Linking the different diameter types of aspherical desert dust indicates that models underestimate coarse dust emission

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Abstract

Measurements of dust size usually obtain the optical or the projected area-equivalent diameters, whereas model calculations of dust impacts use the geometric and the aerodynamic diameters. As such, accurate conversions between the four types of diameters are critical. However, most current conversions assume dust is spherical, which is problematic as numerous studies show that dust is highly aspherical. Here, we obtain conversions between different diameter types that account for dust asphericity. Our conversions indicate that optical particle counters using optical diameter to determine dust size underestimate dust geometric diameter at coarse sizes. We further use the diameter conversions to obtain a consistent observational constraint of size distributions of emitted dust in terms of geometric and aerodynamic diameters. The resulting size distributions are coarser than accounted for by parameterizations used in climate models, which which underestimate the mass of emitted dust within 10[?]D_geo[?]20 µm by a factor of ~2 and do not account for dust emission with D_geo[?]20 µm. This finding suggests that current models substantially underestimate coarse dust emission.

Linking the different diameter types of aspherical desert dust indicates that models underestimate coarse dust emission

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SUMMARY: WE DEVELOPED A PROCEDURE TO CONVERT BETWEEN DIFFERENT DIAMETER TYPES

- We obtain conversions between the geometric, aerodynamic, optical, and projected area-equivalent diameters that account for dust asphericity
- Optical particle counters, the sensors most widely used in *in situ* measurements, underestimate dust size at diameters larger than ~8 μm
- The microscopy method, another common method to measure dust size, overestimates dust size by ~56% at all sizes
- Size distributions of emitted dust after harmonizing the different diameter types indicate that the parameterization used in climate models (the original brittle fragmentation theory) underestimates coarse dust emission (with $D_{geo} \geq 10$ μm)

INTRODUCTION

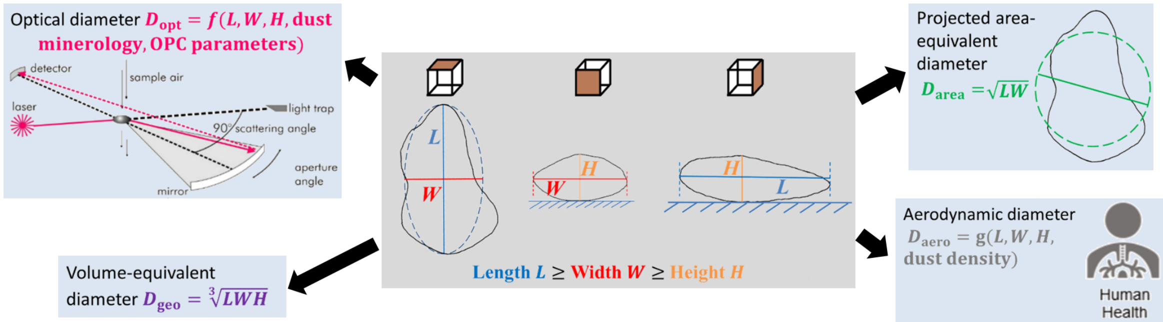

Figure 1. Four different types of diameters used in studies of dust and its various impacts.

- Measurements of dust size usually obtain the optical or projected area-equivalent diameters, whereas model calculations of dust impacts use the geometric or aerodynamic diameters.
- Current conversions among the four types of diameters assume dust is spherical, which is problematic as numerous studies show that dust is highly aspherical
- These problematic diameter conversions cause biases in size-resolved dust properties; these biases propagate into the calculations of dust impacts on weather, climate, biogeochemistry, and human health.
- Here, we obtain conversions between different diameter types that account for dust asphericity

RESULT #1: CONVERSIONS BETWEEN FOUR DIFFERENT DUST DIAMETER TYPES ACCOUNTING FOR DUST ASPHERICITY

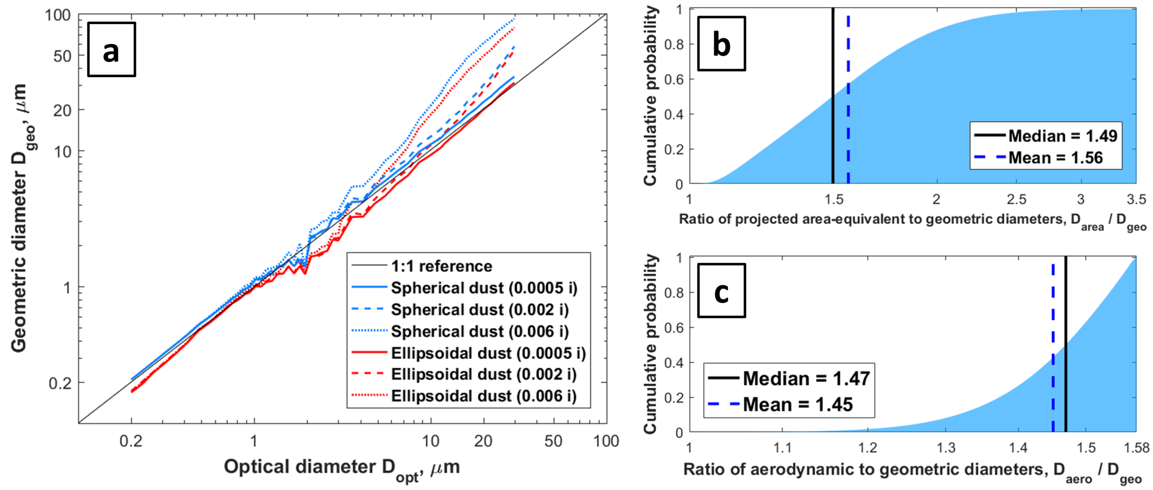

Figure 2. Conversion factors linking the four different diameter types of aspherical dust.

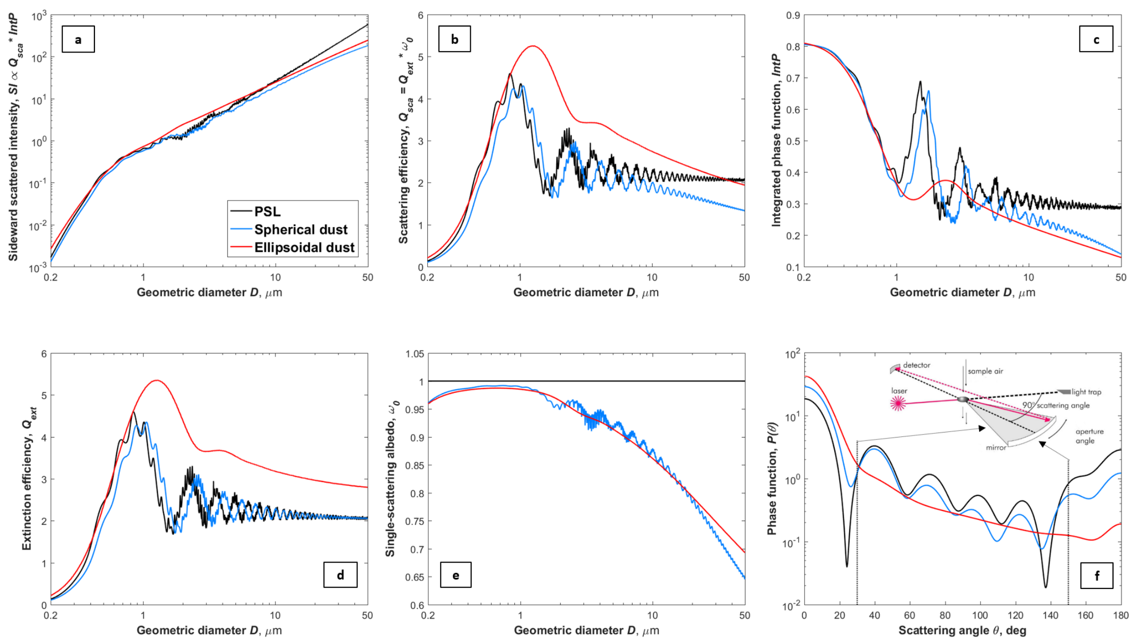

Figure 3. Diagnosis of the factors causing optical particle counters (OPCs) to underestimate the size of coarse dust.

- OPCs using optical diameter underestimate dust geometric diameter at $D_{opt} \geq \sim 8$ μm, due to the combined effect of dust refractive index and dust asphericity (Fig. 2a and Fig. 3)
- Microscopy measurements using the projected area-equivalent diameter overestimate dust geometric diameter by ~56% (Fig. 2b)
- The aerodynamic diameter exceeds dust geometric diameter by ~45% (Fig. 2c)

RESULT #2: PSDS OF EMITTED DUST ARE COARSER AFTER HARMONIZING DIFFERENT DIAMETER TYPES

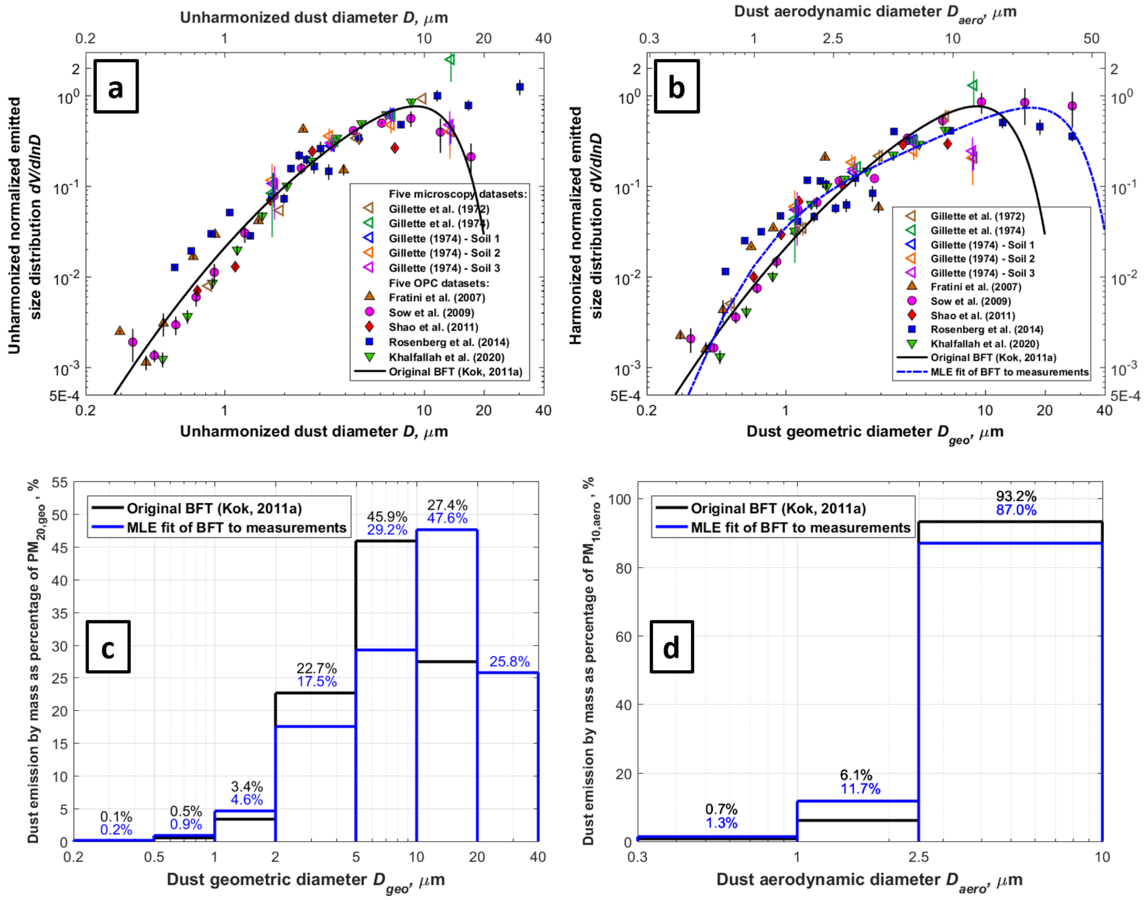

Figure 4. Normalized size distributions of dust at emission (a) before and (b) after harmonizing the different diameter types. Also shown are the percentages of dust emission of individual particle size ranges relative to (c) the size range with $0 \leq D_{geo} \leq 20$ μm ($PM_{20,geo}$) and (d) the size range with $0 \leq D_{aero} \leq 10$ μm ($PM_{10,aero}$).

- The harmonization reduces the divergence in emitted dust PSDs at coarse sizes (from a factor of 15 to a factor of 2 at diameters larger than ~12 μm; Fig. 4a and Fig. 4b)
- The original brittle fragmentation theory (BFT; Kok, 2011a) underestimates the mass of emitted dust within $10 \leq D_{geo} \leq 20$ μm by a factor of ~2 (Fig. 4c)
- The original brittle fragmentation theory has a cutoff diameter at 20 μm, whereas measurements show a substantial amount of emitted dust exists at $D_{geo} > 20$ μm (Fig. 4c)
- Climate models that use brittle fragmentation theory have substantially underestimated the emission of super-coarse dust

METHODOLOGY

We approximate dust as tri-axial ellipsoidal particles (Section 1). We next use the shape-resolved optical, geometric, and aerodynamic properties of ellipsoidal dust to link the four types of diameters (Sections 2.1, 2.2, and 2.3). Finally, we use the diameter conversions to harmonize observational studies of emitted dust PSDs that used different types of dust diameters (Section 3).

1. Quantifying dust asphericity

- Asphericity of ellipsoidal dust is quantified by the aspect ratio (AR=L/W, see gray box in Fig.1) and the height-to-width ratio (HWR=H/W, see gray box in Fig.1)
- Huang et al. (2020) compiled dozens of measurements of dust shape across the world and found that both AR-1 and HWR follow a lognormal distribution (paper pdf link (https://eecc0b9e-37d0-4d76-bce4-924555ba1fe5.filesusr.com/ugd/9e18a2_8690d25c7c7d430cbf0900e883b57264.pdf)).

2.1. Linking the projected area-equivalent and geometric diameters (see Fig. 1)

$$\frac{D_{\mathrm{area}}}{D_{\mathrm{geo}}} = \frac{\sqrt{LW}}{\sqrt[3]{LWH}} = \frac{\sqrt[6]{AR}}{\sqrt[3]{HWR}}$$

- Ratio between D_{area} and D_{geo} is a function of AR and HWR

2.2. Linking the optical and geometric diameters

$$SI = \frac{I_{\mathrm{OPC}}}{I_{\mathrm{i}}} = \frac{1}{2} Q_{\mathrm{sca}} A \int_{\Theta_1}^{\Theta_2} P(\Theta) \sin\Theta \, d\Theta$$

- First, we use Lorenz-Mie theory to calculate sideward scattered intensity (*SI*) as a function of optical diameter of polystyrene latex spheres (PSLs; the calibration particle for OPCs)
- We next use the single-scattering database of ellipsoidal particle (Meng et al., 2010) to calculate *SI* as a funtion of geometric diameter of ellipsoidal dust
- Finally, we determine the relationship between optical diameter of spherical PSLs and geometric diameter of ellipsoidal dust that produce the same *SI* as measured by OPCs
- **We provide a look-up table** that contains the dust refractive index-, OPC wavelength-, and OPC scattering angle range-resolved conversions between the optical diameters of spherical PSLs and the geometric diameters of ellipsoidal dust (will be available at http://dustcomm.atmos.ucla.edu/ (http://dustcomm.atmos.ucla.edu/) after paper acceptance)

2.3. Linking the aerodynamic and geometric diameters

$$D_{\mathrm{aero}} = D_{\mathrm{geo}} \sqrt{\frac{\rho_{\mathrm{d}}}{\chi \cdot \rho_0}}$$

$$\chi = \frac{1}{2}\left({F_{\mathrm{S}}}^{1/3} + \frac{1}{{F_{\mathrm{S}}}^{1/3}} \right)$$

$$F_{\mathrm{s}} = HWR \cdot \left(\frac{1}{AR}\right)^{1.3}$$

where ρ_d is dust density, ρ_0 is water density, and χ is the dynamic shape factor that is a function of AR and HWR (further details can be found in section 4 of Huang et al. (2020), paper pdf link (https://eecc0b9e-37d0-4d76-bce4-924555ba1fe5.filesusr.com/ugd/9e18a2_8690d25c7c7d430cbf0900e883b57264.pdf) and Bagheri and Bonadonna (2016).

3. Harmonizing size distributions of emitted dust

- 3 studies measured 5 PSDs of dust at emission in terms of projected area-equivalent diameter (Fig. 4a)
- 5 studies measured 5 PSDs of emitted dust in terms of optical diameter of PSLs (Fig. 4a)
- We converted the ten PSD datasets from either optical or projected area-equivalent diameters to geometric and aerodynamic diameters (Fig. 4b)

DISCUSSIONS AND CONCLUSIONS

- The underestimation of super-coarse dust emission helps explain why models underestimate the concentration of super-coarse dust ($D_{geo} \geq 10$ μm) in the atmosphere
- Our results imply a substantial dust emission (and thus deposition) flux with diameters in excess of 20 μm, which is not accounted for in most models.
- Our results suggest that inconsistencies in diameter types used in measurement versus modeling studies have resulted in substantial biases
- We recommend that the dust research community uses the conversions obtained here to consistently convert between the different diameter types used by measurements and modeling studies

AUTHOR INFORMATION

Yue Huang (hyue4@ucla.edu) is a PhD Candidate at UCLA. She obtained a B.S. in atmospheric science at Sun Yat-sen University in 2015. She then moved to Los Angeles for graduate school. Supervised by Professor Jasper Kok at UCLA, Yue's research focuses on dust emission, aerosol-radiation-climate interactions, and remote sensing techniques. Yue's research is supported by her NASA FINESST graduate fellowship. You can find more information on her webpage (https://huangyue.wixsite.com/mysite (https://huangyue.wixsite.com/mysite)).

Yue Huang will graduate in September 2021, and is looking for a postdoctoral position. Please feel free to contact her if you have any questions!

ABSTRACT

Measurements of dust size usually obtain the optical or projected area-equivalent diameters, whereas model calculations of dust impacts use the geometric or aerodynamic diameters. Accurate conversions between the four diameter types are thus critical. However, most current conversions assume dust is spherical, which is problematic as numerous studies show that dust is highly aspherical. Here, we obtain conversions between different diameter types that account for dust asphericity. Our conversions indicate that optical particle counters using optical diameter to determine dust size underestimate dust geometric diameter at coarse sizes. We further use the diameter conversions to obtain a consistent observational constraint of size distributions of emitted dust. The resulting size distributions are coarser than accounted for by parameterizations used in climate models, which underestimate the mass of emitted dust within $10 \leq D_{geo} \leq 20$ µm by a factor of ~2 and do not account for dust emission with $D_{geo} \geq 20$ µm. This finding suggests that current models substantially underestimate coarse dust emission.

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