021), using the C and multiple scattering fitted values provided therein in a mountain-top station during Saharan dust outbreaks. The obtained C value from the fit is 4.82, which is on the upper limit of those obtained for dust by Di Biagio et al. (2017), reported in Yus-Díez et al. (2025) for Saharan mineral soil samples collected during the same FRAGMENT-Morocco campaign and later resuspended and analysed under controlled laboratory conditions. This correction is therefore directly linked to the dust sampled in the present study. To account for uncertainty in the AE33 multiple-scattering correction, we performed a sensitivity analysis using lower and upper values of C derived from the 95 % confidence interval reported in Table S2 of (Yus-Díez et al., 2025). This sensitivity results in an uncertainty of approximately 5% in the corrected absorption coefficient at 370 nm, increasing up to approximately 20 % at 950 nm, where the relative contribution of the scattering artefact is larger for mineral dust.

Scattering coefficients (b_{scat}) were measured using an LED-based multi-angle integrating nephelometer (Aurora 4000, ECOTECH Pty Ltd, Knoxfield, Australia), which operates at three wavelengths (450, 525 and 635 nm) and collects data at eight angular positions (0°, 10°, 25°, 40°, 55°, 70°, 90°, and 170°). Forward (0°) and backward (170°) scattering measurements were then corrected for non-ideal illumination of the light source and truncation errors using the correction scheme from Müller et al. (2011) for coarse particles.

The aethalometer and nephelometer shared the same sampling line and inlet, with the AE33 pump also used for the nephelometer. During the initial phase of the L'Bour field campaign (2019-09-04 00:00 UTC to 2019-09-26 12:00 UTC), in-situ surface optical measurements were performed using a PM2.5 inlet. After this date and until the end of the campaign (2019-10-01 08:00:00 UTC), a PM10 sampling inlet was used instead. To reduce the instrumental noise while accounting for all significant turbulent structures carrying momentum flux (Dupont et al., 2019), all the campaign measurements, including the optical measurements, were averaged into 15 min intervals for analysis (Dupont et al., 2019).

2.3 Particle size distribution measurements

Number PSDs were measured using a Fine Dust Aerosol Spectrometer (Fidas 200S, Palas GmbH). This instrument sampled aerosol particles across 63 bins spanning optical diameters of equal logarithmic width from logarithmically spaced optical-diameter bins between 0.20 to and 19.1 μm with a, with a time resolution of 120 s time resolution and an inlet flow rate of 4.8 l min⁻¹. Data from the The first three bins were not used as they were found to be unrealistic (cf. González-Flórez et al., 2023). Similar to unreliable (cf. González-Flórez et al., 2023). As for the optical measurements, data was the Fidas data were averaged into 15 min intervals.

The Fidas instrument was calibrated in the field using polystyrene latex spheres (PSLs) with a CRI of 1.59 + 0i. To derive a PSD that better represents dust particles in terms of their geometric diameter, we applied a diameter conversion procedure as

Because mineral dust particles are non-spherical and absorbing, the PSL-calibrated optical diameters must be converted into dust geometric diameters before deriving mass concentrations and optical simulations. We applied the optical-to-geometric diameter conversion described in Sect.2.6.1 ~~and based on the method outlined by Huang et al. (2020), following the method of Huang et al. (2021).~~ This conversion ~~requires assumptions about the particles' CRI and shape. It depends on the assumed~~ particle shape and CRI. For the descriptive analysis in Sect.3.2, ~~we analyze intensive optical properties. For those depending on particle mass, we use mass-dependent quantities were computed using~~ the converted PSD assuming spherical particles and an initial ~~averaged CRI dust refractive-index range~~ guided by Di Biagio et al. (2019). ~~These initial estimates correspond to CRIs, with real parts of between 1.47, 1.50, and 1.52, and imaginary parts ranging from between 0.0001 to 0.005. The initial assumptions are subsequently refined through an inversion procedure described retrieval of k under different prescribed~~ assumptions for particle shape, particle density, and n is described separately in Sect.2.6, ~~where the dust imaginary CRI is consistently retrieved and further analyzed in Sect. 3.3.~~

From the ~~resulting converted~~ number PSD, we calculated the mass concentration (M_{PM}) and the effective radius (R_{eff}). M_{PM} is given by the third moment of the number PSD,

$$M_{PM} = \rho \cdot \frac{\pi}{6} \cdot \int_{D_0}^{D_x} D^3 N(D) dD; \quad (1)$$

where D is the particle geometric diameter, and $N(D)$ is the dust number PSD for diameter D derived from the Fidas, and ρ is the particle density ~~(2500 kgm⁻³ as in González-Flórez et al., 2023).~~ Here, we have used a density of 2.15 gcm⁻³. This value was obtained from samples collected at the site and analysed with a helium pycnometer. The method estimates particle density from the volume accessible to helium gas, including open and semi-open pores. The results indicate that particle density decreases with decreasing particle size, reaching approximately 2.15 gcm⁻³ for particles with diameters below 20 μ m. This value is therefore considered a reasonable approximation for the dust particles sampled in the size range relevant to this study.

R_{eff} is then defined as the ratio of the third to the second moment of the number PSD,

$$R_{eff} = \frac{1}{2} \cdot \frac{\int_{D_0}^{D_x} D^3 N(D) dD}{\int_{D_0}^{D_x} D^2 N(D) dD}; \quad (2)$$

Here, D spans the relevant diameter range between the first ~~used valid~~ bin D_0 and ~~and the upper diameter~~ D_x . The value of D_x is corresponds to the geometric diameter corresponding to associated with the aerodynamic diameter of the inlet cut-off, which will vary depending on the inlet cut-off period ~~and therefore differs between the PM2.5 or and PM10.~~ The conversion from optical to geometric diameters from the Fidas is explained periods. The optical-to-geometric diameter conversion is described in Sect. 2.6.1. For $\rho_p = 2.15$ gcm⁻³ and spherical particles, the PM2.5 aerodynamic cut-off corresponds to a geometric diameter of 1.72 μ m.

2.4 Meteorological measurements

225 ~~We used wind measurements that~~ Wind measurements were conducted at 2 m above ground level, approximately matching the inlet heights of the optical and PSD instruments, ~~with~~. We used a 2-D sonic anemometer (model WINDSONIC4-L, Campbell Scientifics, USA) mounted on a 10 m meteorological tower. As ~~detailed-described~~ in González-Flórez et al. (2023), ~~this-the~~ tower also hosted multiple 2-D and 3-D sonic anemometers, ~~with the data from these instruments undergoing extensive processing to derive parameters such as~~ whose data were processed to derive turbulence parameters, including the wind friction velocity (u_*). Briefly, u_* was obtained via an iterative law-of-the-wall approach, which assumes a (pseudo)logarithmic wind profile in the atmospheric surface layer (cf. González-Flórez et al., 2023, and references therein). Although the raw wind data were recorded at 0.5 Hz, they were averaged ~~to~~ into 15 min intervals during post-processing to facilitate a stable, consistent comparison with the other collocated instruments.

2.5 Intensive aerosol optical properties

235 By combining the extensive optical properties ~~(, namely~~ absorption from the AE33 and corrected scattering from the polar nephelometer) ~~,~~ with the PSDs from the Fidas, we derived time series of intensive optical properties. These ~~intensive-optical~~ properties depend on the physico-chemical properties of the dust particles, including mineralogy, PSD, and shape. ~~Below is a brief description of each parameter:~~ Unless otherwise stated, the scattering coefficients used in this section are the corrected scattering coefficients described in Sect. 2.2. The truncated scattering coefficient, $tsca$, and the corresponding truncated single
240 scattering albedo, $tssa$, are used only for the retrieval of k described in Sect. 2.6.

- a. The Scattering Ångström Exponent (SAE) mostly reflects particle size, with values less than 1 typically indicating coarse particles (Seinfeld and Pandis, 1998; Schuster et al., 2006), as often observed during fresh dust emissions in our campaign. ~~The~~ SAE was calculated by fitting the scattering coefficients ~~(at three nephelometer wavelengths)~~ in a log-log space.

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$$\ln(b_{\text{scat}}(\lambda)) = -\text{SAE} \cdot \ln(\lambda) + \beta. \quad (3)$$

where β is the intercept of the linear fit.

- b. The Absorption Ångström Exponent (AAE) is strongly influenced by the ~~composition of the sampled particles~~ particle composition. Under anthropogenic-dominated conditions ~~the~~ AAE typically ranges from 0.9 to 1.1 (Kirchstetter et al., 2004; Petzold et al., 2013), whereas dust-rich environments yield ~~values~~ higher values, typically between 2 and 6.5 (Schuster et al., 2016; Caponi et al., 2017). This higher AAE ~~stems from~~ reflects the dust enhanced absorption in the short-UV region relative to near-infrared wavelengths (Kirchstetter et al., 2004; Chen and Bond, 2010). ~~This spectral behavior of the absorption efficiency of the particles is attributed to the optical properties of the iron oxides contained in mineral dust,~~ largely associated with iron oxides such as hematite and goethite (e.g. Schuster et al., 2006; Müller et al., 2009; Schladitz et al., 2009). Here, ~~we derived~~ AAE was derived by fitting the wavelength dependence of the AAE using

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a similar log-log fit, but applied to multi-wavelength absorption from the AE33 ~~absorption coefficients in log-log space,~~

$$\ln(b_{\text{abs}}(\lambda)) = -\text{AAE} \cdot \ln(\lambda) + \beta. \quad (4)$$

where β is the intercept of the linear fit.

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- c. The Single Scattering Albedo (SSA) is calculated as the ~~ratio of the~~ scattering (b_{scat}) to ~~the extinction~~ extinction, ($b_{\text{ext}} = b_{\text{scat}} + b_{\text{abs}}$) ratio, $SSA = b_{\text{scat}}/b_{\text{ext}}$ ~~coefficients at all the AE33 wavelengths, is a crucial parameter in climate modeling because it indicates whether aerosols predominantly scatter (cooling effect) or absorb (warming effect) radiation.~~ SSA indicates the relative importance of aerosol scattering and absorption and is therefore a key parameter for assessing aerosol radiative effects. Values close to 1 indicate predominantly scattering particles, whereas lower values indicate stronger absorption. Typical values for Saharan dust range from 0.92 at 370 nm to 0.98 at 880 nm (Di Biagio et al., 2019), and from 0.90 to 0.96 at the green wavelengths ~~depending on the estimated dust iron content (Claquin et al., 1999; Schladitz et al., 2009).~~ –We computed the SSA (Claquin et al., 1999; Schladitz et al., 2009), depending on source region, iron content, particle size, and mixing state. In this section, SSA was calculated at the seven AE33 wavelengths by extrapolating the nephelometer scattering data–corrected nephelometer scattering coefficients using the derived SAE. This standard SSA should be distinguished from t_{ssa} , the truncated SSA used only in the retrieval of k in Sect. 2.6.

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- d. The ~~Single Scattering Albedo~~ SSA Ångström Exponent (SSAAE) ~~helps identify coarse particles (e. g. dust) with values below zero often tied to~~ describes the wavelength dependence of SSA. Negative SSAAE values are often associated with coarse dust-dominated conditions (Collaud Coen et al., 2004; Ealo et al., 2016). ~~We obtained the SSAAE, because dust SSA generally increases with wavelength as absorption decreases towards the near-infrared (Collaud Coen et al., 2004; Ealo et al., 2009).~~ SSAAE was obtained by fitting the wavelength dependence of the derived SSA values (at the AE33 wavelengths) in a SSA in log-log space, analogous to the SAE/AAE approach.

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$$\ln(SSA(\lambda)) = -\text{SSAAE} \cdot \ln(\lambda) + \beta. \quad (5)$$

where β is the intercept of the linear fit.

280

- e. The asymmetry parameter (g) is the first moment of the Legendre decomposition of the scalar scattering phase function and describes the mean scattering direction. It ranges ~~between from~~ -1 ~~and 1, where a value of -1 indicates pure backward scattering and a value of 1 refers to pure forward scattering.~~ for purely backward scattering to $+1$ for purely forward scattering. For airborne dust particles, values between 0.6 and 0.85 are commonly used in numerical models (Sokolik and Toon, 1999;

Horvath et al., 2018; Ryder et al., 2018). Here we ~~have-obtained-derived~~ g from the phase function of the nephelometer multi-angle measurements, corrected by angular truncation as ~~indicated-described~~ in Sect. 2.2.

$$g = \frac{1}{2} \int_{-1}^1 P(\cos \theta) \cos \theta d \cos \theta, \quad (6)$$

285 where $P(\cos \theta)$ is the ~~scattering~~ phase function (Liou, 2002; Horvath et al., 2018).

f. The Backscatter Fraction (BF) is ~~computed-calculated~~ as the ratio between ~~the~~ hemispheric backward scattering and ~~the total scattering from total scattering, using~~ the corrected nephelometer measurements. ~~BF provides complementary information to g , with lower BF values generally indicating stronger forward scattering by larger particles.~~

290 g. The Mass Absorption, Scattering, and Extinction efficiencies (MAE, MSE, and MEE) represent the absorption, scattering, and extinction efficiencies, respectively, of the measured particles per unit of mass. ~~The MAE, MSE and MEE. They~~ were obtained as the ratio between the absorption, scattering, and extinction coefficients, respectively, and the mass concentration derived from the number PSD (M_{PM}) ~~which, given the location of the measurements site,~~ ~~During strong dust-emission events at the study site, this mass concentration~~ can be attributed ~~exclusively-predominantly~~ to mineral dust ~~during the strong mineral dust emission events,~~ ~~Outside these periods, particularly during episodes influenced by anthropogenic advection, the mass-normalized optical quantities may also reflect the contribution of non-dust absorbing particles. The mass efficiencies are therefore interpreted primarily for the dust-event periods and used to assess how optical properties vary with particle size and inlet cut-off.~~ Values of dust MEE around $0.32 \text{ m}^2 \text{ g}^{-1}$ have been reported in previous studies (Ryder et al., 2018).

2.6 ~~Complex-Imaginary part of the complex~~ refractive index retrieval

300 The imaginary part of the complex refractive index (k) was ~~estimated-using-a-combination-of-optical-property-measurements and-absorption-and-scattering-simulations-based-on-the-measured-PSDs. In particular, we determined the~~ ~~retrieved by comparing measured and simulated optical properties during PM2.5 dust-event periods. The retrieval uses the truncated scattering, denoted~~ t_{sca} in Sect. 2.2, together with the AE33 absorption coefficient, b_{abs} . We define the truncated SSA, t_{ssa} , as:

$$t_{ssa} = \frac{t_{sca}}{t_{sca} + b_{abs}}. \quad (7)$$

305 ~~The~~ value of k ~~that minimizes the discrepancy is then obtained by minimizing the difference~~ between simulated and measured SSA. ~~This optimization was performed under different assumptions regarding particle shape~~ t_{ssa} . ~~The optimization is performed under prescribed assumptions for particle shape, particle density, and real part of the refractive index, n . Therefore, the retrieval should be interpreted as a conditional estimate of k for each set of assumptions, rather than as a simultaneous retrieval of particle shape, PSD, n , and k .~~

310 Our ~~optimization~~ methodology builds on the approach of Di Biagio et al. (2019) ~~but introduces key modifications, particularly in its minimization structure. The process~~, but introduces two main modifications motivated by the characteristics of our field dataset. First, the conversion of Fidas optical diameters into dust geometric diameters is coupled to the retrieval, because this conversion depends on the assumed particle shape and refractive index. Second, the cost function is based on *tssa*, rather than on absorption and scattering coefficients separately. This choice reduces the sensitivity of the retrieval to possible differences in
315 the absolute particle number sampled by the OPC and by the optical instruments, and avoids correcting the measured truncated scattering coefficient to a full-phase-function scattering coefficient in the retrieval itself.

The retrieval procedure consists of three main steps: (1) ~~estimating the number PSD in terms of converting the Fidas PSL-calibrated optical diameters into dust geometric diameters, which depends on both particle shape and k under prescribed assumptions for particle shape, density, and real refractive index~~; (2) simulating truncated scattering and absorption coefficients
320 ~~based on the measured number from the converted PSD~~; and (3) minimizing a quadratic cost function based on ~~SSA, *tssa*. A general overview of the procedure is shown in Figure 2.~~

A key ~~difference from Di Biagio et al. (2019)~~ is that our optimization of k accounts for the interdependence between the PSD aspect of the method is that the OPC diameter conversion and the ~~simulated optical coefficients. Since the transformation of the PSD optical simulations are treated consistently. The transformation~~ from PSL-based optical diameters to dust geometric
325 diameters depends on k , ~~and the absorption coefficient is directly influenced while absorption is also directly controlled by k , both must be optimized simultaneously. Therefore, for a given~~. To avoid a sequential inconsistency, we first retrieve the value of k , ~~the scattering and absorption coefficients, and the size-resolved phase function are computed. The phase function and the scattering coefficients are used in the PSD conversion; while the integration of the phase function, scattering and absorption coefficients are combined with the converted PSD to simulate the measured absorption and scattering coefficients.~~
330 ~~This procedure ensures full consistency in the size distribution transformation and the simulated optical properties, at the wavelength relevant for the OPC diameter conversion. This value is then used to convert the Fidas optical diameters into dust geometric diameters. The resulting dust PSD is subsequently used to retrieve k at the AE33 wavelengths.~~

Another key difference from the ~~Di Biagio et al. (2019) method~~ method of Di Biagio et al. (2019) is that we define the cost function directly in terms of ~~SSA, as this parameter is highly sensitive the truncated single scattering albedo, *tssa*~~. This choice
335 is motivated by both the sensitivity of *tssa* to k . ~~Although we~~, and the sampling configuration of the field experiment. The Fidas measured number size distributions through its own inlet over a broad optical-diameter range of approximately 0.2–19 μm , whereas the AE33 and nephelometer sampled through a common PM2.5 inlet during the period used for the refractive-index retrieval. To make the Fidas PSD representative of the aerosol population sampled by the optical instruments, we applied an effective PM2.5 cut-off to the converted dust geometric PSD. However, this procedure cannot fully reproduce possible
340 differences in inlet transmission, size-dependent particle losses, counting efficiency, or absolute particle number between the Fidas and the optical sampling line.

We tested alternative cost functions incorporating ~~extensive additional~~ information from the polar nephelometer, ~~including a combined cost function based on quadratic departures of *tssa* and the backscatter fraction (BF). However,~~ our dataset did not support a robust simultaneous retrieval of both ~~n and k~~ and k . This limitation likely ~~stems from the sensitivity of k to particle~~

345 ~~shape assumptions, reflects the combined sensitivity of the inversion to particle-shape assumptions, particle density, inlet cut-~~
~~off modelling~~, and PSD uncertainties. ~~To address this, we retrieved~~ In particular, closure tests comparing inversions
based on *tssa* with inversions using extensive optical properties suggested a possible mismatch between the OPC-derived
PSD and the aerosol population sampled by the nephelometer and aethalometer. Expressed as an equivalent scaling of the
OPC particle number concentration, this mismatch was of the order of at least 20 % in some cases. Moreover, the spectral
350 dependence of the required scaling suggests that the mismatch may not be a simple constant offset in particle number, but may
include size-dependent effects, with larger discrepancies towards the lower and upper ends of the PM_{2.5} size range.

Because the available data do not allow this potential mismatch to be quantified robustly, we use *tssa* in the cost function
instead of relying on inversions based directly on extensive absorption and scattering coefficients. Since *tssa* is a ratio between
truncated scattering and extinction, it is less sensitive to absolute concentration differences between the OPC and the optical
355 instruments, while retaining sensitivity to the absorption-to-scattering balance controlled by *k*. The drawback is that *tssa* is not
sufficiently sensitive to *n* to support a robust simultaneous retrieval of *n* and *k* ~~for multiple fixed values of *n*~~ from this dataset.
We therefore retrieve *k* for a range of fixed *n* values representative of mineral dust, rather than solving for both parameters
simultaneously. As ~~demonstrated shown~~ in Sect. 3.3, the retrieved *k* ~~remains largely insensitive to the choice of *n* within its~~
~~plausible range, reinforcing the reliability of our approach. Below we describe the three steps in detail.~~ is only weakly sensitive
360 to the prescribed value of *n* within the plausible range tested here.

2.6.1 Estimation of the dust PSD

The number PSD ~~obtained from the Fidas instrument is calibrated using polystyrene latex spheres (PSL, $CRI = 1.59 + 0i$),~~
~~requiring conversion to~~ measured by the Fidas is reported in terms of PSL-calibrated optical diameters. Since PSL particles are
spherical and non-absorbing, whereas mineral dust particles are non-spherical and absorbing, these optical diameters must be
365 ~~converted into~~ dust geometric diameters ~~before being used in the retrieval~~. As described in González-Flórez et al. (2023), we
~~transform the default PSL diameters into dust geometric diameters following Huang et al. (2020), which involves calculating~~
~~the theoretical scattered intensities of the PSLs and those of the aspherical and absorbing dust. The comparison of both sideward~~
~~scattered intensities allows remapping the PSL into dust geometric diameters after a monotonization procedure for ensuring~~
~~uniqueness of the solution. The calculation of the scattered intensities depends on the wavelength of the light beam used in~~
370 ~~the Fidas, the scattering angle range of the OPC's light sensor, and the shape and CRI of the particles. We first inferred the~~
~~scattered light spectrum of the Fidas instrument (which is not provided by the manufacturer) by analyzing its manufacturer's~~
~~follow the general approach of Huang et al. (2021), which compares the sideward scattered intensity expected for PSL particles~~
~~with that expected for dust particles under prescribed assumptions for shape and refractive index.~~

The Fidas manufacturer does not provide the full spectral response of the light source. We therefore inferred an effective
375 light-source spectrum by analysing the Fidas conversion software, which ~~translates PSL-based PSDs to those of~~ converts
PSL-calibrated PSDs into PSDs for spherical aerosols with 16 different refractive indices. Using the known side-scattering
geometry of the instrument, $90^\circ \pm 5^\circ$ ~~scattering angle and a Lorenz-Mie, and a Lorenz-Mie~~ scattering model, we opti-
mized a Gaussian spectral function that best reproduced ~~these conversions, yielding an estimated light spectrum centered~~

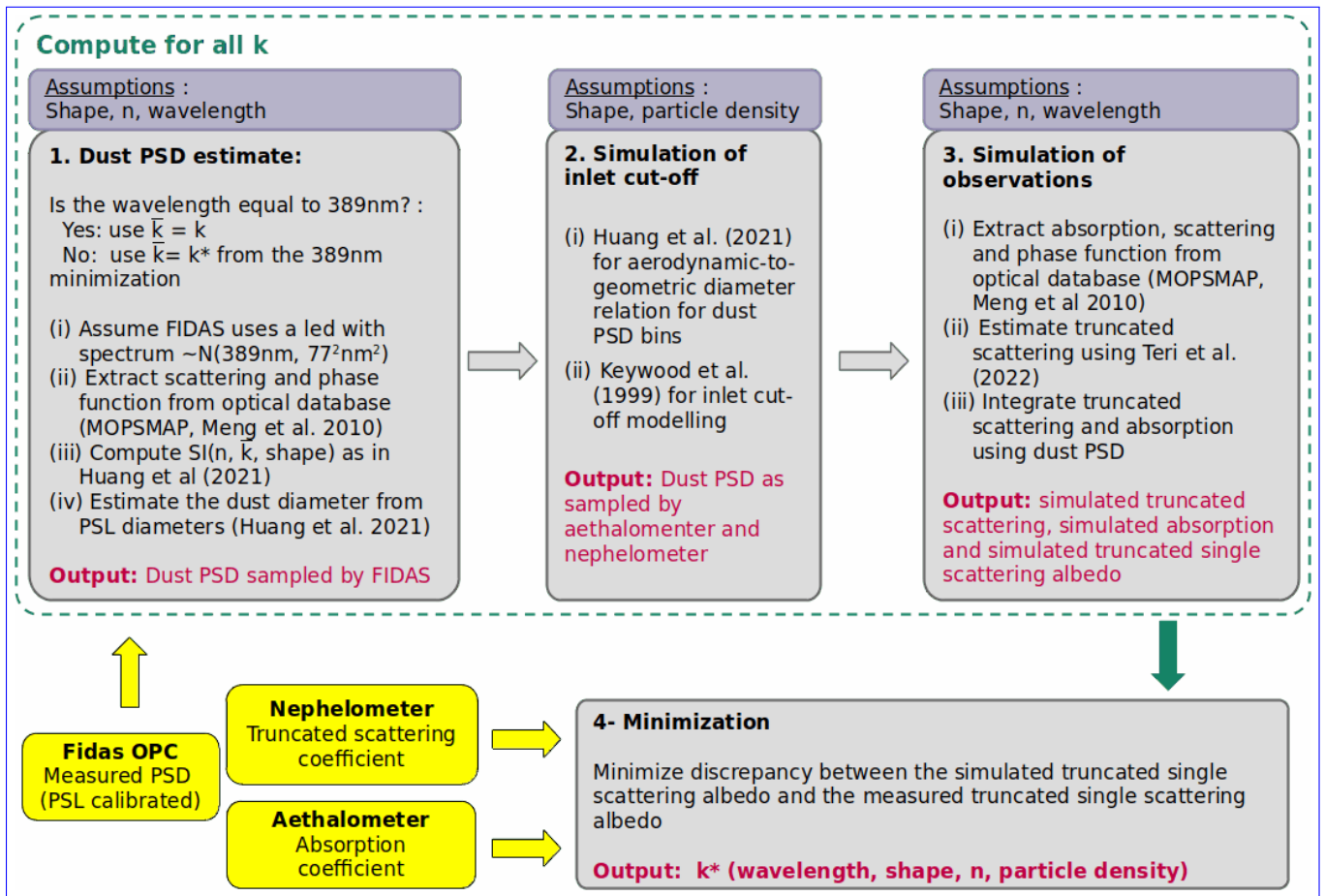


Figure 2. Procedure to estimate k . The algorithm is done for every 15-minute averaged measurement and for every shape, n, particle density and wavelength independently

the manufacturer-provided conversions. The resulting effective light source was centred at 389nm with a nm, with a standard deviation of 77nm standard deviation nm. This optimized spectrum was then applied to transform used to convert PSL optical diameters into dust geometric diameters.

The For PSL particles, the sideward scattered intensity depends on particle shape. Since PSLs are spherical, we obtained their single-scattering properties based on was computed using Lorenz-Mie theory. For dust, we used a wide range of particle shapes available in the MOPSMAP database (Gasteiger and Wiegner, 2018) to assess the impact of shape assumptions on the retrieval of k . We tested spherical particles and biaxial prolate ellipsoids with aspect ratio of 1.46, along with a distribution of biaxial prolate ellipsoids based on aspect ratios measured during our campaign using Scanning Electron Microscopy single particle analysis (Panta et al., 2023). Additionally, we included six irregular dust particle shapes (A to F) defined in Gasteiger et al. (2011) and MOPSMAP (Gasteiger and Wiegner, 2018). Beyond these, we incorporated particles, the scattered

intensity depends on the assumed particle shape and refractive index. We therefore performed the conversion for several
390 prescribed particle-shape assumptions. These include spheres as a reference case (*Sph*); biaxial spheroids using aspect-ratio
information derived from campaign-specific single-particle analyses by Panta et al. (2023) (*Bi dist*); the spheroid aspect-ratio
distribution of Dubovik et al. (2006) and reported in the GRASP spheroid package, which is relevant for comparison with
remote-sensing retrievals (*Dub-06*); triaxial ellipsoids from Meng et al. (2010) ~~-, selecting also 1.46 as aspect ratio (Panta et al., 2023)~~
~~-, using also the campaign-specific median aspect ratio and a height-to-width ratio of 0.45. -This choice aligns with the median~~
395 ~~height-to-width ratio (0.4) reported in Huang et al. (2020) and represents the closest available match in the Meng et al. (2010)-~~
~~database for our measured size range and wavelengths. By testing this diverse set of shape assumptions, we ensure a more~~
~~comprehensive assessment of morphological effects on the derived optical properties. (Huang et al., 2021); and the six irregular~~
dust shapes (A to F) from the MOPSMAP database (Gasteiger and Wiegner, 2018).

The single-shape calculations are not intended to represent the full atmospheric dust population. Instead, they are used as
400 controlled sensitivity cases to quantify how different plausible particle morphologies affect the OPC diameter conversion and
the retrieved k . Where observationally or methodologically justified distributions are available, such as the campaign-derived
spheroid distribution and the Dubovik et al. (2006) distribution, we use these distributions as more representative spheroidal
cases.

The conversion from optical to geometric diameter was performed independently for each prescribed particle-shape assumption,
405 particle density, and refractive-index configuration. For the retrieval, the value of k at the effective OPC wavelength was first
estimated consistently with the diameter conversion. Once this conversion was obtained, the resulting dust geometric PSD was
used to simulate absorption and truncated scattering at the AE33 wavelengths and to retrieve k at each wavelength.

2.6.2 Scattering and absorption simulations

Using the dust PSD as input, we computed scattering and absorption coefficients using the single-particle optical property
410 ~~databases for each shape assumption from~~ For each prescribed particle-shape assumption, particle density, and real refractive
index, the converted dust geometric PSD was used to simulate absorption and truncated scattering coefficients. Single-particle
optical properties databases were obtained from the optical-property databases of Gasteiger and Wiegner (2018) and Meng
et al. (2010). ~~To accurately reproduce the nephelometer's measurement characteristics, depending on the assumed particle~~
shape. The simulated optical coefficients were then integrated over the converted PSD and over the size range corresponding
415 ~~to the PM2.5 optical inlet.~~

For consistency with the measurements used in the retrieval, we simulated ~~its angular sensitivity and truncation effects,~~
~~applying the correction method from equation~~ the angular response and truncation of the Aurora 4000 nephelometer rather
than comparing the observations with a full-phase-function scattering coefficient. Specifically, the simulated scattering phase
function was integrated over the nephelometer angular sensitivity following Eq. (11) of Teri et al. (2022). ~~These computations~~
420 ~~provided the~~ This provided the simulated truncated scattering coefficient and the absorption coefficient. To avoid introducing
additional assumptions, we defined a modified SSA, using the truncated scattering coefficient rather than an assumed, directly

comparable to the uncorrected nephelometer scattering coefficient, (t_{sca}), defined in Sect. 2.2. The corresponding simulated truncated single scattering albedo, t_{ssa} was then calculated.

This use of truncated scattering avoids applying an additional correction from truncated to full-phase-function scattering coefficient. Finally, a quadratic cost function was used to compare the simulated and observed SSA, with k optimized via grid-search minimization as in Di Biagio et al. (2019) in the retrieval itself, which would introduce further assumptions about particle shape and the scattering phase function.

We note that, while the aethalometer and nephelometer measurements were taken using a The Fidas measures particles over a broader size range and through a different inlet than the optical instruments. Therefore, before computing the optical coefficients, the converted Fidas PSD was transformed into a PM2.5 inlet, the PSD measurements used an inlet with a larger diameter cut-off (González-Flórez et al., 2023). In order to use the PSD measurements to simulate to the optical property measurements during the k retrieval algorithm, we also estimated the aethalometer and nephelometer effective inlet cut-off by applying .5-equivalent PSD representative of the aerosol population sampled by the optical instruments. To do this, we applied an inlet transmission efficiency using a sigmoid function following the PM2.5 URG model described in Keywood et al. (1999). In addition, we assumed an aerodynamic-to-geometric diameter ratio for dust of 1.7 (Huang et al., 2020) by Keywood et al. (1999), rather than imposing a sharp cut-off.

The inlet transmission was applied in aerodynamic-diameter space and then related to the dust geometric PSD. The conversion between aerodynamic and geometric diameter depends on particle density and particle shape. We computed this conversion following Huang et al. (2021), based on the formulation of (Bagheri and Bonadonna, 2016), which accounts for dust density and shape factor corrections. The sensitivity of the the effects of particle density and dynamic shape factor. Thus, for each particle-shape assumption and particle density, the PM2.5 inlet efficiency was mapped onto the corresponding dust geometric diameters and applied to the converted Fidas PSD before simulating absorption and truncated scattering.

Particle density affects the aerodynamic-to-geometric diameter conversion and therefore the effective upper diameter included in the PSD. We use a central density value of $2.15 \text{ g} \cdot \text{cm}^{-3}$, derived from samples collected during the campaign, and perform sensitivity tests using 1.8 and $2.5 \text{ g} \cdot \text{cm}^{-3}$. These values are used to quantify the effect of density uncertainty on the PM2.5-equivalent PSD and on the retrieved k to this assumption was later quantified by repeating the whole procedure for and inlet cut-off diameter 10% larger (equal 1.87) and 10% smaller (equal 1.53) than our best guess value of 1.7. The retrieval is also repeated for the prescribed range of real refractive indices and for the lower, central, and upper values of the AE33 multiple-scattering correction parameter (C), derived from the 95 % confidence interval reported by Yus-Díez et al. (2025). These sensitivity tests quantify how uncertainties in particle density, n , particle shape, inlet-efficiency mapping, and AE33 absorption correction propagate into the retrieved k .

The retrieval is restricted to the PM2.5 period because this period provides the longest and most stable dataset for matching the optical measurements with the Fidas PSD. Extending the retrieval to the PM10 period would increase the sensitivity to large-particle sampling, inlet transmission, particle losses, and the validity range of the optical-property databases, and is therefore not attempted here.

2.6.3 Minimization procedure

The minimization was performed independently for each AE33 wavelength, using 15-minute averaged measurements with collocated PSD and optical data. We repeated the optimization for multiple fixed values of n within the Fidas PSD, AE33 absorption, and nephelometer scattering data. The retrieval was restricted to periods classified as dust events during the PM2.5 part of the campaign, following the criteria described in Sect. 3.1.

For each time step, wavelength, prescribed particle-shape assumption, particle density, real refractive index n , and AE33 correction case, we searched for the value of k that minimized the quadratic difference between the measurement-derived and simulated truncated single scattering albedo.

$$J(k) = \left(\frac{tssa_{\text{measured}}(k) - tssa_{\text{simulated}}(k)}{tsca(k)} \right)^2 \quad (8)$$

The minimization was performed on a predefined grid of plausible k values. The algorithm therefore does not require an iterative stopping criterion: all grid values are evaluated, and the value of k corresponding to the minimum is retained as the retrieved value for that specific set of assumptions.

The real part of the refractive index was not retrieved simultaneously with k . Instead, the retrieval was repeated for fixed values of n between 1.48 and 1.55 range, in 0.01 increments, in increments of 0.005, following the reported values from Di Biagio et al. (2019). To assess particle shape effects, we conducted calculations for the diverse set of particle morphologies described above range of values reported for mineral dust by Di Biagio et al. (2019). This choice reflects the limited sensitivity of $tssa$ to n , as well as the uncertainties associated with using a Fidas PSD measured through a different inlet from the AE33 and nephelometer. The resulting dependence of retrieved k on the prescribed value of n is evaluated in Sect. 3.3.

The retrieval was also repeated for the particle-shape assumptions described in Sect. 2.6.1, for the particle densities described in Sect. 2.6.2, and for the lower, central, and upper AE33 multiple-scattering correction cases. The resulting values of k should therefore be interpreted as conditional retrievals under prescribed assumptions for particle shape, particle density, n , and AE33 absorption correction. We do not retrieve particle shape, and the different shape assumptions are used to quantify the sensitivity of k to the optical representation of dust morphology.

For each configuration, we report two complementary estimates. First, we retrieve k from the optical and PSD measurements averaged over all PM2.5 dust-event periods. Second, we retrieve k independently for each 15 min dust-event interval and summarize the resulting distribution. The former provides a retrieval representative of the mean dust-event optical properties, whereas the latter quantifies the temporal variability of the retrievals during dust-event conditions.

2.6.4 Retrieval of k from AERONET

To contextualize and compare our retrieved k values our in-situ retrievals, we derived a dust-specific k climatology from the AEROSOL ROBOTIC NETWORK (AERONET) version 3, level 2.0 Almucantar retrievals (Giles et al., 2019; Sinyuk et al., 2020). The purpose of this comparison is not to provide a strict validation of the in-situ retrievals, because AERONET products are

column-integrated and retrieval-dependent, whereas our measurements are near-surface and source-region observations during a specific field campaign. Instead, the AERONET retrievals are used to place the campaign results in the context of longer-term dust-dominated retrievals from nearby and regional dust-source areas.

490 Dust-dominated ~~conditions~~ AERONET retrievals were identified following the filtering methodology of Obiso et al. (2023), which applied a ~~series-set~~ of criteria to exclude retrievals contaminated by other absorbing aerosols, such as carbonaceous species.

AERONET hourly retrievals were classified as dust events when the fine-mode volume fraction was below 10%, ensuring that the dataset was dominated by coarse particles. ~~Additionally, we required that the SSA increased~~ We additionally required
495 SSA to increase from 440 to 675 nm, a spectral ~~trend-behaviour~~ characteristic of dust that helps distinguish it from fine anthropogenic aerosols and sea salt (Dubovik et al., 2002). To further ~~exclude-reduce~~ the influence of absorbing black and brown carbon, we ~~filtered-out-excluded~~ cases where the mean k at red and infrared wavelengths (~~calculated over~~ 675, 870, and 1020 nm) ~~exceeded~~ 0.0042, following the ~~thresholds-threshold~~ proposed by Schuster et al. (2016).

Using this filtered dataset, we ~~computed the climatological dust~~ first computed the dust-specific climatology of k at the
500 Ouarzazate AERONET station, the closest site to our field measurements (160 km). ~~Additionally, we away).~~ We then extended
our analysis to major global dust source regions (see Fig. S9) to assess the broader variability of dust absorption properties. In
including western and eastern North Africa, the Sahel, the Arabian Peninsula, central Asia, and India, using the stations shown
in Fig. S10a. For the regional analysis, we applied optical depth weighting to compute statistical metrics ~~the statistical metrics~~
of k , including mean values and percentiles, ensuring that the retrieved were computed using optical depth weighting. This
505 weighting gives greater influence to retrievals with larger dust optical depth and therefore better represents dust-dominated
conditions.

For the comparison with our in-situ retrievals, the values of k retrieved at the AE33 wavelengths were interpolated or extrapolated to the AERONET wavelengths of 440, 550, 675, 870, and 1020 nm. We compare AERONET-derived k ~~values reflect both temporal and geographical variability in dust retrievals~~ primarily with the in-situ retrievals obtained using the
510 Dubovik et al. (2006) spheroid aspect-ratio distribution, because this particle-shape representation is more consistent with assumptions used in AERONET-type retrievals. Other particle-shape assumptions are also shown to illustrate the sensitivity of the in-situ k retrievals to shape.

In addition to k , we extracted the dust-filtered AERONET volume size distributions at Ouarzazate for qualitative comparison with the Fidas-derived PSDs measured during the campaign. This comparison is used only to assess potential differences in
515 particle-size representativeness between the two datasets. The Fidas measurements represent near-surface in-situ PSDs at the source-region site and are restricted to the period and size range used in the retrieval, whereas AERONET size distributions are column-integrated and depend on the assumptions of the radiance inversion. Differences between the two PSDs can therefore contribute to discrepancies between in-situ and AERONET-derived k , in addition to differences associated with particle shape, mineralogy, and possible residual aerosol contamination. This caveat is important because previous studies
520 have shown that AERONET dust retrievals may be affected by uncertainties in the representation of coarse and super-coarse dust, with implications for retrieved absorption properties.

3 Results

3.1 Overview of the optical properties during the measurement campaign

The campaign was characterized by ~~overall~~ generally calm conditions in the early morning, followed by stronger winds in the afternoon, leading to frequent local saltation and dust emission. This pattern followed the diurnal cycle of solar heating and the resulting destabilization of the near-surface atmospheric layers. ~~Some daysshowed~~ On some days, the site was also influenced by the advection of local anthropogenic particles from up-river villages. Additionally, two intense cold pool outflows, referred to as "~~Haboobs~~" haboobs, were recorded on ~~the 4th and 6th of~~ 4 and 6 September 2019. A more detailed discussion of the atmospheric conditions, turbulence parameters, and dust fluxes during the campaign ~~can be found~~ is provided in González-Flórez et al. (2023).

Two distinct measurement periods were defined based on the inlet cut-off of the optical measurements: ~~an initial period with~~ . During the initial part of the campaign, from 4 September until 26 September 2019, the AE33 and nephelometer sampled through a PM2.5 inlet ~~from the beginning~~ . From 26 September 2019 until the end of the campaign ~~until September 26, followed by~~ , the optical measurements were performed using a PM10 inlet ~~period from that point onward~~ . Figure S1 presents ~~shows~~ the temporal evolution of extensive and intensive optical properties, mass concentration, particle effective radius, wind speed, and friction velocity throughout the ~~whole duration of the~~ full campaign.

To analyze the dominant aerosol conditions during the measurement period, we identified three representative ~~scenarios~~ periods. ~~Period A corresponds to~~ Period A corresponds to local dust emissions (~~Period A, 21st of September 2019~~), ~~Haboob-driven dust events (Period B, 6th of on 21-22 September 2019~~), ~~Period B corresponds to the haboob-driven dust event on 6-7 September 2019~~), ~~and~~ . Period C corresponds to a period influenced by anthropogenic pollution advection mixed with minor local dust emissions (~~Period C, 7th–10th of September 2019~~), ~~between 7 and 11 September 2019~~. These periods are highlighted in Figure 3 ~~and are used to illustrate the range of optical conditions observed during the campaign~~.

Table 1 ~~provides a summary of~~ summarizes the time-averaged optical properties for the PM2.5 and PM10 periods, distinguishing between ~~overall measurements, dust events~~ the full measurements, dust-event conditions, and the three defined periods. Dust events during the PM2.5 period were identified ~~based on an~~ using three criteria: AAE above 1.5, ~~an~~ SSAAE below 0, and a mass concentration ~~exceeding above~~ $10 \mu\text{g} \cdot \text{m}^{-3}$ (Collaud Coen et al., 2010; Ealo et al., 2016). Extensive optical properties are presented with their standard errors, ~~while intensive properties are averaged~~. Intensive optical properties are summarized using two approaches: (i) weighting by extensive properties (averages weighted by the corresponding extensive properties, namely absorption, scattering, and extinction for their corresponding variables) or extinction, and (ii) direct time-averaging with standard error representation ~~time averages with standard errors~~. The weighted averages ~~provide insight into aerosol properties under conditions of~~ emphasize conditions with elevated dust concentrations, while the direct averages reflect the overall ~~campaign conditions~~ variability of the campaign. This variability is further showcased in Figs. S2-S5.

Period A, dominated by local dust emissions, closely resembles the ~~overall dust event averages~~ average dust-event conditions, confirming that such local emissions were common ~~throughout during~~ the campaign. Period B (~~Haboob event~~) ~~exhibits similar~~ corresponding to the haboob event, exhibits intensive optical properties ~~to similar to those of~~ Period A, ~~though with substantially~~.

Table 1. Summary of mean values and standard errors for the measured and computed optical properties described in Sect. 2 during the full period, dust events, and during the three specific periods (A,B,C). Data are presented for selected wavelengths (grey-shaded rows) and weighted means (non-shaded rows). Results are categorized by inlet cut-off periods: PM_{2.5} (from 2019-09-04 00:00 UTC to 2019-09-26 12:00 UTC) and PM₁₀ (from 2019-09-26 12:00 UTC to the end of the measurements). The number of measurements (N) corresponds to the 15 min averages used in the analysis.

	units	PM _{2.5}					PM ₁₀
		Full Period (N=2156)	Dust Events (N=1160)	Period A (N=96)	Period B (N=96)	Period C (N=379)	Full period (N=464)
b _{abs,370}	Mm ⁻¹	3.87±4.29 ± 0.48±0.53	6.92±7.89 ± 0.34±0.37	5.11±5.69 ± 0.52±0.59	25.81±28.53 ± 8.18±9.03	2.40±2.31 ± 0.10	4.38±5.21 ± 0.45±0.20
b _{abs,880}	Mm ⁻¹	0.66±0.37 ± 0.05±0.02	0.93±0.36 ± 0.03±0.01	0.72±0.33 ± 0.06±0.02	2.95±0.69 ± 0.87±0.30	0.49±0.36 ± 0.01	0.77±0.36 ± 0.05±0.02
b _{scat,525}	Mm ⁻¹	83.72 ± 12.25	162.77 ± 8.31	114.16 ± 12.18	616.23 ± 214.87	40.70 ± 2.23	92.90 ± 10.77
b _{scat,525}	Mm ⁻¹	9.09 ± 1.15	16.32 ± 0.74	12.39 ± 1.14	59.31 ± 20.16	4.91 ± 0.21	12.38 ± 1.33
N	#	43.14 ± 2.45	56.33 ± 1.84	47.97 ± 3.49	153.17 ± 43.41	34.93 ± 0.65	32.30 ± 2.20
M	μg m ⁻³	26.38 ± 3.28	51.14 ± 2.34	37.24 ± 4.16	192.28 ± 55.32	13.09 ± 0.76	247.5 ± 31.36
R _{eff}	μm	0.469	0.545	0.528	0.579	0.417	1.649
MAE ₃₇₀	m ² g ⁻¹	0.445 ± 0.004	0.525 ± 0.009	0.517 ± 0.003	0.564 ± 0.006	0.420 ± 0.004	1.604 ± 0.004
		0.156±0.154	0.140±0.141	0.139±0.137	0.178±0.134	0.182	0.019
MAE ₈₈₀	m ² g ⁻¹	0.180±0.203 ± 0.003±0.085	0.145±0.167 ± 0.004±0.051	0.148±0.164 ± 0.003±0.038	0.140±0.157 ± 0.007±0.041	0.194±0.216 ± 0.004±0.091	0.021 ± 0.001
		0.041±0.039	0.020±0.014	0.021±0.011	0.016±0.006	0.058±0.005	0.004±0.002
MSE ₅₂₅	m ² g ⁻¹	0.048±0.038 ± 0.001±0.033	0.023±0.012 ± 0.000±0.009	0.024±0.013 ± 0.001±0.008	0.018±0.007 ± 0.001±0.042	0.051±0.047 ± 0.002±0.031	0.004±0.003 ± 0.001
		3.41	3.67	3.19	3.73	3.25	0.396
MEE ₃₇₀	m ² g ⁻¹	3.30 ± 0.034±0.75	3.21 ± 0.03±1.02	3.25 ± 0.06±0.60	3.19 ± 0.23±0.76	3.31 ± 0.04±0.76	0.40 ± 0.003
		3.66±3.67	3.73±3.45	3.39±2.76	3.66±3.09	3.90±3.34	0.391±0.330
MEE ₈₈₀	m ² g ⁻¹	3.98±3.42 ± 0.052±1.00	3.34±2.85 ± 0.03±1.46	3.40±2.88 ± 0.06±0.53	3.24±2.69 ± 0.22±0.88	4.19±3.61 ± 0.062±1.03	0.390±0.338 ± 0.005±0.004
		3.61±3.60	3.88±3.48	3.39±2.81	4.18±3.51	3.42±2.63	0.469±0.391
SSA ₃₇₀	—	0.942±0.49 ± 0.040±0.74	0.322±0.83 ± 0.03±1.51	0.382±0.84 ± 0.06±0.53	0.50±2.91 ± 0.27±1.12	0.782±0.37 ± 0.04±0.72	0.440±0.366 ± 0.005
		0.957±0.952	0.958±0.952	0.957±0.952	0.958±0.954	0.956±0.951	0.957±0.948
SSA ₅₅₀	—	0.954±0.949 ± 0.001±0.016	0.955±0.948 ± 0.000±0.016	0.956±0.951 ± 0.001±0.010	0.954±0.948 ± 0.002±0.018	0.954±0.948 ± 0.001±0.011	0.945±0.935 ± 0.001±0.067
		0.984±0.985	0.987±0.989	0.986±0.988	0.979±0.990	0.977	0.985
SSA ₈₈₀	—	0.976±0.973 ± 0.001±0.017	0.985±0.986 ± 0.000±0.007	0.985±0.986 ± 0.001±0.006	0.986±0.988 ± 0.002±0.006	0.972±0.968 ± 0.001±0.011	0.974±0.972 ± 0.001±0.056
		0.992±0.995	0.994±0.998	0.996±0.997	0.987±0.998	0.990	0.993
AAE ₃₇₀₋₉₅₀	—	0.982±0.985 ± 0.001±0.014	0.993±0.996 ± 0.000±0.003	0.993±0.996 ± 0.002	0.994±0.997 ± 0.002	0.978±0.981 ± 0.001±0.011	0.984±0.987 ± 0.001±0.046
		1.97±13.02	2.30±3.78	2.13±3.52	2.39±4.21	1.57±2.34	2.04±3.28
SAE ₄₅₀₋₆₃₅	—	1.602±0.42 ± 0.02±0.04	2.02±3.24 ± 0.01±0.02	2.013±0.24 ± 0.03±0.08	2.233±0.81 ± 0.04±0.17	1.462±0.11 ± 0.02±0.04	1.702±0.70 ± 0.01±0.02
		-0.010	-0.100	-0.077	-0.183	0.214	-0.092
SSAAE ₃₇₀₋₉₅₀	—	0.31 ± 0.019	-0.05 ± 0.005	-0.038 ± 0.01	-0.131 ± 0.021	0.433 ± 0.022	-0.174 ± 0.01
		-0.027±0.039	-0.036±0.046	-0.036±0.044	-0.039±0.048	-0.024±0.037	-0.038±0.051
BF ₅₂₅	—	-0.022±0.038 ± 0.001	-0.036±0.046 ± 0.003	-0.036±0.044 ± 0.001	-0.039±0.048 ± 0.002	-0.024±0.037 ± 0.001	-0.055±0.059 ± 0.002±0.003
		0.109	0.102	0.109	0.096	0.121	0.125
g ₅₂₅	—	0.130 ± 0.001	0.112 ± 0.0004	0.117 ± 0.001	0.102 ± 0.001	0.135 ± 0.001	0.140 ± 0.001
		0.680	0.699	0.684	0.701	0.654	0.654
k _{ext,extinct(10³)} k _{scat,scat(10³)}	—	0.639 ± 0.002	0.679 ± 0.001	0.673 ± 0.002	0.694 ± 0.002	0.627 ± 0.002	0.631 ± 0.001
		—	1.1±1.15	1.2±1.29	0.9±0.85	—	—
k _{ext,extinct(10³)} k _{scat,scat(10³)}	—	—	1.31±1.33 ± 0.01±0.07	1.321±1.35 ± 0.04±0.06	1.061±1.13 ± 0.07±0.05	—	—
		—	1.7±1.59	1.9±1.78	1.6±1.12	—	—
height	—	—	1.89±1.83 ± 0.01±0.10	1.941±1.85 ± 0.06±0.08	1.63±1.62 ± 0.10±0.07	—	—
		—	—	—	—	—	—

higher-values-in-but with substantially larger extensive optical properties due-to-increased-dust-mass-concentrationsbecause of the higher dust mass concentration. In contrast, Period C, influenced by anthropogenic pollution, shows lower mass concentrations and therefore reduced-lower absorption and scattering coefficients,-yet-. However, it exhibits much higher mass absorption efficiencies, particularly at longer wavelengths. This indicates an enhanced influence-contribution of fine carbonaceous particles on-the-site's-optical-properties-to the optical properties measured at the site during periods of weak easterly winds and the absence-of-local-dust-emissions,-as-analyzed-limited local dust emission, as discussed in González-Flórez et al. (2023).

Figure 3 and Table 1 show thatduring-, during PM2.5 dust events, SSA was around 0.955 at 370 nm, 0.985 at 550 nm and 0.993 at 880 nmfor PM2.5-, while the AAE remained near 2-and-the-. During the same conditions, AAE values were elevated relative to anthropogenic-dominated periods and SAE remained below 0-0-, consistent with a dominant contribution from coarse mineral dust and stronger absorption at shorter wavelengths. Brief decreases in effective radius, accompanied by dips in SSA and increases in SAE and k , again suggest intermittent advection of anthropogenic particles to the site under-low-wind and dust-contributions-, driven-by-local-meteorologyduring periods of low wind speed and weak dust emission. For PM10, SSA is-reduced-to-around-was lower, with values of approximately 0.945 at 370 nm, 0.974 at 550 nm and 0.984 at 880 nm (Table 1).

A comparison with other dust SSA measurements in-the-literature-(Table-S-1-in-compiled in Table S1 of the Supplementary Material of Adebisi et al. (2023)) shows that our PM10 results lie well within the general range of Saharan dust SSA values reported by other-previous in-situ and remote-sensing studies(-. For example, Schladitz et al. (2009) reported an SSA of 0.957 at 537 nm in Tinzou from Schladitz et al. (2009) and Tinou and Johnson and Osborne (2011) reported an SSA of 0.971 at 550 nm in Western Saharafrom Johnson and Osborne (2011)). As expected, the measured PM2.5-based values —focusing-on-finer particles—tend-toward-in our study, which emphasize the finer fraction of the sampled dust, tend towards slightly higher SSA at near-infrared wavelengths.

Many of the references-in-Adebisi-et-al.-(2023)-measure-a-measurements compiled in Adebisi et al. (2023) correspond to broader particle size spectrum-or-ranges or to long-range transported dust,-potentially-lowering-SSA-due-to-. Such differences can affect SSA because the inclusion of coarser and-more-absorbing dust particles,-whose-effect-is-analyzed particles, as well as changes in particle morphology, composition, and mixing state during transport, can modify both scattering and absorption. The effect of particle size on the optical properties measured during our campaign is analysed in Sect. 3.2. Furthermore, Adebisi-et-al.-(2023)-Table S1 reflects-of Adebisi et al. (2023) includes dust sampled across various-regions where mineralogy and aerosol mixing states often-differ-from-fresh-emissions-can differ from freshly emitted dust in southeastern Morocco, with some-including samples collected far from the source area(in-Cabo-Verdeand-, such as Cabo Verde, the Canary Islands-over-the Atlantic-or-in-, the Atlantic outflow and the West Mediterranean). While-our-measurements-capture-the-optical-properties-both-at PM2.5 and PM10-fractions-, they-focus-on-a-near-source-environment-and-may-not-mirror-the-particle-ageing-and-compositional evolution-encountered-during-trans-Atlantic-transport-or-in-other-source-areas-. Consequently,-. Therefore, although our SSA measurements overlap with previous studies, differences in size range, sampling region, and-dust-ageingprocesses dust ageing, and possible aerosol mixing must be considered when comparing results across multiple-datasets.

The mass efficiencies, MAE, MSE and MEE, as-expected-, show-a-high-variation-with-show strong sensitivity to inlet cut-off—, with variations approaching 1 order of magnitude—since-. This is expected because most of the mass concentration of

dust particles mineral dust is found in the coarse fraction. The ~~MEE found herein~~ MAE obtained here for dust events during the PM_{2.5} period (~~0.145~~, 0.141 m²g⁻¹ at ~~375 nm~~) 370 nm, is higher than the ~~one found in value reported by~~ Caponi et al. (2017) for Saharan dust (0.107 m²g⁻¹ at 375 nm), ~~but lower than dust from the Sahel region (~~, but much lower than the value reported for Sahelian dust, 0.711 m²g⁻¹ at 375 nm), ~~which showcases~~. This comparison illustrates the large variability ~~on the~~ absorption efficiency of dust depending on the source region. The backscatter fraction and the asymmetry parameter for in dust absorption efficiency across source regions. The asymmetry parameter and backscatter fraction during dust events, 0.68 and 0.11, respectively, fall within the range ~~of values found reported~~ by Horvath et al. (2018) for Saharan dust, 0.71 ± 0.03 and 0.094 ± 0.014 , respectively.

The higher absorption efficiency in Period C ~~associated to~~ is associated with the presence of anthropogenic aerosol particles, ~~happened especially particularly~~ between midnight and noon, ~~as denoted by the~~. This interpretation is supported by AAE and SAE values close to 1, ~~a SSAE values~~ close to zero or positive SSAE, a significantly smaller effective radius compared with dust events (0.42 vs 0.54 μ m), and a smaller lower SSA at 880 nm (~~of~~ around 0.978) ~~showeasing both the~~. Together, these features indicate a larger relative contribution of fine particles (González-Flórez et al., 2023) and ~~the higher a higher~~ apparent imaginary refractive index (k). ~~Related with that~~ Consistently, the mass absorption efficiency strongly increases from ~ 0.145 0.141 to ~ 0.191 0.182 m²g⁻¹.

Although the average of the ~~entire full~~ measurement period exhibits a clear ~~optical dust~~ dust optical signature, the overall values are influenced by ~~those observed during Period C, highlighting that even in Period C~~. This highlights that, even at remote and relatively isolated dust-source locations, regional and local anthropogenic pollution can impact dust measurements.

The last row of Fig. 3 illustrates the temporal evolution of the conditionally estimated imaginary part of the complex refractive index (k) at ~~525~~ 520 nm for different shape assumptions: spheres (solid line), triaxial ellipsoids (dashed line), and the full range of values considered in Sect. 2.6. During dust events, k remains relatively stable, ~~while~~. In contrast, Period C and the calm wind phases of Periods A and B exhibit increases of up to an order of magnitude, highlighting ~~a the~~ stronger influence of absorbing anthropogenic particles during these periods. These k estimates are used here diagnostically to interpret the temporal variability of the optical measurements; the dust-event retrievals and their sensitivity to particle shape, density, and n are analysed in detail in Sect. 2.6.

3.2 Optical properties and their relationship with effective radius

At this measurement site, mineral dust fluxes, wind friction velocity, and particle size are closely interrelated (González-Flórez et al., 2023). In this section, we examine the dependence of the observed optical properties on the effective radius (R_{eff} , cf. Section 2.3). ~~It is important to note that the~~ The campaign consisted of two distinct measurement periods with different inlet cut-offs (PM_{2.5} and PM₁₀), which strongly influence R_{eff} ~~due to the dominance of coarse particles because coarse particles dominate the mass~~ during dust emission events.

Figure 4 ~~features shows~~ the absorption (b_{abs}) and scattering (b_{scat}) coefficients, and SSA as a function of R_{eff} . The upper panels correspond to the PM_{2.5} period, while the lower panels represent the PM₁₀ period. The average absorption Ångström exponent (~~AAE~~), AAE, for each R_{eff} bin is also indicated in Figs. 4a,d. For the PM_{2.5} period, b_{abs} exhibits a non-monotonic

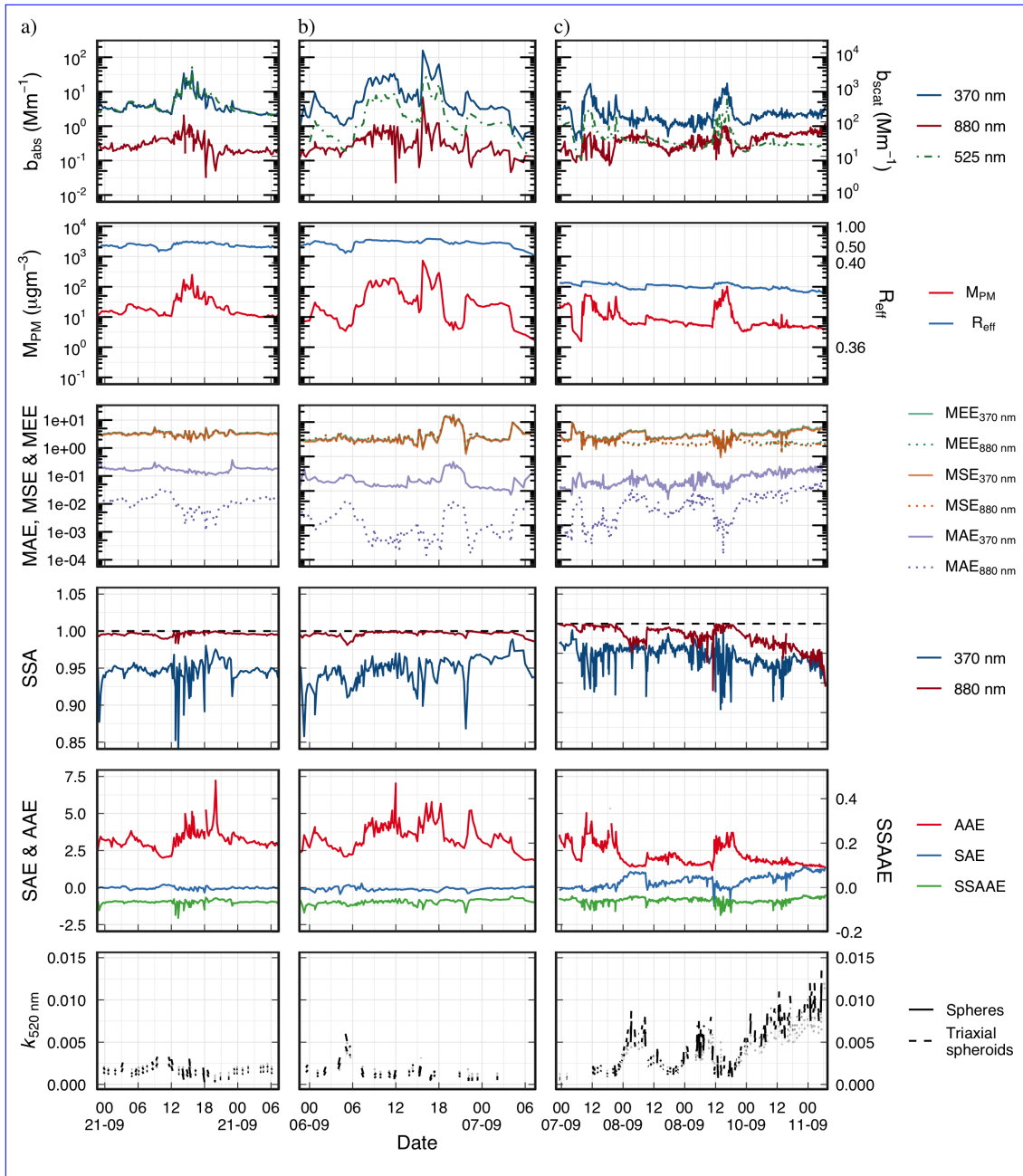


Figure 3. Time evolution of key optical and physical properties during the highlighted measurement periods: a) Period A (midnight 21st to morning 22nd September 2019), b) Period B (midnight 6th to morning 7th September 2019), and c) Period C (midnight 7th to noon 11th September 2019). Each row represents the time series of: absorption (b_{abs}) and scattering (b_{scat}) coefficients at 370 and 880 nm; mass concentration (M_{PM}) and effective radius (R_{eff}); mass absorption, scattering, and extinction efficiency (MAE, MSE, MEE) at 370 and 880 nm; single scattering albedo (SSA) at 370 and 880 nm; absorption, scattering, and SSA Ångström exponents (AAE, SAE, SSAE); and the estimated imaginary part of the refractive index (k) at 525 nm for spheres (solid line), triaxial ellipsoids (dashed line), and a range of values for other shape assumptions described in Sect. 2.6

625 U-shaped dependence on R_{eff} , initially decreasing until the 0.4–0.5 μm bin ~~before increasing again at and then increasing again~~ for larger sizes. In contrast, b_{scat} increases consistently for $R_{\text{eff}} > 0.4 \mu\text{m}$. The SSA also shows a clear dependence on R_{eff} , with distinct spectral ~~variations behaviour~~ between the PM2.5 and PM10 periods.

The observed U-shaped ~~trend dependence~~ in b_{abs} ~~reflects different source contributions during the campaign: smaller during~~ the PM2.5 period ~~reflects the varying contribution of different aerosol sources. The smallest~~ R_{eff} values ~~(AAE, associated with~~ AAE values close to ~ 1) ~~, correspond to periods influenced by transported fine carbonaceous particles, while larger. Larger~~ R_{eff} values are associated with local and nearby dust emissions. At ~~smaller-small~~ R_{eff} , b_{abs} decreases ~~due to increasing SSA~~ as SSA increases, despite similar b_{scat} values across the first three size bins. For larger R_{eff} , SSA stabilizes ~~, and and both~~ b_{scat} and b_{abs} increase with dust abundance. The spectral dependence of SSA during the PM2.5 period ~~aligns with a mix of~~ is therefore consistent with a transition from conditions influenced by fine carbonaceous aerosols ~~and coarser dust particles to~~ conditions dominated by coarser mineral dust. The PM10 period exhibits optical ~~behavior behaviour~~ consistent with the larger R_{eff} bins of the PM2.5 period, ~~reflecting the stronger influence of coarse dust when the broader inlet cut-off is used.~~

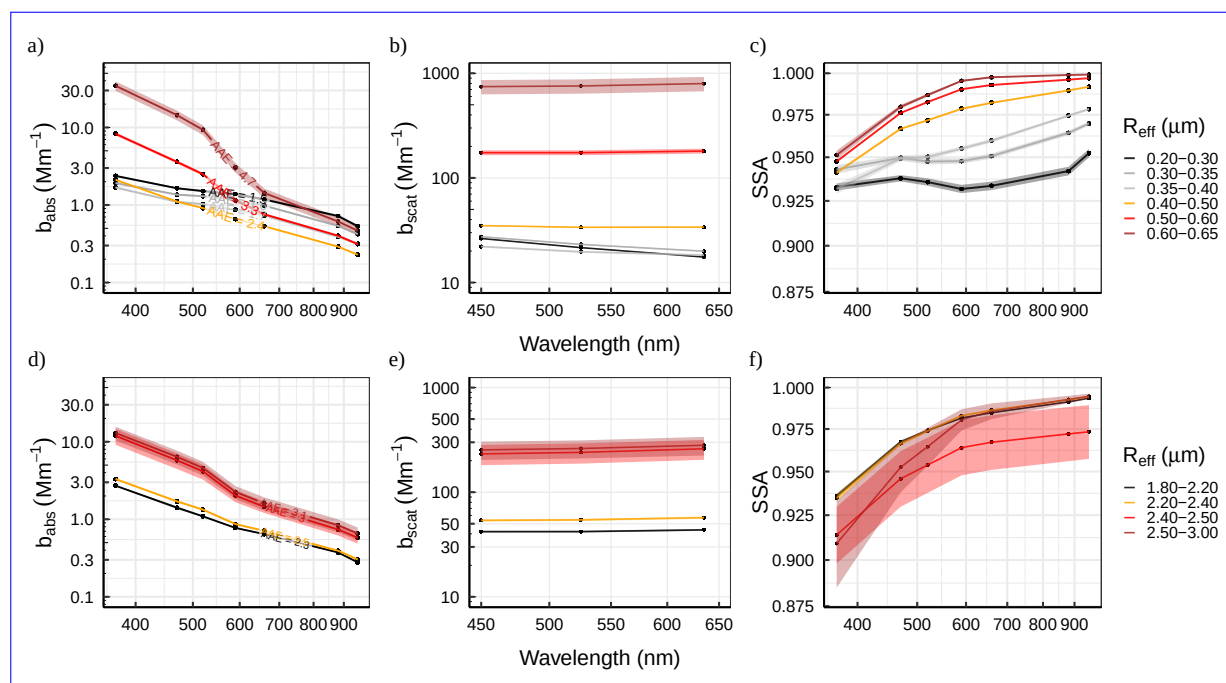


Figure 4. Mean and standard error (se) values of the absorption (a,d) and scattering (b,e) coefficients, and the single scattering albedo (SSA; c,f) as a function of wavelength (x-axis) and effective radius (colour scale) at M’Hammid for both PM2.5 (upper panel) and PM10 (lower panel) periods. The log-log plot highlights the enhanced absorption efficiency of dust at short-UV wavelengths, where absorption increases more significantly compared to longer wavelengths. In contrast, BC-influenced particles typically exhibit a nearly linear spectral dependence. The absorption Ångström exponent (AAE) values are indicated along each absorption coefficient curve: from between 1.5 and 1.7 for $u_* < 0.40$ up to 4.7 for the highest u_* ’s for PM2.5, and with a range between 2.3 and 3.1 for PM10.

The spectral dependence of b_{abs} , b_{scat} , and SSA is further examined through their respective Ångström exponents (Fig. 5). The AAE increases with effective radius, particularly ~~in~~ during the PM2.5 period for R_{eff} values above 0.45 μm , where it rises from approximately 1.2 to 2.5. This trend is consistent with increasing friction velocity (u_*), indicating stronger local
640 dust emissions. ~~Indeed, Fig. Fig. S7 shows that the~~ further shows that, during the PM2.5 period, the increase in R_{eff} during the PM2.5 period with wind the with wind friction velocity is also associated to higher AAE measurements values. In contrast, during the PM10 period, the AAE exhibits a more gradual and steady increase with R_{eff} and u_* .

Figure 5 also shows a strong relationship between SAE and effective radius. During the PM2.5 period, SAE decreases significantly markedly, from around 1 to values near or below 0, as R_{eff} increases. During the PM10 period, the high concentration of coarse particles results in SAE remaining keeps SAE consistently low, generally below 0. A negative SSAAE Negative SSAAE values has been recognized as a key indicator of Saharan dust events over Europe (Collaud Coen et al., 2004), and this criterion is met for R_{eff} values above 0.3 μm during the PM2.5 period and throughout the entire PM10 period.

Overall, these results indicate that during the PM2.5 period, where fine particles were sampled, the influence of dust particles on optical properties was only prominent when the optical instruments sampled a narrower size range, the dust optical signature
650 became prominent mainly under strong emission conditions. In contrast, during the PM10 period, the presence inclusion of coarser particles led to produced a consistently stronger dust optical signature, significantly shaping the spectral behavior behaviour of b_{abs} , b_{scat} , and SSA.

Additionally, we computed two key parameters related to the scattering phase function of the particles: the backscatter fraction (BF) and the asymmetry parameter (g). As shown in Fig. 6, forward scattering (indicated by higher values of g and lower values of BF) increases with particle effective radius (R_{eff}), as indicated by increasing g and decreasing BF. The spectral dependency dependence of these parameters also shifts as particles become coarser, with the slope of BF transitioning from negative to positive and that of g from positive to negative. This trend indicates that finer particles exhibit stronger backscattering at shorter wavelengths, while coarser particles favour forward scattering. During the PM2.5 period, for $R_{\text{eff}} > 0.4 \mu\text{m}$, the BF (g) decreases (increases) with the wavelength from ~ 0.1 (0.68) at the short-UV to $\sim_{\text{eff}} > 0.4 \mu\text{m}$, BF decreases from approximately
660 0.10 at the shortest nephelometer wavelength to approximately 0.09 (0.7) at the near-infrared at the longest wavelength, while g increases from approximately 0.68 to 0.70. During the PM10 period, these spectral variations are less pronounced, with BF values ranging between 0.12 and 0.16 and g values between 0.6 and 0.64. These values align with previously reported BF and asymmetry parameters. Horvath et al. (2018) found for Saharan mineral dust advected to the Western Mediterranean a g ranging from are consistent with previous measurements of Saharan dust. Horvath et al. (2018) reported (g) values from about 0.75 to 0.65 and a BF ranging from BF values from about 0.07 to 0.12, respectively, which matches the results found here in the source area, specially in the case of PM2.5. Similarly, Ryder et al. (2018) found a g of 0.74 for for Saharan dust advected to the western Mediterranean, while Ryder et al. (2018) reported ($g \approx 0.74$) from airborne measurements within the Saharan Aerosol Layer over the Atlantic.

As shown in Figure 7, regardless of Figure 7 shows the mass absorption, scattering, and extinction efficiencies as a function
670 of wavelength and R_{eff} . Regardless of the inlet cut-off period (PM2.5 or PM10), MAE consistently decreases as particle size increases. For During the PM2.5 period (noting the logarithmic y-axis), MAE values drop by approximately an 1 order of

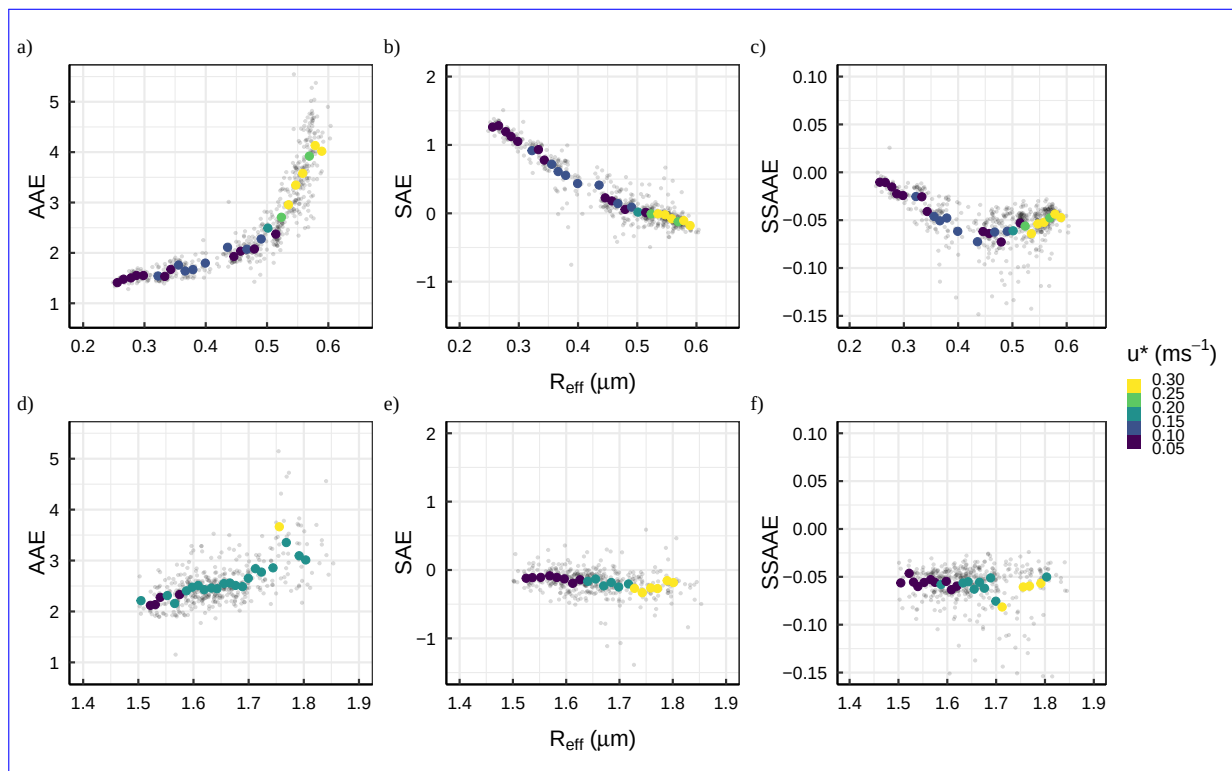


Figure 5. Scatter plot of the Absorption Ångström Exponent, AAE (a,d), the Scattering Ångström Exponent, SAE (b,e), and the single-scattering albedo Ångström exponent (SSAAE) as a function of the particle effective radius (R_{eff}) —x-axis— at M’Hammid for both PM2.5 (upper panel) and PM10 (lower panel) periods. The colour scale indicates the average friction velocity, u_* , for each R_{eff} bin, with this averaging resulting in the smaller range of u_* values. Bins were determined using the Freedman-Diaconis rule (Freedman and Diaconis, 1981) to ensure an optimal balance between resolution and statistical robustness.

magnitude, from ~ 0.30 to $0.15 \text{ m}^2\text{g}^{-1}$ at short-UV wavelengths and from ~ 0.12 to $0.02 \text{ m}^2\text{g}^{-1}$ at near-infrared wavelengths. This decrease reflects the lower absorption per unit mass of larger mineral dust particles compared with smaller particles, which include a greater relative contribution from fine absorbing aerosols during some periods.

675 ~~Conversely, the scattering, and consequently the extinction efficiency, presented a different pattern~~ The scattering and extinction efficiencies show a different behaviour across the two inlet ~~cut-offs~~ cut-off periods. During the PM2.5 period, MSE decreases with wavelength for particles with R_{eff} below $0.4 \mu\text{m}$, consistent with the stronger scattering efficiency of fine particles at shorter wavelengths (Hansen and Travis, 1974). For coarser particles within the PM2.5, MSE remains ~~similar~~. In more similar across wavelengths. During the PM10 period, MSE declines significantly, both compared to the PM2.5 period
680 and as R_{eff} increases. This ~~trend~~ behaviour reflects the shifting peak scattering efficiency toward longer wavelengths, beyond the measurement range of this study (Hansen and Travis, 1974). The ~~cumulative effect of high~~ combined effects of absorption and scattering efficiencies ~~, particularly for smaller particles likely dominated by fine carbonaceous aerosols, is~~ are captured

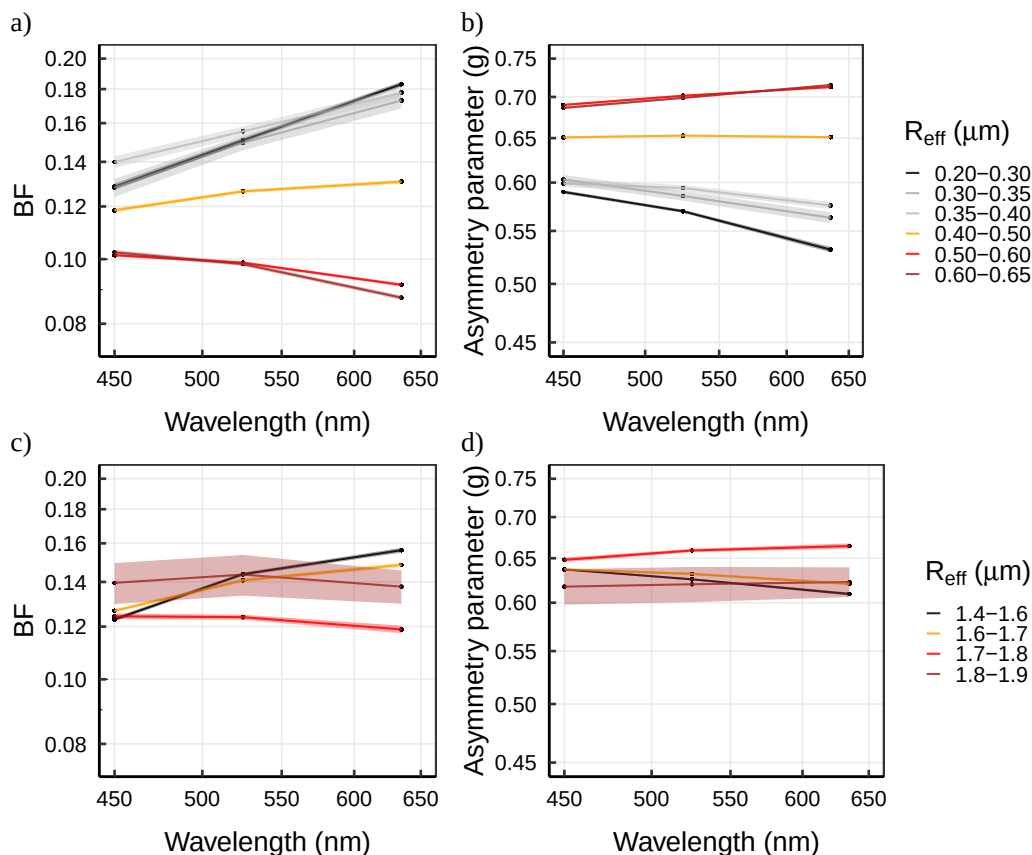


Figure 6. Mean (lines) and standard error (se, shaded colours) values of the backscatter fraction, BF (a,c) and the asymmetry parameter (b,d) as a function of the wavelength (x-axis in logarithmic scale) and the effective radius (colour scale) at M’Hammid for both PM2.5 (upper panel) and PM10 (lower panel) periods.

in the MEE trends-trend (Figs. 7c,d). These trends-f), which highlight the distinct optical behaviours-behaviour of different aerosol sources, with fine particles-exhibiting-regimes: fine particles exhibit higher MAE and MSE, while-whereas coarser dust particles contributing-contribute more strongly to total scattering.

3.3 Imaginary part of the refractive index of mineral dust

This section presents the retrieval of the imaginary part of the complex refractive index(k), for mineral dust, following the methodology described in Sect. 2.6. The analysis focuses exclusively on periods classified as dust events (see Sect. 3.1) during the PM2.5 measurement period. For-each-of-the-15-minute-averaged-measurements, the value-As discussed in Sect. 2.6, the retrieved values should be interpreted as conditional estimates of k was-retrieved (see for example the last row of Fig. 3), these

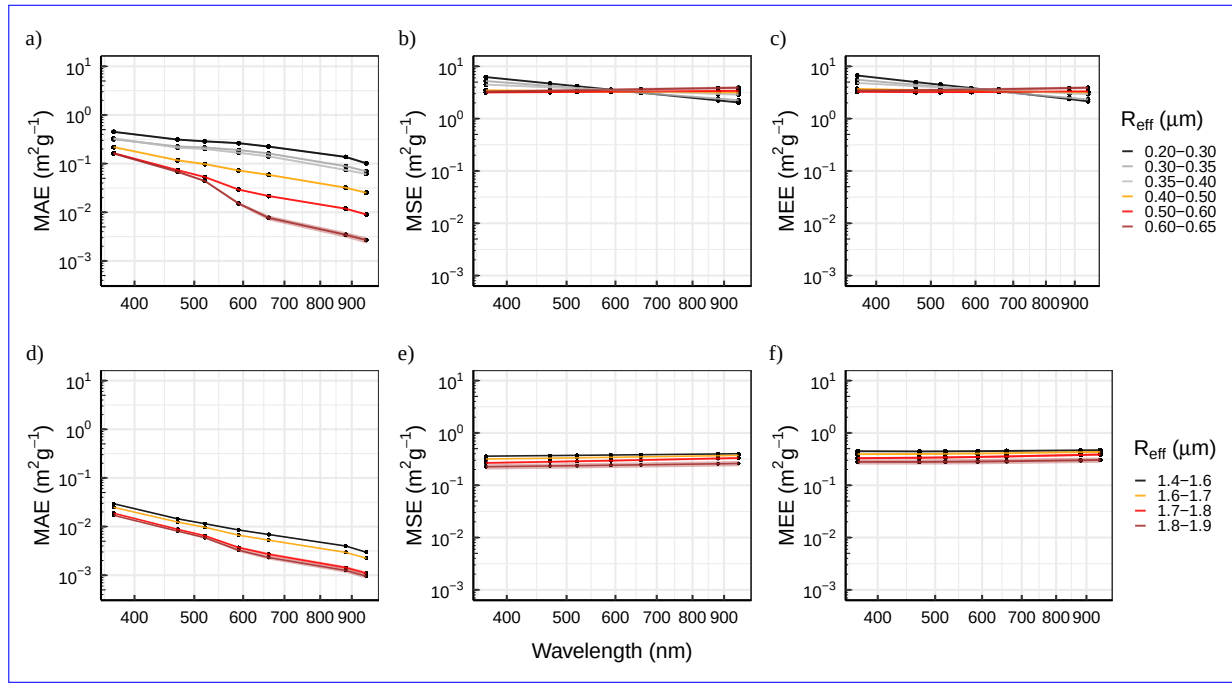


Figure 7. Mean and standard error (se) values of the mass absorption, MAE (a,d), scattering, MSE (b,e), and extinction, ~~MSE-MEE~~ (c,f) efficiency as a function of the wavelength (x-axis in logarithmic scale) and the effective radius (colour scale) at M'Hammid for both PM2.5 (upper panel) and PM10 (lower panel) periods.

under prescribed assumptions for particle shape, particle density, the real part of the refractive index, and the AE33 absorption correction.

Two complementary retrieval averages are reported. First, ~~k s~~ were retrieved independently for each 15 min dust-event interval. The temporal average of these retrievals is referred to as the average (of k) of the retrievals. Complementarily Second, ~~k retrievals over the measurements flagged as dust events in Sect. 3.1 were also computed by taking as input the time averaged measurements of~~ was retrieved from the time-averaged dust-event measurements of truncated scattering, absorption and PSD, which lead to a set of single estimates of k , which we refer to through the text, and PSD. This single estimate is referred to as the retrieval (of k) of the average. The first approach gives equal weight to each dust-event interval, whereas the second gives greater influence to periods with larger dust loading and more representative mean optical properties.

Fig. 8 summarizes the ~~results, illustrating retrieved k values.~~ Panel (a) shows the spectral dependence of ~~k under different particle shape assumptions (Fig. 8a).~~ (k) for different particle-shape assumptions using the central values ($n=1.49$, $\rho_p=2.15 \text{ g cm}^{-3}$), and the central AE33 correction. The particle-shape assumptions include spheres (Sph), biaxial spheroids using the aspect-ratio distribution measured during the campaign by Panta et al. (2023) (Bi dist; including oblate and prolate spheroids), biaxial spheroids using the Dubovik et al. (2006) aspect-ratio distribution (Dub-06), triaxial ellipsoids with aspect ratio 1.46 and

705 height-to-width ratio 0.45 (Tri), and the six irregular shapes A–F from Gasteiger et al. (2011). The values reported for the Moroccan sample by Di Biagio et al. (2019) are also shown for comparison.

~~Panels b-d show the variability in k due to different values of the real part of the refractive index (n) of Fig. 8~~ of Fig. 8 show the distributions of 15 min retrievals for spheres, biaxial spheroids, and triaxial ellipsoids. Each distribution includes the variability arising from the range of prescribed (n) values, from 1.48 to 1.55 in steps of 0.01 increments of 0.005, and the three inlet-out-off diameter efficiencies (1.7 and $1.7 \pm 10\%$) for spheres, biaxial ellipsoids and triaxial ellipsoids. For comparison, particle-density assumptions, ($\rho_p = 1.8, 2.15$, and 2.5 g cm^{-3}). The red symbols indicate the retrieval of the average for the central value of (C), while the error bars show the variability introduced by the lower and upper (C) values derived from the 95 % confidence interval of Yus-Díez et al. (2025). The corresponding results for the Moroccan sample from Di Biagio et al. (2019) (dB19) are also included individual irregular shapes are provided in the Supplement.

715 ~~All panels Across the five shortest AE33 wavelengths, all shape assumptions show an overall decrease of in k with increasing wavelength across the five shortest, consistent with stronger absorption by iron-bearing minerals at shorter wavelengths. The dB19 values of for the Moroccan sample fall within the range of our retrievals, except at 950 nm, where their retrieved k in Fig.8a are similar to our retrievals at shorter wavelengths but fall toward the lower end of our k estimates at longer wavelengths increases against the general decreasing trend. The slope of the dB19 k curve in the shorter wavelengths is steeper spectrum is somewhat steeper at shorter wavelengths than in our retrievals. Additionally, our retrievals assuming spherical particles are consistently lower than the dB19 values.~~

~~Although Di Biagio et al. (2019) also assumes spherical particles, several~~ Several factors may explain the discrepancies between their results and ours differences between our estimates and those of Di Biagio et al. (2019). First, the samples are not identical; while both originate from nearby regions on a global scale, the dust in our field campaign may not be directly comparable to the resuspended dust used in dB19 and measurement conditions differ: Di Biagio et al. (2019) analysed resuspended dust under controlled chamber conditions, whereas our retrievals are based on ambient, freshly emitted dust measured in the field. Second, we employed a the sampled size ranges differ. Our retrieval is based on the PM2.5 inlet period, whereas Di Biagio et al. (2019) used a PM10 inlet measurements. This difference can influence the retrievals if the composition and shape of the particles changes vary with size (Panta et al., 2023) retrieval if particle composition, shape, or density varies with size, even though the retrievals assume our inversion assumes size-independent k . Third, different inlets for measuring the in our field setup, the Fidas PSD and the optical properties, which introduced additional uncertainties in our retrievals (see Table 2), likely more strongly affecting the longer wavelengths. Another contributing factor is the potential influence of anthropogenic aerosols in our samples (Sect. 3.1), which may enhance overall absorption and lead to higher k values. While this effect is important when the average of k is used as comparison, it is less relevant when k is computed from the averaged measurements (Fig. S8) measurements were obtained through different sampling lines, which introduces additional uncertainty in the absolute PSD-optical closure. Finally, our retrieval procedure includes consistent corrections to the Fidas PSD for particle shape and refractive index, which is not the case in dB19, although the impact of this difference may be relatively small procedure applies a consistent Fidas optical-to-geometric diameter conversion for each prescribed particle shape and refractive index

740 assumption, whereas Di Biagio et al. (2019) used a prescribed refractive-index range for the OPC conversion. The OSSE tests in the Supplement indicate that this latter difference has a relatively small effect when the assumed particle shape is consistent.

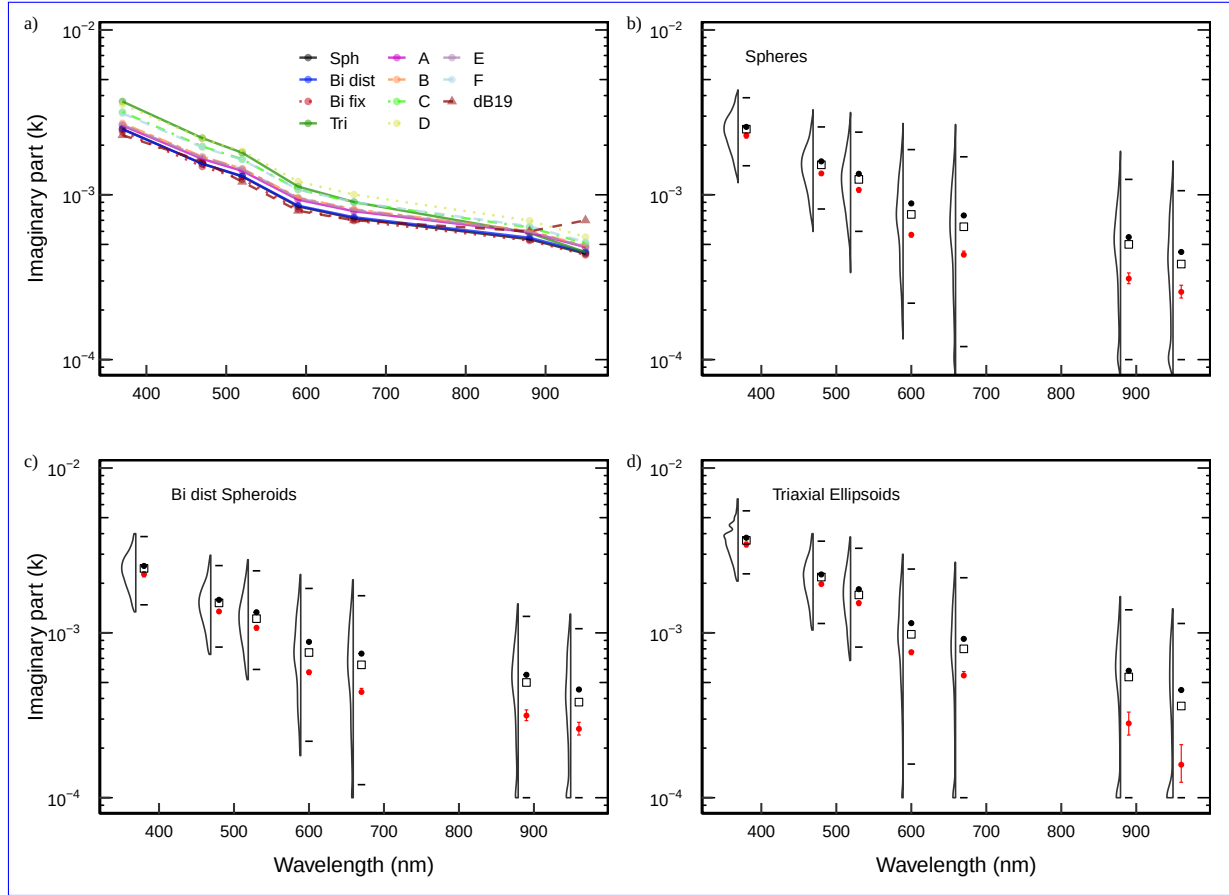


Figure 8. Imaginary part of the complex refractive index (k) as a function of wavelength. (a) Coloured lines indicate the average of the k retrieved for each timestamp for which there was dust emission under different shape assumptions, spheres, bi-axial, tri-axial and irregular shapes –A to F from Gasteiger and Wiegner (2018)– using the best-estimate real refractive index (1.49) and an inlet cut-off particle density of $1.70\text{--}2.15\text{ g}\cdot\text{cm}^{-3}$, as well as the k from Di Biagio et al. (2019) for the Morocco sample as dB19; (b–d) Distributions of k for spheres (b), biaxial ellipsoids (c), and triaxial ellipsoids (d) during dust events, showing the mean (dot), median (square), mean of the retrievals of the average (red triangle), and 5th to 95th percentiles (flat segments). The red dots in (b–d) represent the mean of the retrievals of the average for the C values obtained in Yus-Díez et al. (2025) with the error bar showcasing the variability introduced by using an upper/lower C based on its CI. Each distribution reflects the range of retrievals for various real refractive index values and inlet cut-off particle density assumptions, highlighting the sensitivity of k to shape and measurement parameters.

Panels b,c and d of FigA notable difference is observed between the average of the retrievals and the retrieval of the average in panels b-d of Fig. 8. 8feature the distribution of 15-min k retrievals for three particle shape assumptions. In each case, the average of these retrievals (indicated by dots) is consistently equal to or higher. The average of the 15 min retrievals

is generally larger than the k value derived from the averaged optical measurements (indicated by triangles), obtained from the time-averaged dust-event measurements, especially at longer wavelengths. This behaviour is also evident in Fig. S8. We attribute this systematic difference to the over-representation of absorbing aerosols other than dust (cf. Sect. 3.1) in the time-averaged data. This occurs because periods with low dust concentrations — potentially richer in more absorbing particles — are weighted equally with disproportionate influence of short periods with lower dust concentration and stronger relative contribution from absorbing non-dust aerosols. When each 15 min interval is weighted equally, these periods can raise the average retrieved k . In contrast, the retrieval of the average is more strongly influenced by high-dust events in the averaging process periods, such as the haboob event, which exhibit higher SSA in the near-infrared and infrared and are more representative of mineral dust optical properties.

The violin plots in Fig. 8 illustrate the spread sensitivity of k values obtained under eight different assumptions for the real part of the refractive index (n), across three simulated cut-off of the inlet. The contributions of cut-off diameter to particle density, ρ_p , and n to the variability in k are further detailed in Figure S9 shows the violin plots also for irregular shapes A-F from Gasteiger et al. (2011). Tables 2 and 3 provide the corresponding numerical values. Table 2 shows the time-average estimate of k presents time-averaged k values at selected wavelengths for the three cut-off diameters ρ_p , averaged over all n values. On the other hand, Table 3 reports k estimates as a function of n , averaged over the different inlet cut-off values dust particle density assumptions. Both tables include results for a subset of particle shapes; the complete wavelength range is available in Tables S1–S4S10.

The results in Table 2 reveal a strong dependence of show a clear dependence of retrieved k on the assumed inlet cut-off diameter. Specifically, retrievals yield lower particle density. Lower particle densities lead to lower retrieved k values when larger particles are included, and higher values when the cut-off diameter is reduced. This dependency is asymmetric: increasing the cut-off diameter by 10% results in a decrease in k of approximately 6–15%, whereas decreasing it by 10% leads to an increase of about 9–19% relative to the 1.7 baseline, whereas higher particle densities lead to higher retrieved k . This sensitivity arises because particle density affects the aerodynamic-to-geometric conversion used to map the PM_{2.5} inlet efficiency onto the dust geometric PSD. As a result, the effective size distribution used in the optical simulations changes with the prescribed density.

A similar, though weaker, sensitivity is observed for the assumed value of n . The sensitivity to the assumed n is weaker. Table 3 shows that k decreases slightly with increasing n , with maximum k values occurring at the lower end of the n range. For example, varying n from 1.48 to 1.55 (a 5% range around a central estimate of 1.49) causes changes in k on the order of 0.0002 at 370 nm for irregular particles. Extrapolating this to a 10% change in n suggests a maximum sensitivity of around 14%, which — although modest — is comparable to the sensitivity to inlet cut-off diameter. However, a 10% uncertainty in n is unrealistic, as reported values for mineral dust typically fall within a much narrower range; for instance, Di Biagio et al. (2019) reports values between 1.48 are typically confined to a narrower range than would be required to produce large changes in k . This supports the use of fixed, plausible n values rather than attempting a simultaneous retrieval of n and k , a variation of less than 5% from the lower bound k from the present field dataset.

The third factor explored in Tables 2 and 3 is particle shape. ~~The variability in Particle-shape assumptions exert a substantial influence on the retrieved k due to shape assumptions is larger than that from either. For a given wavelength and set of ρ_p and n or inlet cut-off diameter. Depending on wavelength and configuration, differences between particle shapes can account for 20–54% variation in the median k value.~~

Imaginary part of the complex refractive index (k) retrieved for the same shape assumptions as in Fig. 8 as a function of the asphericity of the particles as defined by Gasteiger et al. (2011), ξ_{vc} for three wavelengths (370, 520 and 880 nm) for the retrieval of k for the averaged optical values (triangles) and for the temporal average of the retrievals filtered for dust events (points).

Spheres and biaxial ellipsoids show similar k estimates, whereas triaxial ellipsoids and shapes C, D, and F produce significantly higher values (Fig. 8a assumptions, non-spherical particles generally require larger k values than spheres to reproduce the observed ($tssa$)). This outcome is consistent with the findings of Kong et al. (2024), who demonstrated through numerical experiments that greater particle non-sphericity leads to higher k is particularly evident for triaxial ellipsoids and for the more elongated or irregular MOPSMAP shapes. To quantify the relationship between particle morphology and retrieved k values. To verify this in our study, we used, we use the ratio of volume-equivalent to cross-section equivalent particle radii (cross-section-equivalent particle radii, ξ_{vc}), from Gasteiger et al. (2011). Lower ξ_{vc} values indicate more non-spherical particles. Shapes C, D, and F and triaxial ellipsoids feature, as well as the triaxial ellipsoids, have lower ξ_{vc} values (0.911, 0.871, 0.866 than spheres, biaxial spheroids, and 0.907, respectively) than irregular shapes A, B and E, biaxial ellipsoids and their distribution (0.955, 0.932, 0.925, 0.983 and 0.988, respectively), confirming that more elongated or irregular particles tend to produce higher some of the less elongated irregular shapes, and they yield higher retrieved k retrievals than spherical particles.

As a results, This outcome is consistent with the findings of Kong et al. (2024), who demonstrated through numerical experiments that greater particle non-sphericity leads to higher retrieved k estimated retrieved using triaxial ellipsoids can be up to 60% higher than those from spherical assumptions at shorter wavelengths, and around 30% higher at longer wavelengths. values.

This relationship is further illustrated in Fig. 9, which shows the correlation between retrieved k values and particle shape, as quantified by as a function of ξ_{vc} . A relatively linear trend is observed across all three panels, near linear tendency is observed (with increasing k values corresponding to more non-spherical particles (corresponding to decreasing ξ_{vc}), i.e. ; lower ξ_{vc}) to more non-spherical particles. The slope of the linear fit between ξ_{vc} and k becomes less negative as the wavelength increases this relationship becomes weaker at longer wavelengths. While this relationship appears consistent, it is based on a limited number of data points, and any extrapolation should therefore be treated with caution. Nonetheless, establishing a robust connection between particle non-sphericity and retrieved k could provide a valuable tool for reinterpreting past measurements and datasets—many of which rely on spherical particle assumptions—within the context of more realistic, non-spherical dust models (e.g. Saito et al., 2021). For the central assumptions, k retrieved using triaxial ellipsoids can be substantially higher than that retrieved using spherical particles, with the largest relative differences occurring at shorter wavelengths, up to 46 %, and smaller differences at longer wavelengths, up to 10%.

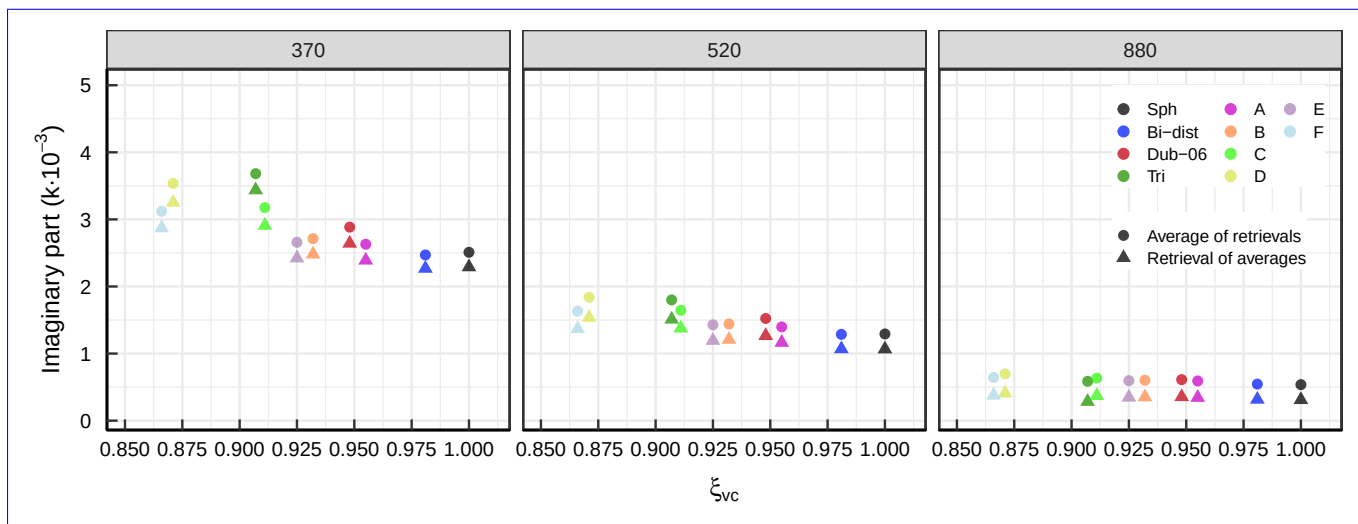


Figure 9. Imaginary part of the complex refractive index (k) retrieved for the same shape assumptions as in Fig. 8 as a function of the asphericity of the particles as defined by Gasteiger and Wiegner (2018), ξ_{vc} for three wavelengths (370, 520 and 880 nm) for the retrieval of k for the averaged optical values (triangles) and for the temporal average of the retrievals filtered for dust events (points).

This apparent relationship between non-sphericity and retrieved k should be interpreted with caution because it is based on a limited set of prescribed shape assumptions. The single irregular shapes are sensitivity cases rather than realistic descriptions of the full atmospheric dust population. Nevertheless, the result demonstrates that particle-shape representation can substantially affect retrieved k . Establishing a more robust link between particle morphology and retrieved absorption properties could help reinterpret past datasets that relied on spherical assumptions and improve the treatment of non-spherical dust in remote-sensing retrievals and climate-model optical-property parametrizations.

3.3.1 Comparison with dust-dominated AERONET retrievals

Figure 10 shows the comparison of our in-situ k estimates, extrapolated to the AERONET wavelengths of 440, 550, 675, 870, and 1020 nm, with dust-filtered AERONET retrievals compiled over two decades from various-several mid-latitude dust emission regions. These include Ouarzazate (OUARZ), western and eastern North Africa (WNAFR, ENAFR), the Sahel (SAHEL), the Arabian Peninsula (ARPEN), central Asia (CASIA), and India (INDIA). Our The selected AERONET stations are shown in Fig. S10a. Our in-situ retrievals are shown for three-four particle shape assumptions: spheres, biaxial ellipsoids, with aspect ratios from Dubovik et al. (2006), biaxial ellipsoids with aspect ratios from Panta et al. (2023), and triaxial ellipsoids. The comparison with the Dubovik et al. (2006) spheroid distribution is included to provide a shape assumption more consistent with AERONET-type retrievals, while the other shape assumptions illustrate the sensitivity of the in-situ k estimates to particle morphology.

Table 2. Imaginary part of the complex refractive index k for periods characterized as *dust events* throughout the PM2.5 part of the campaign. The retrieval of the averaged optical measurements is shown in bold, while the 5th percentile, the mean, and the 95th percentile of the distribution from the 15-min retrievals are shown within the parenthesis. All retrievals in this table were computed under the assumption of $n = 1.49$ and they are shown multiplied by 10^3 for clarity. They have been obtained for different shapes: spheres, [distribution-distributions](#) of biaxial ellipsoids, [spheroid shape distribution from Dubovik et al. \(2006\)](#), the [triaxial ellipsoid shape](#), and the average of the A to F irregular shapes from [Gasteiger and Wiegner \(2018\)](#), and the [triaxial ellipsoid shape](#) [Gasteiger et al. \(2011\)](#); for 3 wavelengths ranging between the near-UV to the near-infrared and 3 different [inlet efficiency cut-off assumptions](#) mineral dust particle density (ρ_p in $\text{g} \cdot \text{cm}^{-3}$).

Shape	λ (nm)	$\rho_p = 1.53\text{--}1.8$	$\rho_p = 1.70\text{--}2.15$	$\rho_p = 1.87\text{--}2.5$
Spheres	370-370.00	2.11.99 (1.6-2.4-3.71.34-2.30-3.47)	1.82.22 (1.3-2.1-3.01.48-2.57-3.88)	1.62.44 (1.2-1.9-2.71.63-2.82-4.25)
	520-520.00	1.20.93 (0.9-1.4-2.30.54-1.19-2.12)	1.11.04 (0.8-1.2-2.00.60-1.33-2.38)	0.91.15 (0.7-1.1-1.80.66-1.47-2.63)
	880-880.00	0.80.28 (0.5-1.0-1.80.10-0.50-1.12)	0.70.30 (0.5-0.9-1.60.10-0.55-1.24)	0.60.33 (0.4-0.8-1.40.10-0.60-1.34)
Biaxial dist	370-370.00	2.11.97 (1.5-2.5-3.41.34-2.27-3.39)	1.82.20 (1.4-2.1-3.11.48-2.54-3.80)	1.62.43 (1.2-1.9-2.91.62-2.79-4.00)
	520-520.00	1.20.93 (0.9-1.4-2.40.54-1.19-2.11)	1.11.04 (0.8-1.3-2.10.60-1.33-2.36)	1.01.15 (0.7-1.1-1.80.67-1.46-2.60)
	880-880.00	0.80.28 (0.5-1.0-1.80.10-0.51-1.14)	0.70.31 (0.5-0.9-1.60.10-0.56-1.24)	0.60.34 (0.4-0.8-1.50.10-0.60-1.34)
Dub-06	370.00	2.34 (1.58-2.68-4.00)	2.59 (1.74-2.97-4.50)	2.82 (1.90-3.25-5.00)
	520.00	1.11 (0.64-1.42-2.49)	1.24 (0.72-1.57-2.78)	1.35 (0.78-1.72-3.04)
	880.00	0.32 (0.10-0.57-1.28)	0.35 (0.10-0.62-1.38)	0.37 (0.10-0.66-1.47)
Triaxial	370-370.00	3.43.00 (2.6-3.7-5.82.06-3.38-5.00)	3.03.34 (2.2-3.4-4.62.28-3.76-5.50)	2.63.66 (2.0-3.0-4.12.50-4.12-6.50)
	520-520.00	1.81.28 (1.4-2.1-3.30.72-1.63-2.89)	1.61.45 (1.2-1.8-2.90.82-1.83-3.26)	1.41.61 (1.0-1.6-2.60.90-2.02-3.58)
	880-880.00	0.90.21 (0.6-1.2-2.10.10-0.53-1.26)	0.80.26 (0.6-1.1-1.90.10-0.59-1.38)	0.70.31 (0.5-1.0-1.70.10-0.64-1.50)
Irregular	370-370.00	2.72.27 (1.9-3.0-4.61.62-2.80-4.50)	2.42.49 (1.7-2.7-4.01.76-3.05-4.50)	2.12.72 (1.6-2.4-3.71.88-3.30-5.00)
	520-520.00	1.61.08 (1.1-1.8-3.00.66-1.46-2.60)	1.41.19 (1.0-1.6-2.70.72-1.60-2.86)	1.31.30 (0.9-1.5-2.40.78-1.74-3.10)
	880-880.00	0.90.31 (0.6-1.2-2.10.10-0.59-1.28)	0.80.34 (0.6-1.1-1.90.10-0.64-1.38)	0.80.36 (0.5-1.0-1.80.10-0.68-1.48)

heightheight

Table 3. Imaginary part of the complex refractive index k , with the same table structure as in Table 2 but fixing the best estimate of the [inlet efficiency cut-off](#) [particle density](#) to $\phi_{cut} = 1.70$ $\rho_p = 2.15 \text{ g} \cdot \text{cm}^{-3}$ and varying the n between 8 different values. Please note the in the table k is multiplied by 10^3 .

Shape	λ (nm)	$n=1.48$	$n=1.49$	$n=1.50$	$n=1.51$	$n=1.52$	$n=1.53$	$n=1.54$	$n=1.55$
Spheres	370-370.00	4.82.24 (1.3-3.4-4.01.54-2.59-3.99)	4.82.22 (1.3-3.4-4.01.57-2.61-3.84)	4.82.2 (1.3-3.4-4.01.44-2.51-3.83)	4.82.18 (1.3-3.4-4.01.5-2.51-3.85)	4.82.16 (1.3-3.4-4.01.52-2.53-3.72)	4.82.15 (1.3-3.4-4.01.4-2.44-3.72)	4.82.13 (1.3-3.4-4.01.45-2.45-3.73)	4.82.12 (1.3-3.4-4.01.48-2.46-3.6)
	520-520.00	1.1.85 (0.60-0.62-1.35-2.29)	1.04 (0.61-1.32-2.37)	1.03 (0.56-1.33-2.47)	1.01 (0.6-1.34-2.22)	1.11 (0.61-1.34-2.22)	1.00.99 (0.61-1.34-2.22)	1.00.98 (0.61-1.34-2.22)	1.00.97 (0.61-1.34-2.22)
	880.00	0.40.31 (0.2-0.4-0.40-1.0-0.55-1.27)	0.40.3 (0.2-0.4-0.40-1.0-0.55-1.24)	0.3 (0.1-0.55-1.14)	0.3 (0.1-0.54-1.24)	0.3 (0.1-0.54-1.24)	0.40.3 (0.2-0.4-0.40-1.0-0.55-1.27)	0.29 (0.1-0.52-1.24)	0.28 (0.1-0.52-1.17)
Biaxial dist	370-370.00	0.72.22 (0.5-0.9-1.61.56-2.57-3.76)	0.72.2 (0.5-0.9-1.61.56-2.57-3.76)	0.72.18 (0.5-0.9-1.61.42-2.48-3.74)	0.72.16 (0.5-0.9-1.61.48-2.48-3.76)	0.72.14 (0.5-0.9-1.61.51-2.49-3.64)	0.62.12 (0.4-0.6-1.41.39-2.43-63)	0.62.1 (0.4-0.6-1.41.42-2.43-63)	0.62.08 (0.4-0.6-1.41.46-2.43-53)
	520-520.00	1.41.85 (1.1-1.8-3.00.66-1.46-2.60)	1.41.81 (1.1-1.8-3.00.66-1.46-2.60)	1.41.83 (1.1-1.8-3.00.66-1.46-2.60)	1.41.81 (1.1-1.8-3.00.66-1.46-2.60)	1.41.81 (1.1-1.8-3.00.66-1.46-2.60)	1.40.99 (1.1-1.8-3.00.66-1.46-2.60)	1.40.98 (1.1-1.8-3.00.66-1.46-2.60)	1.40.97 (1.1-1.8-3.00.66-1.46-2.60)
	880-880.00	0.40.31 (0.2-0.4-0.40-1.0-0.56-1.28)	0.40.31 (0.2-0.4-0.40-1.0-0.56-1.24)	0.40.31 (0.2-0.4-0.40-1.0-0.55-1.15)	0.40.3 (0.2-0.4-0.40-1.0-0.55-1.24)	0.40.3 (0.2-0.4-0.40-1.0-0.55-1.22)	0.40.3 (0.2-0.4-0.40-1.0-0.55-1.22)	0.40.3 (0.2-0.4-0.40-1.0-0.55-1.22)	0.40.3 (0.2-0.4-0.40-1.0-0.55-1.24)
Dub-06	370-370.00	0.72.62 (0.5-0.9-1.61.82-3.4-5)	0.72.59 (0.5-0.9-1.61.82-3.02-4.5)	0.72.55 (0.5-0.9-1.61.66-2.89-4.5)	0.72.53 (0.5-0.9-1.61.76-2.89-4.5)	0.72.51 (0.5-0.9-1.61.76-2.91-4)	0.72.47 (0.5-0.9-1.61.81-2.84-27)	0.72.45 (0.5-0.9-1.61.7-2.8-4)	0.72.42 (0.5-0.9-1.61.7-2.8-4)
	520.00	1.25 (0.76-1.59-2.65)	1.24 (0.74-1.56-2.78)	1.23 (0.68-1.56-2.85)	1.21 (0.72-1.54-2.55)	1.19 (0.71-1.5-2.68)	1.17 (0.65-1.5-2.74)	1.17 (0.7-1.48-2.45)	1.15 (0.68-1.45-2.58)
	880.00	0.35 (0.1-0.62-1.42)	0.35 (0.1-0.62-1.38)	0.35 (0.1-0.62-1.28)	0.35 (0.1-0.61-1.4)	0.34 (0.1-0.61-1.36)	0.34 (0.1-0.61-1.26)	0.34 (0.1-0.61-1.38)	0.33 (0.1-0.6-1.34)
Triaxial	370-370.00	3.03.36 (2.2-3.4-4.62.28-3.76-5.50)	3.03.34 (2.2-3.4-4.62.28-3.76-5.50)	3.03.32 (2.2-3.4-4.62.28-3.76-5.50)	3.03.29 (2.2-3.4-4.62.28-3.76-5.50)	3.03.26 (2.2-3.4-4.62.28-3.76-5.50)	3.03.23 (2.2-3.4-4.62.28-3.76-5.50)	3.03.21 (2.2-3.4-4.62.28-3.76-5.50)	3.03.17 (2.2-3.4-4.62.28-3.76-5.50)
	520-520.00	1.61.46 (1.2-1.8-2.90.82-1.83-3.26)	1.61.45 (1.2-1.8-2.90.82-1.83-3.26)	1.61.45 (1.2-1.8-2.90.82-1.83-3.26)	1.61.42 (1.2-1.8-2.90.81-1.83-3.04)	1.61.42 (1.2-1.8-2.90.81-1.83-3.2)	1.61.41 (1.2-1.8-2.90.75-1.79-3.33)	1.61.4 (1.2-1.8-2.90.79-1.77-2.98)	1.61.39 (1.2-1.8-2.90.78-1.75-3.12)
	880-880.00	0.80.26 (0.6-1.1-1.90.10-0.59-1.37)	0.80.26 (0.6-1.1-1.90.10-0.59-1.37)	0.80.26 (0.6-1.1-1.90.10-0.59-1.37)	0.80.26 (0.6-1.1-1.90.10-0.59-1.37)	0.80.26 (0.6-1.1-1.90.10-0.59-1.37)	0.80.26 (0.6-1.1-1.90.10-0.59-1.37)	0.80.26 (0.6-1.1-1.90.10-0.59-1.37)	0.80.26 (0.6-1.1-1.90.10-0.59-1.37)
Irregular	370-370.00	2.42.52 (1.7-2.7-4.01.76-3.05-4.50)	2.42.49 (1.7-2.7-4.01.76-3.05-4.50)	2.42.47 (1.7-2.7-4.01.76-3.05-4.50)	2.42.44 (1.7-2.7-4.01.76-3.05-4.50)	2.42.42 (1.7-2.7-4.01.76-3.05-4.50)	2.42.37 (1.7-2.7-4.01.76-3.05-4.50)	2.42.37 (1.7-2.7-4.01.76-3.05-4.50)	2.42.34 (1.7-2.7-4.01.76-3.05-4.50)
	520-520.00	1.41.21 (1.0-1.6-2.70.72-1.60-2.86)	1.41.19 (1.0-1.6-2.70.72-1.60-2.86)	1.41.18 (1.0-1.6-2.70.72-1.60-2.86)	1.41.16 (1.0-1.6-2.70.72-1.60-2.86)	1.41.15 (1.0-1.6-2.70.72-1.60-2.86)	1.41.14 (1.0-1.6-2.70.72-1.60-2.86)	1.41.13 (1.0-1.6-2.70.72-1.60-2.86)	1.41.12 (1.0-1.6-2.70.72-1.60-2.86)
	880-880.00	0.80.34 (0.6-1.1-1.90.10-0.64-1.42)	0.80.34 (0.6-1.1-1.90.10-0.64-1.42)	0.80.34 (0.6-1.1-1.90.10-0.64-1.42)	0.80.33 (0.6-1.1-1.90.10-0.63-1.48)	0.80.33 (0.6-1.1-1.90.10-0.63-1.41)	0.80.33 (0.6-1.1-1.90.10-0.63-1.30)	0.80.33 (0.6-1.1-1.90.10-0.63-1.44)	0.80.33 (0.6-1.1-1.90.10-0.63-1.38)

Due to differences in spatio-temporal representativeness and observational context, a strict quantitative comparison between AERONET and in-situ k values is not appropriate. ~~Nevertheless, we observe~~ [AERONET retrievals are column-integrated](#)

and rely on inversion assumptions regarding particle size, shape, and refractive index, whereas our estimates are based on near-surface, source-region measurements during a specific field campaign and are restricted to the PM_{2.5} dust-event period. Differences in the vertical distribution of dust, the sampled size range, particle ageing, mineralogical composition, and possible aerosol mixing can all affect the comparison. The AERONET comparison is therefore used here to provide context rather than direct validation of the in-situ retrievals.

Despite these caveats, our retrievals show qualitative agreement with the AERONET retrievals from OUARZ, the nearest station, located approximately 200 km north of our closest AERONET station to the measurement site.

The strongest alignment occurs under the triaxial shape assumption, where median k values closely match those from AERONET. The strongest overlap occurs for the more non-spherical shape assumptions, for instance triaxial ellipsoids and the Dubovik et al. (2006) spheroid distribution. Median values are particularly close at 550 and 675 nm, and the full distribution shows substantial distributions show some overlap at longer wavelengths. At 440 nm, however, our in-situ estimates diverge more noticeably from the AERONET retrievals. When assuming spherical or biaxial shapes, our spherical particles are assumed, the retrieved k values are generally lower than both the triaxial-based non-spherical in-situ retrievals and the AERONET values from OUARZ, especially at shorter wavelengths (440–550 nm).

A key observation from feature of Fig. 10 is the pronounced regional variability in AERONET-derived k . While values retrieved at OUARZ closely align with our in-situ measurements, the median k increases progressively from western to eastern North Africa and further across the Sahel, reaching even higher values in central Asia and India. These differences are likely driven in part by regional variations in dust mineralogy, particularly differences in iron oxide content that influence absorption properties.

Part of this variability may also be affected by residual contamination from, but they may also reflect differences in PSD, dust ageing, retrieval assumptions, and residual contamination by non-dust aerosols in AERONET retrievals, despite the rigorous despite the filtering applied. Additionally, inherent uncertainties in AERONET retrievals contribute to these differences, including potential biases arising from its limited sensitivity to super-coarse dust particles, which could influence both the retrieved particle size distribution.

To further assess the role of particle size, we compared the Fidas-derived size distributions measured during the FRAGMENT-Morocco campaign with the dust-filtered AERONET volume size distribution at OUARZ over the 2000–2020 period. The Fidas distributions, shown in Figs. 6 and associated 7 of González-Flórez et al. (2023), represent near-surface in-situ measurements close to the dust source, whereas the AERONET distribution is column-integrated and retrieval-dependent (Fig. S10b). The comparison shows that the AERONET volume size distribution has a relatively larger contribution from smaller particles and a coarse-mode maximum around 3 μm , whereas the Fidas-derived mass distribution during the campaign peaks closer to 10 μm . This difference is important because particle size affects both the optical response and the retrieved refractive index.

The different size distributions suggest that part of the discrepancy between our in-situ k retrievals and AERONET-derived k may arise from PSD differences, not only from particle shape. In our PM_{2.5} retrieval, the size range includes most of the particles in number and is directly relevant for the AE33 absorption wavelengths used to retrieve k . In contrast, AERONET retrievals are sensitive to a column-integrated size distribution with a different fine-to-coarse partitioning. A larger relative

contribution of smaller particles in the AERONET retrieval could affect the inferred absorption properties and may contribute to the higher AERONET-derived k values. Moreover, assumptions regarding particle sphericity in AERONET inversions may also impact the accuracy of retrieved absorption properties Adebisi et al. (2023).

This interpretation is consistent with Adebisi et al. (2023), who emphasized that dust absorption estimates are sensitive to particle size distribution, particle shape, and refractive index. They also discussed potential limitations in AERONET dust retrievals over North Africa, including uncertainties in the representation of coarse and super-coarse dust and possible biases in retrieved refractive indices. Thus, differences between AERONET and in-situ estimates should not be attributed solely to particle-shape assumptions. They may also reflect differences in PSD, column versus surface sampling, retrieval assumptions, dust ageing, and mineralogy.

These results emphasize the critical need for importance of region-specific in-situ studies, such as the present work, to improve constraints on for constraining dust optical properties. Direct measurements of locally emitted dust provide information that is complementary to column-integrated remote-sensing retrievals and help refine our understanding of regional differences and provide essential data for improving global in dust absorption. Such measurements are essential for improving the representation of dust optical properties in remote-sensing algorithms and climate models, particularly in quantifying dust absorption and its role in the Earth's for quantifying the contribution of mineral dust absorption to the Earth's radiative budget.

4 Summary and conclusions

This study provides new high-resolution high-temporal-resolution, source-region in-situ measurements of mineral dust optical properties, with a specific focus on absorption, scattering, and their spectral dependencies dependence, and the conditional retrieval of the imaginary part of the complex refractive index, k . The measurements, conducted in a dust source of the Moroccan Sahara, offer crucial insights into the morphological and optical characteristics were conducted during the FRAGMENT-Morocco campaign in a Saharan dust source region, allowing the optical properties of freshly emitted dust and their implications for climate modeling and remote sensing retrievals to be characterized under natural emission conditions.

The campaign captured three distinct aerosol scenarios regimes: local dust emissions, haboob-driven dust events, and periods influenced by anthropogenic pollution advection mixed with minor dust emissions. Dust-dominated periods exhibited high SSA values, increasing from 0.955–0.952 at 370 nm to 0.985 at 550 nm to 0.993–0.995 at 880 nm for PM_{2.5} particles and from 0.945–0.948 at 370 nm to 0.974–0.986 at 550 nm to 0.985–0.996 at 880 nm for PM₁₀ particles. These values are broadly consistent with previous Saharan dust observations, while differences among studies reflect variations in size range, source region, mineralogy, atmospheric processing, and aerosol mixing state. Periods with anthropogenic influence showed lower SSA, particularly at near-infrared wavelengths and higher mass absorption efficiencies, suggesting the presence of fine carbonaceous aerosols.

SSA, scattering, and absorption coefficients were shown to be strongly dependent on the particle effective radius (R_{eff}). The AAE increased with R_{eff} , reaching values above 2 during intense dust events, indicative of enhanced short-wave absorption by

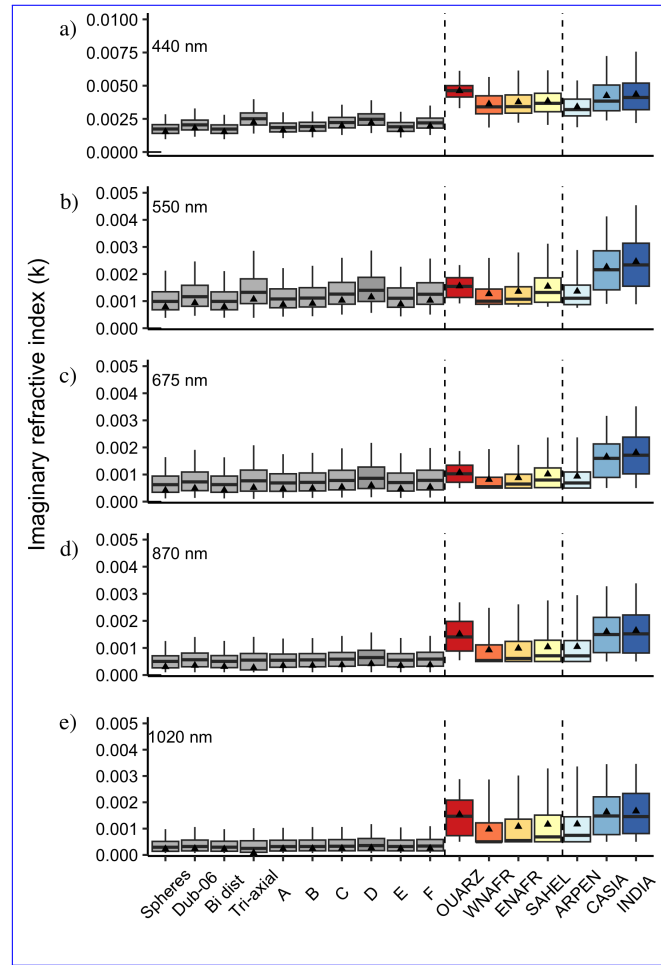


Figure 10. Box-plots of the imaginary part of the retrieved complex refractive index obtained, k , for the dust events as described in Sec. 2.6 for the assumption of the best estimates of n and inlet-cut-off particle density ρ_p of 2.15 g cm^{-3} , from Panta et al. (2023). Here we compare the k for: spheres, and Oblate-Prolate biaxial ellipsoid distributions, Dub-06 spheroids, and triaxial ellipsoids (in greyscale), and A-F irregular shapes from Gasteiger et al. (2011). We compared this k with 20 years of AERONET measurements over different mid-latitude dust emitting areas (from closer to further from our location, in colours). The retrievals of the average for the in-situ measurements and the average for the AERONET estimations are also shown through the black triangles. The regions of the AERONET measurements are shown in FigS9 S10a, with the following acronyms: Ouarzazate (OUARZ), northwestern Africa (WNAFR), northeastern Africa (ENAFR), Sahel (SAHEL), Arabian Peninsula (ARPEN), central Asia (CASIA), and India (INDIA). The box-plots limits represent the 25th and 75th quantiles and the lines represent the 5th and 95th quantiles.

~~iron oxides. The SAE decreased to negative values for larger dust particles, further confirming the dominance of coarse-mode mineral dust during emission events.~~

900 Forward scattering (asymmetry parameter, g) increased with R_{eff} , while BF decreased, highlighting the role of particle size in modifying dust scattering behavior. The MAE decreased significantly with increasing R_{eff} , for instance from ~ 0.30 to 0.15 at 370 , reflecting reduced absorption efficiency for larger dust particles. The optical properties showed a strong dependence on particle size and inlet cut-off. During the PM_{2.5} period, increasing effective radius was associated with a clearer dust optical signature: SAE decreased towards values near or below zero, SSAAE became negative, and AAE increased towards values typical of mineral dust. The mass absorption efficiency decreased with increasing particle size, while the scattering and extinction efficiencies reflected the shift of the optically active particle size range. During the PM₁₀ period, the broader coarse-particle fraction produced a consistently stronger dust signature and lower mass-normalized efficiencies, reflecting the dominant contribution of coarse dust to mass. The asymmetry parameter and backscatter fraction were also consistent with previous Saharan dust measurements, confirming the important role of coarse particles in controlling the angular distribution of scattering. The MSE displayed a distinct wavelength dependency, with stronger scattering

905 The observations also show that even at a remote dust-source site, regional and local anthropogenic pollution can affect the measured optical properties. Period C, influenced by anthropogenic advection, exhibited smaller effective radius, AAE and SAE values closer to 1, a less negative or positive SSAAE, lower SSA at near-infrared wavelengths, and higher mass absorption efficiency. These features point to a larger relative contribution of fine absorbing carbonaceous particles during calm periods with weak local dust emission. This result highlights the importance of separating dust-dominated periods from mixed aerosol conditions when interpreting source-region dust optical measurements.

910 We retrieved k for fine particles and a shift toward longer wavelengths for coarse particles. PM_{2.5} dust-event periods using a cost function based on the truncated single scattering albedo ($tssa$). The retrieval was performed under prescribed assumptions for particle shape, particle density, the real part of the refractive index, and the AE33 multiple-scattering correction. Therefore, the retrieved values should be interpreted as conditional estimates of k , not as a unique unconstrained retrieval of dust shape, PSD, n , and k . This formulation was chosen because the Fidas and the optical instruments sampled through different inlets and over different size ranges, making inversions based directly on extensive absorption and scattering coefficients more sensitive to possible PSD-optical sampling mismatches.

925 We have retrieved values of the imaginary. The retrieved k values decreased with wavelength across the five shortest AE33 wavelengths, consistent with stronger short-wave absorption by iron-bearing minerals. Particle density and particle shape were the dominant assumptions affecting the retrieval. The prescribed real part of the complex refractive index (k) for the campaign measurements, with aspect ratio constraints derived from single particle analysis of samples collected during the campaign. The refractive index had a comparatively weaker effect within the tested range of ($n=1.48$)– 1.55 . The AE33 correction uncertainty also propagated into the retrieved k , particularly at longer wavelengths where the relative contribution of the scattering artefact is larger.

930 Particle shape assumptions had a substantial effect on the retrieved k are comparable to those obtained by Di Biagio et al. (2019) in a resuspension chamber from a Moroccan sediment sample. Our central estimates under spherical and biaxial ellipsoid assumptions yielded lower values (e.g., $k \sim 0.0011$ at 520), while assuming triaxial or more irregular particle shapes resulted in higher values (e.g., $k \sim 0.0016$ at 520). This trend—an increase in. For the central assumptions, non-spherical particles

generally required larger k values than spheres to reproduce the observed (tssa). At 520 nm, k increased from approximately 0.00104 for spheres to approximately 0.00145 for triaxial ellipsoids, corresponding to an increase of about 40 %. The relationship between retrieved k with greater and particle non-sphericity—highlights the sensitivity of absorption retrievals to morphological assumptions. It also underscores the need to account for realistic particle geometries to reduce uncertainty in estimating dust absorption properties from in-situ measurements, represented by the ratio of volume-equivalent to cross-section-equivalent radii, suggests that more elongated or irregular particles require higher k values under otherwise equivalent assumptions. This relationship should be interpreted cautiously because single irregular shapes are used as sensitivity cases rather than as realistic descriptions of the full atmospheric dust population. Nevertheless, the result demonstrates that particle-shape representation can substantially affect retrieved absorption properties.

Comparisons with AERONET-retrieved k values show general agreement, particularly in the near-infrared. The comparison with dust-filtered AERONET retrievals provides useful context but should not be interpreted as a direct validation of the in-situ retrievals. The closest AERONET station, Ouarzazate, showed qualitative agreement with the in-situ retrievals, particularly at 550 nm and 675 nm, when non-spherical shape assumptions were used, including the Dubovik et al. (2006) spheroid distribution. However, discrepancies appear at shorter wavelengths. These differences likely stem from a combination of and longer wavelengths. Differences between AERONET and in-situ k values can arise from several factors, including methodological limitations in both measurements and retrievals, the intrinsic mismatch between column-integrated climatological data (AERONET) and point-based campaign observations, and the potential influence of externally mixed absorbing species (e.g., black carbon), which may persist in AERONET retrievals despite the application of dust filters. Column versus surface sampling, differences in PSD, size sensitivity, retrieval assumptions, mineralogy, dust ageing, and possible residual contamination by non-dust aerosols. The comparison between Fidas and AERONET size distributions further indicates that PSD differences may contribute to discrepancies in retrieved k , in addition to particle-shape effects.

Finally, we found that modelling the effects of the measurement inlet cut-off significantly influences the retrievals, emphasizing the importance of instrument design considerations when interpreting. Overall, this work provides field-based constraints on the optical properties of mineral dust.

The findings of this study improve our understanding of freshly emitted mineral dust optical properties and their dependence on size, shape, and composition. These results contribute to refining dust parametrizations in climate models, reducing uncertainties in direct radiative forcing estimates, freshly emitted Saharan dust and enhance highlights the sensitivity of inferred absorption properties to particle size, density, and shape. The results support the need for improved treatment of non-spherical dust optics in remote-sensing retrieval algorithms. Future work should focus on extending these measurements to additional source regions, retrievals and climate-model parametrizations. At the same time, they show that robust field retrievals of dust refractive index require careful characterization of inlet transmission, PSD–optical closure, particle density, particle shape, and absorption-correction uncertainty. Future campaigns combining co-located PSD and optical measurements over the full optically relevant size range, together with independent constraints on mineralogy, density, and morphology, will be essential to further reduce uncertainties in dust absorption and further exploring the effects of dust ageing on optical properties in dust transport regions.

By providing detailed, source-region observations of dust absorption and scattering, this study strengthens the foundation
970 for more accurate representations of mineral dust in Earth system models, ultimately improving climate predictions and
atmospheric radiative budget assessments its radiative impact.

Code and data availability. Data and code will be made accessible through an open repository once the publication has been accepted.
MOPSMAP dataset is available at <https://doi.org/10.5281/zenodo.1284217>. Triaxial spheroids database is available at <https://zenodo.org/record/4959767>. Aspect ratio distribution from Dubovik et al. (2006) is available in the GRASP Spheroids Package repository at <https://www.grasp-open.com/products/spheroid-package-release/> (last access, 1 April 2026)
975

Author contributions. AA, XQ, MK, KK and CPGP designed the measurement campaign. JYD, AA, CGF, AGR, MK, KK, AP, XQ, CR
and CPGP participated in the field measurement campaign. CGF processed the meteorological data, CGF and JE treated the PNSD datasets,
AP and AGR obtained the airborne and soil mineralogical measurements. JYD processed the optical data-sets, analyzed the results, and
summarized and expressed them in this manuscript. JE provided the complex refractive index modelization analysis, analyzed the results,
980 and summarized and expressed them in this manuscript. All authors provided advice regarding the structure and content as well as contributed
to the writing of the final manuscript.

Competing interests. At the time of the research, MR and MI were also employed by the manufacturer of the Aethalometer AE33. At least
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