Single-scattering properties of ellipsoidal dust aerosols accounting for realistic shape distributions

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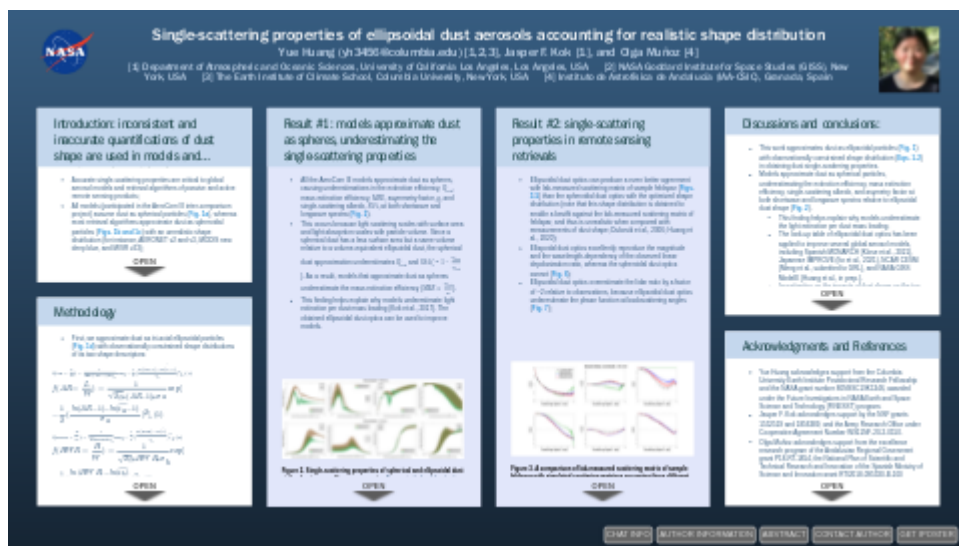[2]University of California
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Abstract

To correctly simulate and retrieve dust distributions and estimate dust impacts, global aerosol models and remote sensing retrieval algorithms need accurate single-scattering properties of dust aerosols. However, inconsistent and inaccurate quantifications of dust shape and shape distributions are used in models and retrieval algorithms, generating biases that propagate into the estimated dust distributions and dust impacts. To improve models and retrieval algorithms, here we for the first time account for the realistic dust shape distributions in obtaining single-scattering properties of dust aerosols. We find that approximating dust as spheres and neglecting dust asphericity, as most global aerosol models do, result in substantial underestimations in the extinction efficiency, the asymmetry factor, and the single-scattering albedo for all dust sizes in both the shortwave and longwave spectra. In addition, we find that the inaccurate quantification of dust shape in retrieval algorithms causes them to generate an incorrect magnitude and wavelength dependence of the linear depolarization ratio relative to observations. Our new ellipsoidal dust optics accounting for realistic shape distributions produce excellent agreement with the measured linear depolarization ratio. Although these new dust optics show potential to improve models and retrieval algorithms, they underestimate the magnitude of the back-scattering intensity relative to laboratory and field observations. This finding indicates that a realistic quantification of dust body shape is not sufficient and that an accurate quantification of dust surface texture is also critical to accurately reproduce dust optical properties at back-scattering angles.

Single-scattering properties of ellipsoidal dust aerosols accounting for realistic shape distribution

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PRESENTED AT:

INTRODUCTION: INCONSISTENT AND INACCURATE QUANTIFICATIONS OF DUST SHAPE ARE USED IN MODELS AND REMOTE SENSING RETRIEVALS

- Accurate single-scattering properties are critical to global aerosol models and retrieval algorithms of passive and active remote sensing products;

- All models (participated in the AeroCom III inter-comparison project) assume dust as spherical particles (**Fig. 1a**), whereas most retrieval algorithms approximate dust as spheroidal particles (**Figs. 1b and 1c**) with an unrealistic shape distribution (for instance, AERONET v2 and v3, MODIS new deep blue, and MISR v23);

- A recent study (Huang et al., 2020 (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL086592)) found that dust shape deviates substantially from spheres and spheroids, and that models and retrieval algorithms underestimate dust asphericity by a factor of ~3 to 5;

- The inconsistent and inaccurate dust shape assumptions in models and retrieval algorithms generate bias in the dust single-scattering properties that further propagate into the estimated dust distributions and dust impacts;

- Here, we approximate dust as tri-axial ellipsoidal particles (**Fig. 1d**) with observationally constrained shape distributions (Huang et al., 2020 (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL086592)) in obtaining dust single-scattering properties at both shortwave and longwave spetra.
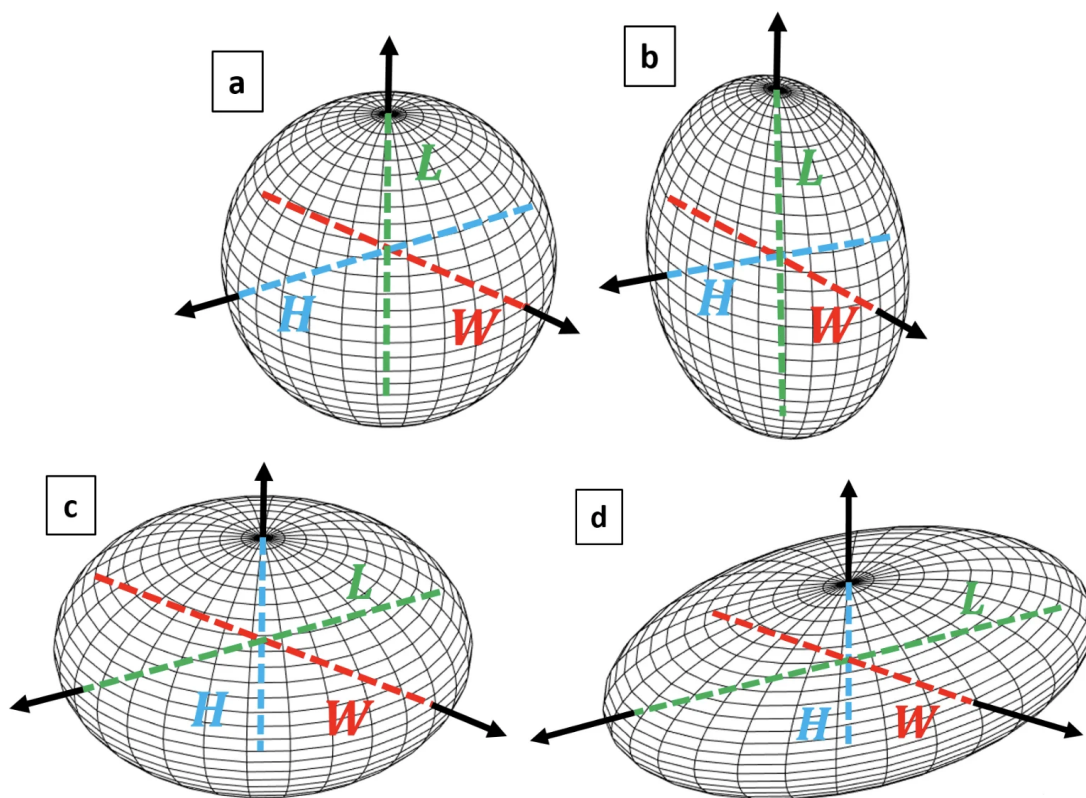

Figure 1. Three-dimensional view of a dust particle approximated as a (a) sphere, (b) prolate spheroid, (c) oblate spheroid, and (d) tri-axial ellipsoid. In each plot, the three perpendicular axes are denoted. The largest, intermediate, and smallest axes are referred to as particle length, L, particle width, W, and height H, respectively. In shape (a) $L = W = H$, in shape (b) $L \geq W = H$, in shape (c) $L = W \geq H$, and in shape (d) $L \geq W \geq H$, such that, to quantify dust

asphericity, shape (a) does not need a shape descriptor, shapes (b) and (c) need one shape descriptor (i.e., aspect ratio $\frac{L}{H}$), and shape (d) needs two shape descriptors (i.e., aspect ratio $\frac{L}{W}$ and height-to-width ratio $\frac{H}{W}$). Note that v2 and v3 inversion algorithms of AERONET assume that dust particles are spheroidal and assume an equal presence of prolate and oblate spheroids with the same aspect ratio (Dubovik et al., 2006).

METHODOLOGY

- First, we approximate dust as tri-axial ellipsoidal particles (**Fig. 1d**) with observationally constrained shape distributions of its two shape descriptors:

$$f(AR = \frac{L}{W}) = \frac{1}{\sqrt{2\pi}*(AR-1)*\sigma_a} exp[-\frac{1}{2}(\frac{ln(AR-1)-ln(\overline{\epsilon_a}-1)}{\sigma_a})^2], (1)$$

$$f(HWR = \frac{H}{W}) = \frac{1}{\sqrt{2\pi}*HWR*\sigma_h} exp[-\frac{1}{2}(\frac{ln(HWR)-ln(\overline{\epsilon_h})}{\sigma_h})^2], (2)$$

where $\sigma_a = 1.73 \pm 0.03, \overline{\epsilon_a} = 0.70 \pm 0.02, \sigma_h = 0.40 \pm 0.07,$ and $\overline{\epsilon_h} = 0.73 \pm 0.09$ at a global scale (Huang et al., 2020);

- Second, we combine the shape distributions (**Eqs. 1 and 2**) with a database of the single-scattering properties of tri-axial ellipsoidal dust particles (Meng et al., 2010) to obtain shape-integrated dust single-scattering properties that are resolved by size, wavelength, and refractive index;

- Third, the obtained single-scattering properties are validated against the laboratory and field measurements of the scattering matrix, the linear depolarization ratio, and the lidar ratio.

RESULT #1: MODELS APPROXIMATE DUST AS SPHERES, UNDERESTIMATING THE SINGLE-SCATTERING PROPERTIES

- All the AeroCom III models approximate dust as spheres, causing underestimations in the extinction efficiency, Q_{ext}, mass extinction efficiency, MEE, asymmetry factor, g, and single-scattering albedo, SSA, at both shortwave and longwave spectra (**Fig. 2**).

- This occurs because light scattering scales with surface area and light absoprtion scales with particle volume. Since a spherical dust has a less surface area but a same volume relative to a volume-equivalent ellipsoidal dust, the spherical dust approximation underestimates Q_{ext} and SSA $(= 1 - \frac{Q_{abs}}{Q_{ext}})$. As a result, models that approximate dust as spheres underestimate the mass extinction efficiency ($MEE \propto \frac{Q_{ext}}{D}$).

- This finding helps explain why models underestimate light extinction per dust mass loading (Kok et al., 2017). The obtained ellipsoidal dust optics can be used to improve models.
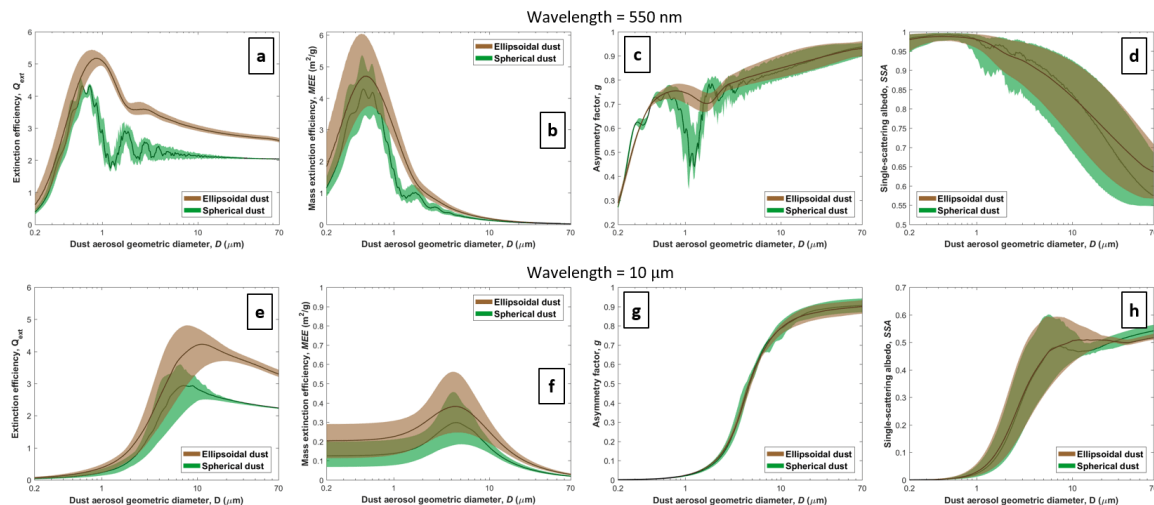

Figure 2. Single-scattering properties of spherical and ellipsoidal dust at the shortwave and longwave spectra. Top row includes: (a) extinction efficiency, Q_{ext}, (b) mass extinction efficiency, MEE, (c) asymmetry factor, g, and (d) single-scattering albedo, SSA, at a wavelength of $550\ nm$. Bottom row includes: (e) Q_{ext}, (f) MEE, (g) g, and (h) SSA at a wavelength of $10\ \mu m$. The refractive index of dust aerosols is $1.53 \pm 0.03 - 10^{-2.75\pm0.25} * i$ at $550\ nm$ convering the ranges of Kok et al. (2017) and Di Biagio et al. (2019), and it is $1.70 \pm 0.2 - 10^{-0.40\pm0.11} * i$ at $10\ \mu m$ convering the ranges of Volz (1972), Volz (1973), Hess et al. (1988), and Di Biagio et al. (2017). In each of the eight plots, the central lines denote the medians, and the shaded ranges denote the 95% confidence intervals.

RESULT #2: SINGLE-SCATTERING PROPERTIES IN REMOTE SENSING RETRIEVALS

- Ellipsoidal dust optics can produce a even better agreement with lab-measured scattering matrix of sample feldspar (**Figs. 3-5**) than the spheroidal dust optics with the optimized shape distribution (note that this shape distribution is obtained to enable a bestfit against the lab-measured scattering matrix of feldspar, and thus is unrealistic when compared with measurements of dust shape; Dubovik et al., 2006; Huang et al., 2020);

- Ellispodal dust optics excellently reproduce the magnitude and the wavelength-dependency of the observed linear depolarization ratio, whereas the spheroidal dust optics cannot (**Fig. 6**);

- Ellipsoidal dust optics overestimate the lidar ratio by a factor of ~2 relative to observations, because ellipsoidal dust optics underestimate the phase function at backscattering angles (**Fig. 7**);
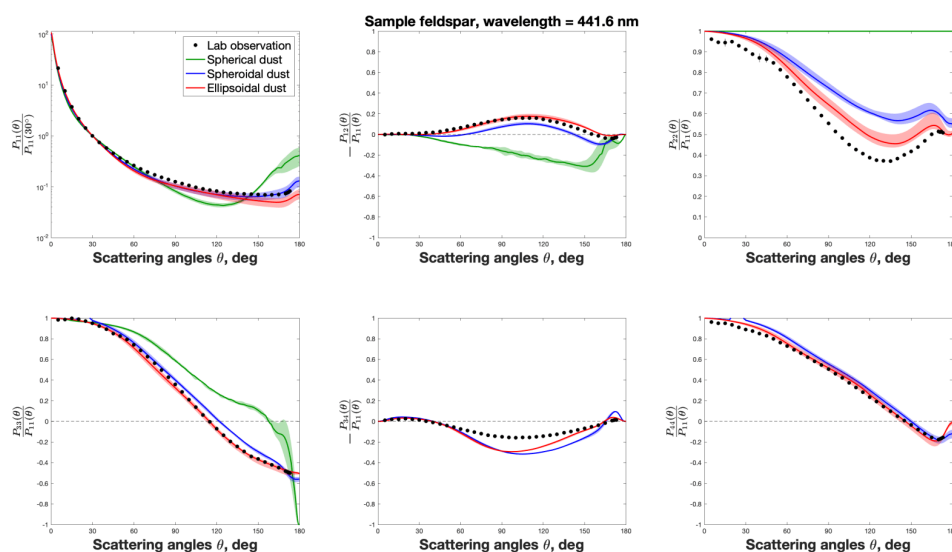

Figure 3. A comparison of lab-measured scattering matrix of sample feldspar with simulated scattering matrices assuming three different dust shapes at wavelength of 441.6 nm. The shaded ranges denote uncertainties from the dust refractive index. The size distribution of the three simulations is taken as the lab-measured size distribution of feldspar that was measured simultaneously as the measured scattering matrix (Volten et al., 2001; Munoz et al., 2012). The shape distribution of ellipsoidal dust optics comes from observational constraints (aka, **Eqs 1 and 2**). The shape distribution of spheroidal dust optics comes from Dubovik et al. (2006), which is obtained to enable a bestfit against the lab-measured scattering matrix of feldspar. Here, the ellipsoidal dust optics can produce a even better agreement with lab-measured scattering matrix than the spheroidal dust optics with optimized shape distribution.
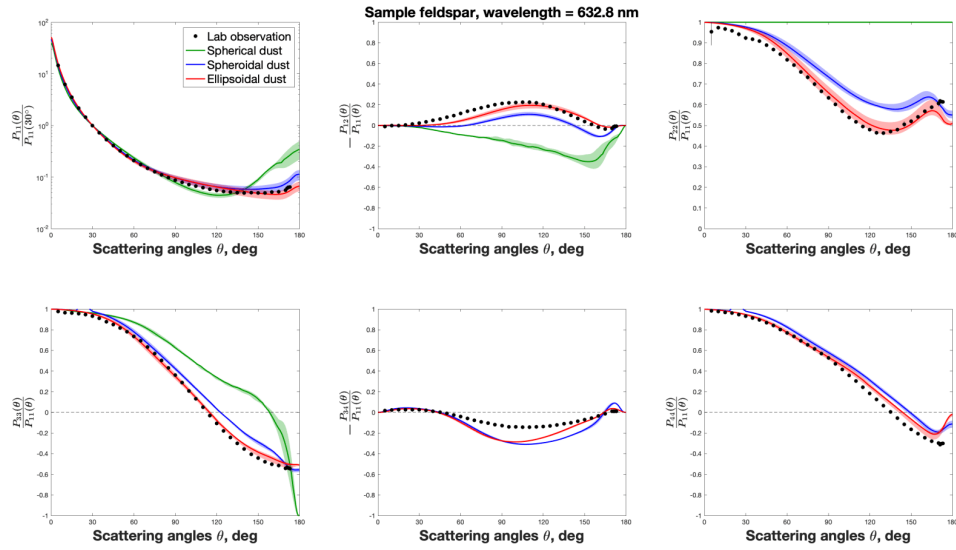
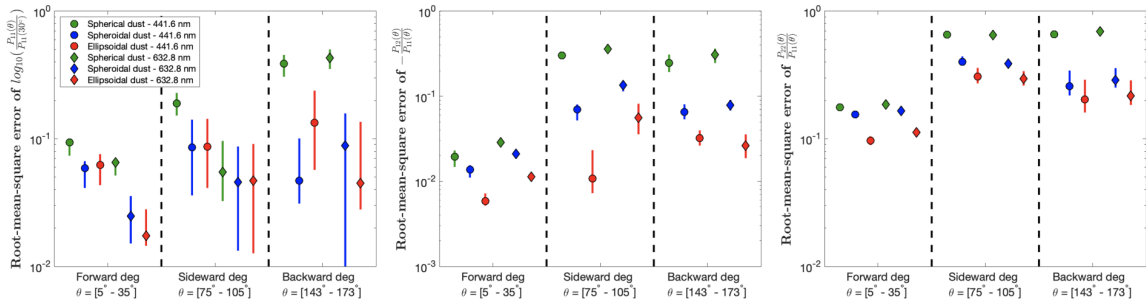**Figure 4. Similar to Fig 3 but at a different wavelength of 632.8 nm.**

Figure 5. Root-mean-square errors between lab-measured and simulated $log_{10}\left(\frac{P_{11}(\theta)}{P_{11}(30^\circ)}\right)$, $-\frac{P_{12}(\theta)}{P_{11}(\theta)}$, **and** $\frac{P_{22}(\theta)}{P_{11}(\theta)}$ **at forward-scattering, sideward-scattering,**

and backward-scattering angles. The vertical error bars denote uncertainties from the dust refractive index. The ellipsoidal dust optics show excellent agreements with

measured $-\frac{P_{12}}{P_{11}}$ and $\frac{P_{22}}{P_{11}}$ at all scattering angles than spherical and spheroidal dust optics. The ellipsoidal dust optics show an improved agreement with measured P_{11}

at almost all scattering angles (except at backward-scattering angles at 441.6 nm) than spherical and spheroidal dust optics.
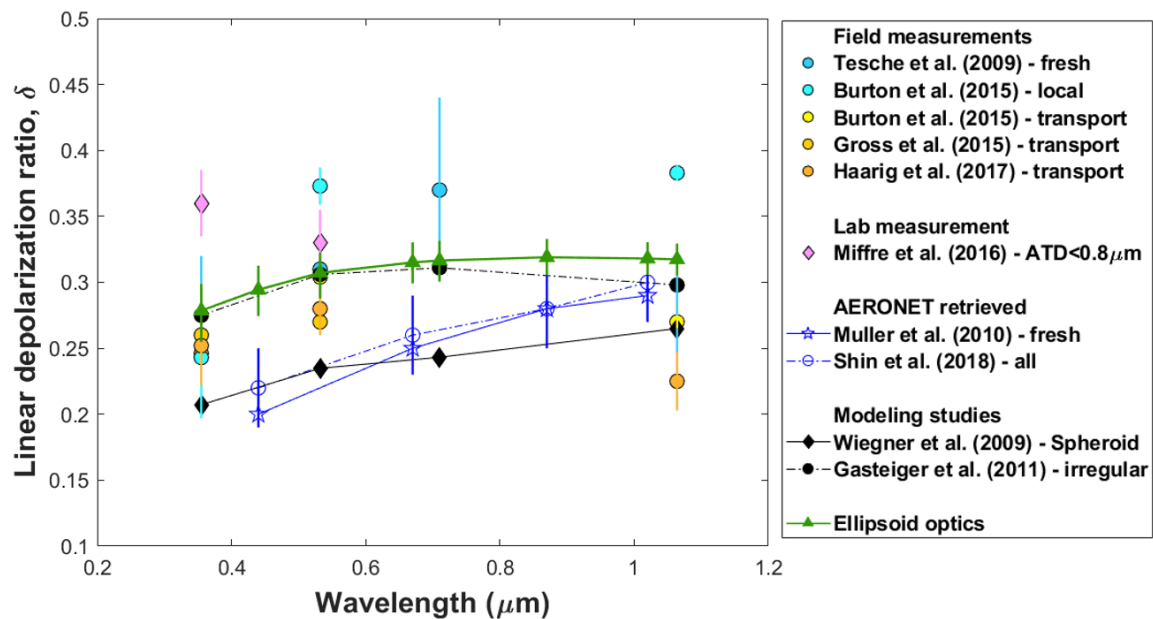
Figure 6. Observed and simulated linear depolarization ratio at various wavelengths. The size distribution of ellipsoidal dust optics is taken as the one from Adebiyi and Kok (2020), which obtained dust size distribution constraints from joint observational-modeling-experimental analysis. The shape distribution of ellipsoidal dust optics comes from observational constraints (aka, **Eqs 1 and 2**). The ellipsoidal dust optics excellently reproduce the magnitude and the wavelength-dependency of the observed linear depolarization ratio, whereas AERONET retrievals assuming a spheroidal dust shape (Dubovik et al., 2006) cannot.
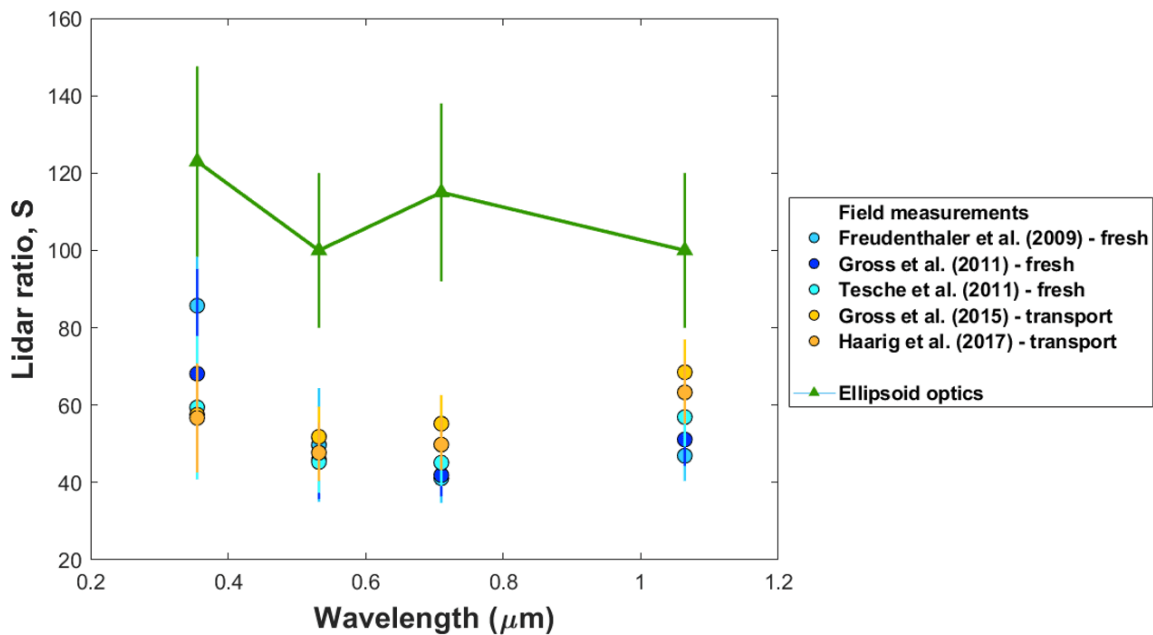

Figure 7. Observed and simulated lidar ratio at various wavelengths. The size distribution of ellipsoidal dust optics is taken as the one from Adebiyi and Kok (2020), which obtained dust size distribution constraints from joint observational-modeling-experimental analysis. The shape distribution of ellipsoidal dust optics comes from observational constraints (aka, **Eqs 1 and 2**). The ellipsoidal dust optics overestimate the lidar ratio by a factor of ~2 relative to observations, because ellipsoidal dust optics underestimate the phase function at backscattering angles (see $\dfrac{P_{11}(\theta)}{P_{11}(30°)}$ in **Figs. 3 and 4**).

DISCUSSIONS AND CONCLUSIONS:

- This work approximates dust as ellipsoidal particles (**Fig. 1**) with observationally constrained shape distribution (**Eqs. 1-2**) in obtaining dust single-scattering properties.

- Models approximate dust as spherical particles, underestimating the extinction efficiency, mass extinction efficiency, single-scattering albedo, and asymmetry factor at both shortwave and longwave spectra relative to ellipsoidal dust shape (**Fig. 2**).
  - This finding helps explain why models underestimate the light extinction per dust mass loading.

  - The look-up table of ellipsoidal dust optics has been applied to improve several global aerosol models, including Spanish MONARCH (Klose et al., 2021), Japanese IMPROVE (Ito et al., 2021), NCAR CESM (Meng et al., submitted to GRL), and NASA GISS ModelE (Huang et al., in prep.).

  - Investigation on the impacts of dust shape on the top-of-atmosphere and surface longwave and shortwave radiative forcings is ongoing.

- Ellipsoidal dust optics can reproduce the observed scattering matrix (**Figs. 3-5**) and observed linear depolarization ratio (**Fig. 6**) in a substantially improved way than spheroidal dust optics which are widely used in remote sensing retrievals. However, ellisoidal duse optics overestimate the lidar ratio by a factor of ~2 relative to observations (**Fig. 7**).
  - This finding indicates that a realistic quantification of dust body shape is not sufficient enough at bacascattering angles.

  - Accurate quantifications of dust surface texture (roughness, pits, and sharp corners) are further needed.

ACKNOWLEDGMENTS AND REFERENCES

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ABSTRACT

Accurate single-scattering properties of dust aerosols are critical to the global aerosol models and retrieval algorithms of remote sensing products to correctly simulate and retrieve dust distributions. However, inconsistent and inaccurate quantifications of dust shape exist, as almost all models approximate dust as spherical particles, whereas most retrieval algorithms approximate dust as spheroidal particles with an unrealistic shape distribution. These problematic shape quantifications can generate biases in the single-scattering properties that further propagate into the estimated dust distributions. Here, we obtain dust single-scattering properties by approximating dust as tri-axial ellipsoidal particles with observationally constrained shape distribution. We find that approximating dust as spherical particles and neglecting dust asphericity, as almost all models do, underestimate the extinction efficiency, mass extinction efficiency, asymmetry factor, and single-scattering albedo for all dust sizes at both shortwave and longwave spectra. We further find that approximating dust as spheroidal particles and underestimating dust asphericity, as most retrieval algorithms do, result in an incorrect magnitude and wavelength dependence of the linear depolarization ratio relative to observations. Conversely, approximating dust as ellipsoidal particles with observationally constrained shape distribution produces an excellent agreement with the measured linear depolarization ratio. Although the new ellipsoidal dust optics show potential to improve models and retrieval algorithms, it underestimates the magnitude of the backscattering intensity relative to observations. This indicates that a realistic quantification of dust body shape is not sufficient and that an accurate quantification of dust surface texture is also critical to accurately reproduce dust optics at backscattering angles.