Look-up Table for Lidar and Polarimeter Liquid Water Cloud Studies

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Introduction

Liquid water clouds are an important radiative constituent of the earth-atmosphere system, but microphysical processes related to clouds remain highly uncertain and poorly represented in climate models. Remote sensing observation are crucial to improve our knowledge on cloud processes. The polarimetric cloudbow observations from the NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission will enable retrievals of cloud-top effective radius, variance, and droplet number concentration. In addition, lidar observations contain information on cloud optical and microphysical properties. NASA's future Atmosphere Observing System (AOS) mission will likely include an imaging polarimeter and high spectral resolution lidar that will make collocated measurements further advancing cloud remote sensing capabilities. **Here we present a new cloud look-up table that can help to retrieve the microphysical properties of liquid water clouds for the next generation and existing remote sensing instruments.** The look-up table can also be used to compute the optical properties of clouds from airborne in situ droplet size distribution data. Our look-up table supports the wide range of size distributions of liquid water cloud droplets and can derive the corresponding optical properties across the ultraviolet, visible, near-infrared and shortwave infrared spectra.

The main function of our look-up table is providing a fast and precise way to compute the cloud inherent optical properties for a single-scattering case. These cases are characterized by a low value of depolarization measured by lidar and can be seen near the cloud edges. The list of cloud inherent optical properties covered by cloud look-up table includes the elements of the normalized scattering matrix, the asymmetry parameter, the absorption, backscatter, extinction, and scattering coefficients.

Summary

- Combined lidar and polarimeter retrievals of aerosol, cloud and ocean microphysical properties involve single-scattering cloud calculations that are time consuming.
- We create a look-up table to speed up calculations for water droplets in the atmosphere. The gained increase in computational efficiency is up to 10^4.
- In our new Lorenz-Mie look-up table we tabulate the light scattering by an ensemble of homogeneous isotropic spheres at wavelengths starting from 0.35 µm.
- The look-up table covers liquid water cloud particles with radii in the range of 0.001—500 µm.
- The covered complex refractive indices range from 1.25 to 1.36 for the real part and from 0 to 0.001 for the imaginary part.
- Using look-up table, we can precisely compute inherent optical properties for the particle size distributions ranging up to 100 µm for the effective radius and up to 0.6 for the effective variance.
- We test wavelengths from 0.35 to 2.3 µm and find that the P_{12} element of the normalized scattering matrix is precise to within 1% for 96.7% of cases; the absorption and backscatter coefficients, and lidar ratio are precise to within 1% for 99% of cases; the P_{11}, P_{33} and P_{34} elements of the normalized scattering matrix, the asymmetry parameter, the extinction and scattering coefficients are precise to within 1% for all cases.
- We provide an example of using the look-up table with in situ measurements to determine agreement with remote sensing.
- **The look-up table along with examples of its use soon will be freely available at https://science.larc.nasa.gov/polarimetry**

Inherent optical properties

For radiative transfer calculations the normalized scattering matrix that relates incident and scattered Stokes parameters is needed. In the standard Lorenz-Mie theory of light scattering by homogeneous spheres this matrix can be represented as

$$\mathbf{P}(\Theta,m,\lambda)=\begin{bmatrix} P_{11}(*) & P_{12}(*) & 0 & 0 \\ P_{12}(*) & P_{11}(*) & 0 & 0 \\ 0 & 0 & P_{33}(*) & P_{34}(*) \\ 0 & 0 & -P_{34}(*) & P_{33}(*) \end{bmatrix}$$

The elements of the matrix **P** can be computed for each vertically-resolved atmospheric layer as

$$P_{ij}(\Theta,m,\lambda)=\frac{1}{k_{\text{sca}}(m,\lambda)}\int_{r_{\min}}^{r_{\max}} C_{ij}(\Theta,m,\lambda,r)\,n(r)\,\mathrm{d}r$$

$C_{ij}(\Theta,m,\lambda,r)=\pi r^2 Q_{ij}(\Theta,m,\lambda,r)$ are the directional scattering cross sections,

$Q_{ij}(\Theta,m,\lambda,r)$ are the directional efficiencies.

The scattering and extinction coefficients can be computed as

$$\{k_{\text{ext}},k_{\text{sca}}\}(m,\lambda)=\int_{r_{\min}}^{r_{\max}} C_{\text{ext,sca}}(m,\lambda,r)\,n(r)\,\mathrm{d}r$$

We compute the backscatter coefficient as $k_{\text{bsc}}(m,\lambda)=\dfrac{k_{\text{sca}}(m,\lambda)\,P_{11}(180^\circ,m,\lambda)}{4\pi}$

the absorption coefficient as $k_{\text{abs}}(m,\lambda)=k_{\text{ext}}(m,\lambda)-k_{\text{sca}}(m,\lambda)$

the asymmetry parameter as $\langle\cos(m,\lambda)\rangle=\dfrac{1}{2}\displaystyle\int_{0^\circ}^{180^\circ} P_{11}(\Theta,m,\lambda)\sin\Theta\cos\Theta\,\mathrm{d}\Theta$

and the lidar ratio as $\mathrm{lr}(m,\lambda)=\dfrac{k_{\text{ext}}(m,\lambda)}{k_{\text{bsc}}(m,\lambda)}$

Precise computation of the elements of the normalized scattering matrix **P** and other single-scattering properties requires a significant amount of time. **For the purpose of fast retrievals of cloud microphysical properties, it is necessary to find a way to compute all these inherent optical properties to within ±1% precision using a look-up table (LUT).**

Scale invariance rule

The most efficient way to organize the look-up table for the case of Lorenz-Mie scattering calculations is to use the scale invariance rule (SIR). The scale invariance rule exploits the fact that all the Lorenz-Mie computations are done using the size parameter $x=2\pi r/\lambda$. **For a given complex refractive index, the size parameter relates the wavelength and radius such that the Lorenz-Mie scattering properties for a specified radius and wavelength are the same as those at another wavelength after adjusting the radius.** If the complex refractive index is fixed, then we can establish a direct connection between the efficiencies *Q* at wavelengths λ and λ_r using a simple scaling in the radius domain given by

$$Q_p(\Theta,m,\lambda,r)=Q_p\left(\Theta,m,\lambda_{\mathrm{r}},\frac{\lambda_{\mathrm{r}}}{\lambda}r\right)$$

A direct connection between the efficiencies can also be expressed in terms of integrals using a linear scaling of the integration range as

$$\int_{r_{\min}}^{r_{\max}} Q_p(\Theta,m,r,\lambda)\,\mathrm{d}\ln r=\int_{\frac{\lambda_{\mathrm{r}}}{\lambda}r_{\min}}^{\frac{\lambda_{\mathrm{r}}}{\lambda}r_{\max}} Q_p(\Theta,m,r,\lambda_{\mathrm{r}})\,\mathrm{d}\ln r$$

It allows us to calculate the inherent optical properties using the corresponding values of integrated cross sections C_p precomputed at the reference wavelength λ_r on the discretized grids (quadratures) of radius, scattering angle, complex refractive index, and stored on the hard drive as a look-up table file.

References
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2. Chemyakin, E., S. Stamnes, S. P. Burton, et al., 2021: Improved Lorenz-Mie look-up table for lidar and polarimeter retrievals. Front. Rem. Sens. 2:711106.

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Quadratures

The quadratures of radius, scattering angle, and complex refractive index define the precision of look-up table and the amount of information stored on the hard drive and in RAM. It is inefficient to store redundant information, but its reduction can have a negative effect on the precision. **Our look-up table represents balance between the two conflicting criteria of precision and size**.

Based on numerical simulations and earlier studies [2], **we use the radius quadrature consisting of 700 log-equidistant grid bins to cover the full-size range of liquid water cloud particles from r_{min} = 10^{-3} to r_{max} = 500 µm**. The look-up table coefficients are computed over the integration intervals formed by the neighboring radius grid bins [2]. We used 10^4 points over each integration interval by setting the Mishchenko et al. Lorenz-Mie program's parameters N=100 and NK=100.

The quadrature of complex refractive index has 1,400 elements to cover:

- **56 real parts of the complex refractive index in the range between 1.25 and 1.36 with a step 0.002**;
- **25 imaginary parts of the complex refractive index: 0, and 24 log-equidistant values between 10^{-5} and 10^{-3}**.

The quadrature of scattering angle consists of 203 angles in the range between 0° and 180°. The quadrature near angles of 0° and 180° has 0.2° and 0.5° spacing because the elements of the normalized scattering matrix **P** can rapidly change there. The rate of change in **P** is comparably small between the angles of 5° and 175° that allows a coarser 1° spacing. The values of inherent optical properties of interest for the other scattering angles can be estimated using interpolation [2].

Table 1. Scattering angles included into the look-up table

##	Scattering angle
1 … 11	0° … step 0.2 ° … 2°
11 … 17	2° … step 0.5° … 5°
17 … 187	5° … step 1° … 175°
187 … 193	175° … step 0.5° … 178°
193 … 203	178° … step 0.2° … 180°

Example of application

NASA's Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE) field campaign is a good source of data to investigate relationships between cloud microphysics and lidar ratio. ACTIVATE employs two aircraft: UC-12 King Air with the NASA LaRC High Spectral Resolution Lidar (HSRL-2) on-board, and HU-25 Falcon with instruments conducting in situ aerosol, cloud, and trace gas measurements.

We use the results of measurements from the Cloud Droplet Probe (CDP) that provides the size distribution of cloud droplets in the radius range of 1—25 µm in 30 size bins. We can assume the complex refractive index to be equal to m = 1.33557 - i1.825 · 10^{-9}, and then with the help of look-up table compute the lidar ratio at wavelength λ = 0.532 µm.

Using HSRL-2 data, it is possible to determine the cloud top height and measure the lidar ratio at wavelength λ = 0.532 µm. For the comparisons with CDP results, we should include only the single-scattering liquid cases near cloud top. Low values of depolarization measured by HSRL-2 can help us to identify such kind of liquid water cloud cases.

The UC-12 King Air and HU-25 Falcon aircraft flight patterns are complementary but different. For the comparisons, we use only the HSRL-2 and CDP data that are collocated in space and time.

The measurement day of Sep 22nd 2020 provided us with five cloud measurement points that are collocated within 150 seconds in time, 500 meters horizontally, and 50 meters vertically. Figure 1 shows distribution of lidar ratios measured by HSRL-2 and derived from CDP measurements using direct integration (see triangles in Fig. 1) and look-up table (see squares in Fig. 1) for these five points. **The results obtained from direct integration match those obtained from the look-up table within 1%**. The HSRL-2 and CDP lidar ratios are within 0.8 sr from each other (see dashed lines in Fig. 1 showing the 0.8 sr border) and the error introduced by using the look-up table is small.

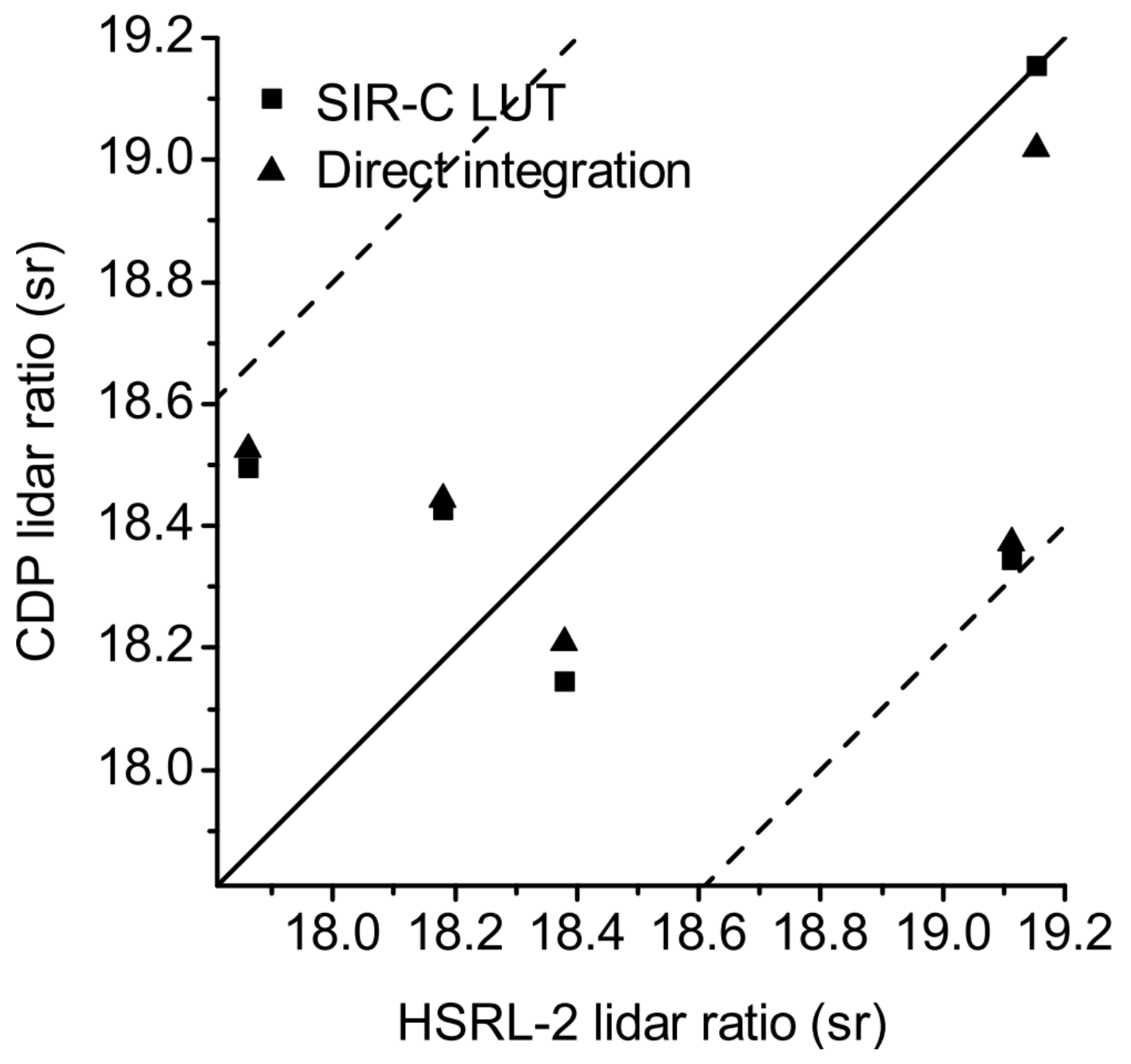

Fig. 1. Comparison of lidar ratios at wavelength λ = 0.532 µm resulting from the HSRL-2 and CDP measurements.

Unit tests

For the comparisons we conducted 10^5 random unit tests. We used monomodal lognormal particle size distributions n(r) defined by its effective radius and effective variance. A uniform random number generator provided evenly distributed values of wavelength λ in the range from 0.35 to 2.3 µm, effective radius from 0.1 to 100 µm, effective variance from 0.05 to 0.6, real part of the complex refractive index from 1.25 to 1.36, and imaginary part of the complex refractive index from 0 to 10^{-3}. **Using random inputs together with the Bohren and Huffman program, we computed the simulated truth values for all the inherent optical properties and compared them to the corresponding look-up table values.**

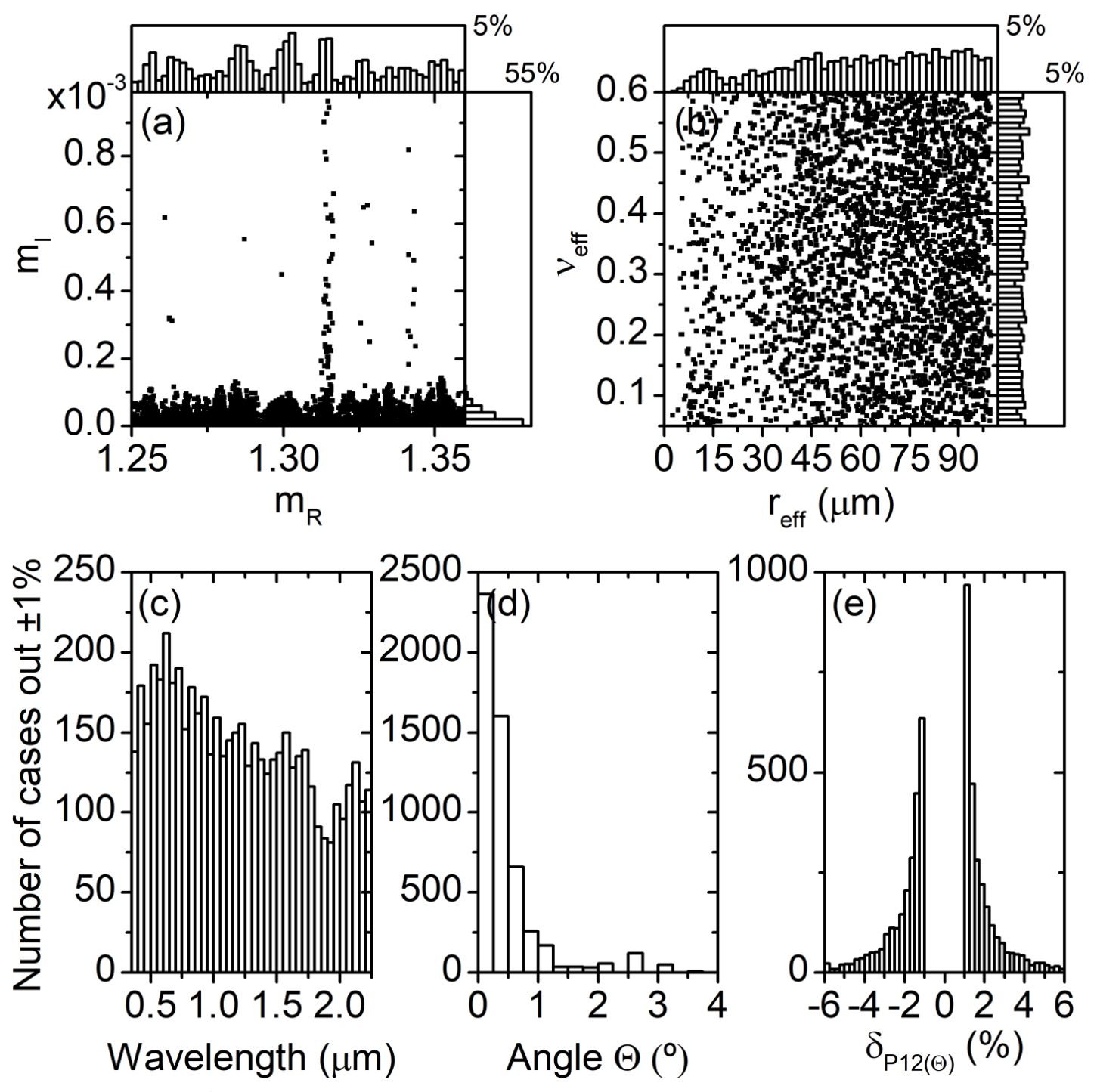

Fig. 2. **The ±1% precision for normalized scattering matrix element P_{12} was not achieved in 3.34% (or 3,342) of the test cases.** Panels (a) and (b) show the distribution of problematic test cases for microphysical properties; (c) and (d) show the problematic wavelengths and scattering angles; (e) shows the relative difference.

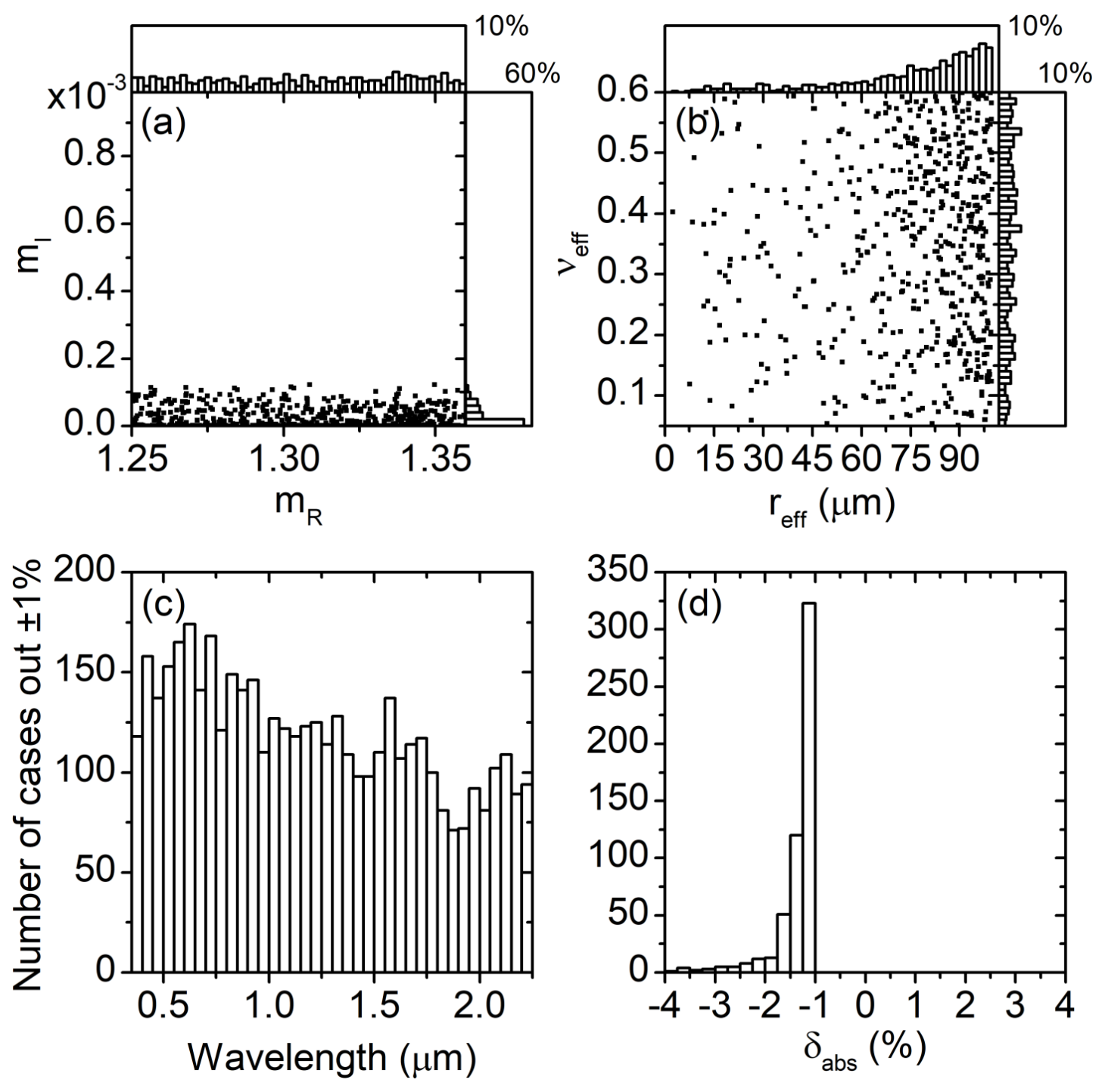

Fig. 3. **The ±1% precision for absorption coefficient k_{abs} was not achieved in 0.55% (or 549) of the test cases.** Panels (a) and (b) show the distribution of problematic test cases for microphysical properties; (c) show the problematic wavelengths; (d) shows the relative difference.

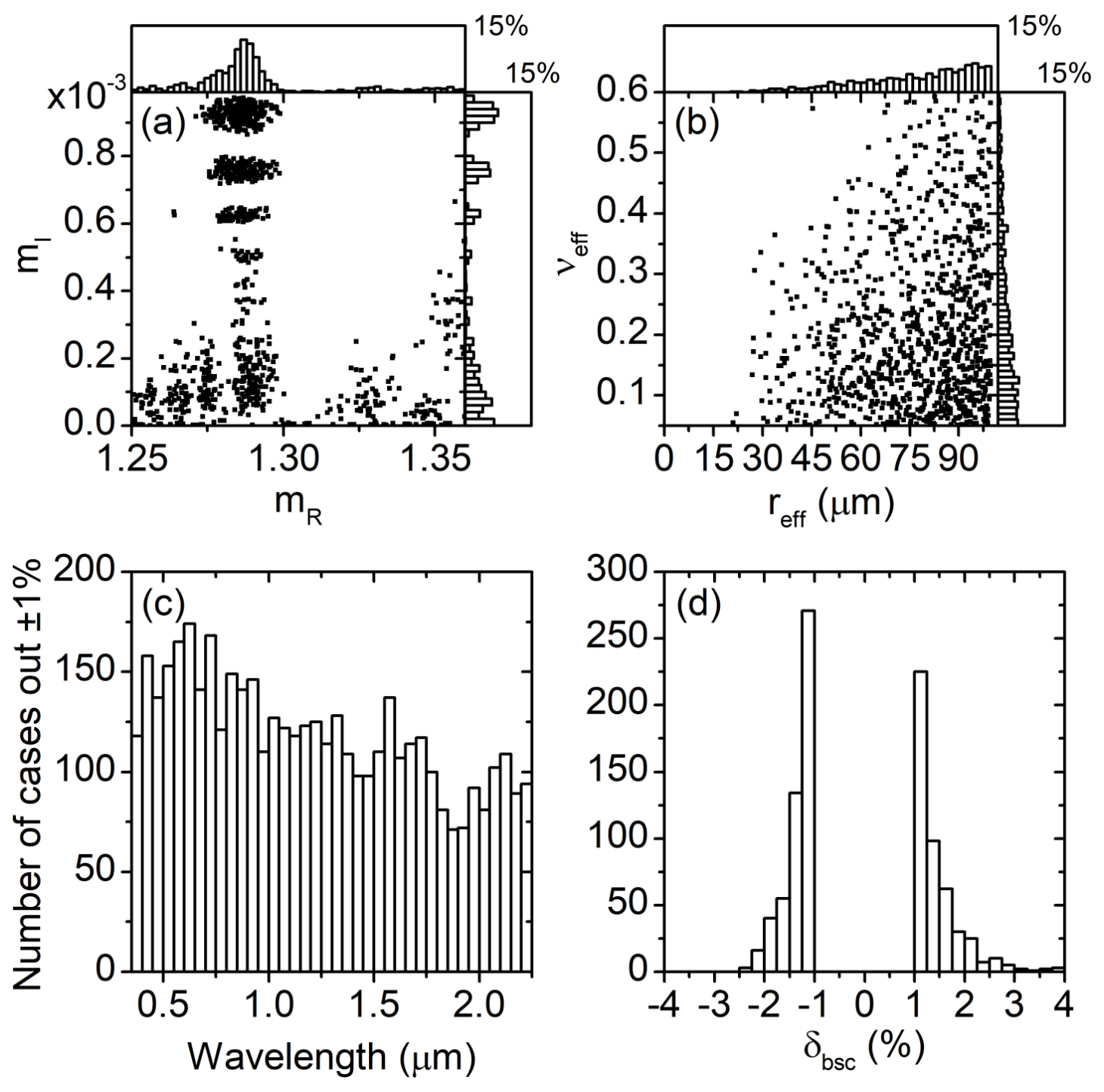

Fig. 4. **The ±1% precision for backscatter coefficient k_{bsc} was not achieved in 1% (or 993) of the test cases.** Panels (a) and (b) show the distribution of problematic test cases for microphysical properties; (c) show the problematic wavelengths; (d) shows the relative difference. Problematic test cases for the lidar ratio are distributed similarly.