Contrails and Induced Cirrus: Optics and Radiation

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ABSTRACT

This paper summarizes the assessment of the current state of knowledge, areas of uncertainties and recommendations for future efforts, regarding the optical and radiative properties of contrails and contrail-cirrus clouds, which have been reported in two detailed subject-specific white papers for the Aviation Climate Change Research Initiative undertaken by the U.S. Federal Aviation Administration. To better estimate the radiative forcing of aircraft-induced clouds, there is an urgent need to improve the present understanding of the optical properties of nonspherical ice crystals within contrails and contrail cirrus and to enhance the global satellite detection/retrieval of these clouds. It is also critical to develop appropriate parameterizations of ice crystal bulk optical properties for climate models on the basis of the state-of-the-art scattering simulation results and available in situ measurements of ice crystal size and habit distributions within contrail and contrail cirrus. More accurate methods are needed to retrieve contrail and contrail-cirrus cloud bulk radiative properties to separate natural from anthropogenic ice cloud effects. Such refined techniques should be applied to past and future satellite imagery to develop a contrail climatology that would serve to evaluate contrail radiative forcing more accurately, determine trends in anthropogenic cirrus, and guide and validate parameterizations of contrails in numerical weather and climate models. To point the way forward, we recommend four near-term and three long-term research priorities.

CAPSULE

Improving the present understanding of optical properties of contrails and contrail cirrus and enhancing the global satellite detection/retrieval of these clouds will greatly benefit the evaluation of the radiative impact of aircraft-induced clouds on climate change.

Cloud radiative forcing, the difference between the top-of-atmosphere radiative fluxes for all-sky and clear skies, is a straightforward metric to gauge the climate impacts of contrails and contrail-cirrus clouds, which constitute a potentially serious long-term environmental issue associated with aviation (Minnis et al. 2004; Wuebbles et al. 2009). The IPCC Special Report on Aviation and the Global Atmosphere (1999) reported a best estimate of the global mean contrail radiative forcing of approximately 0.02 Wm^{-2} based on the study of Minnis et al. (1999), albeit this value is highly uncertain. Even if the global mean radiative forcing is that small, regional effects may be much larger.

Studies of the radiative effects of contrails have made use of various datasets, models, and methods and have examined satellite images of both linear contrails and contrail clusters. Duda et al. (2001) used satellite data to investigate the evolution of radiative properties of contrail clusters over the United States and suggested that ice crystal shape may exert important effects on contrail radiative forcing. To better estimate the radiative forcings of these aircraft-induced clouds, it is necessary to improve our knowledge about their fundamental optical and radiative properties. This study, based on two subject-specific white papers for the Aviation Climate Change Research Initiative undertaken by the U.S. Federal Aviation Administration, assesses the present state of knowledge and identifies areas of uncertainty with recommendations for future action.

Contrails and contrail-cirrus clouds consist almost exclusively of nonspherical ice crystals. For example, in situ samples of contrail ice crystals taken at –61°C reveal several ice habits:

hexagonal plates (75%), columns (20%), and a few triangular plates (<5%) (Goodman et al. 1998). The nonsphericity of these crystals must be taken into account in parameterizing the bulk contrail single-scattering properties for climate model applications and in simulating contrail and contrail-cirrus cloud radiative forcing. Moreover, to infer correctly contrail or contrail-cirrus properties from remote sensing techniques, single-scattering properties associated with realistic ice crystal morphologies must be used.

Scientific Context

Due to substantial increase in air traffic over the globe, it is likely that a large amount of soot particles, sulfur compounds, and water vapor emitted from aircraft have infiltrated the upper atmosphere, causing increased frequency in the occurrence of contrails and contrail-induced cirrus clouds (Liou et al. 1990; Minnis et al. 2004). Figure 1 shows that, based on surface observations and satellite data, there is an upward trend of cirrus cloud cover over the past 50 years near U. S. flight corridors, and that this increase corresponds to the rising trend of jet fuel consumption. Although the overall coverage of contrails and contrail-cirrus clouds is much less than that of naturally formed cirrus clouds, their radiative effects are not negligible near the flight corridors where they occur most frequently. The assessment of impacts of increased cloud cover due to contrails requires the continuous characterization of contrails and their environment over their entire lifetimes.

The optical properties of contrails are strong functions of their optical depth, effective radius, and ice crystal habit, as well as the background radiation fields, all of which vary with time. Since

few field campaigns have been designed to study contrails from formation to dissipation, the temporal variation of contrail ice crystal shape during a contrail's lifetime is unknown. Figure 2 illustrates the importance of ice crystal shape for characterizing radiative processes. Specifically, the solar albedos for ice clouds, calculated by assuming mixtures of various ice particle habits (blue lines) and spherical ice particles (red lines) are compared with in situ measurements (Stackhouse and Stephens 1991) from a field campaign. For ice clouds with effective particle sizes less than 100 µm, the assumption of ice spheres leads to an underestimation of solar albedos, particularly so for effective particle sizes less than 60 µm, a range that overlaps the range of ice crystal sizes for contrails (see Heymsfield et al. 2009).

While the radiative differences between various nonspherical particles are likely to be smaller than those shown in Fig. 2, it is clear that the ice crystal shape is an important component in determining the contrail radiative impact. Figure 3 shows the scattering phase function (a quantity describing the angular distribution of the scattered energy) computed from an improved geometric optics method (Yang and Liou 1996) for six randomly oriented ice crystal habits, at a wavelength of 0.65 µm and for a maximum particle dimension of 50 µm. All habits except aggregate display pronounced halos in the forward-scattering direction of the phase functions. In the case of aggregate, the prescribed surface roughness smoothes out the halo peaks. The shape of the phase function in the backscattering directions also differs from one habit to another, implying representative ice crystal habit distribution models are needed for accurate remote sensing of contrails and simulation of the contrail radiative properties.

Ice crystal size is also a key factor governing the spectral variation of ice crystal single-scattering properties. Figure 4 shows the mass extinction coefficient, single-scattering albedo, and asymmetry factor for the solar spectral region (0.2–4 μm) and for four different effective ice particle sizes, based on the same mixture of ice particle habits as in Fig. 2. It is noted that the bulk optical properties of ice crystals are quite sensitive to the effective particle size.

Various methods (Mishchenko et al. 2000, and references cited therein), such as the finite-difference time-domain, discrete dipole approximation, T-matrix, and geometric optics methods, have been developed for scattering computations involving nonspherical particles. The applicability of each method depends strongly on the shape and size of the particle. Thus, a suite of the existing state-of-the-art scattering computational methods allows us to compute single-scattering properties of ice particles in contrails, provided that sufficient computational resources are allocated.

Accounting for the ice particle optical properties is the first step in determining the radiative effects of aircraft-induced clouds. The variation of ice water path along with the particle shape and size distributions determine the spectral optical depths and, hence, how much shortwave radiation is either reflected or absorbed and how much longwave radiation is absorbed. The shortwave radiative forcing is further governed by the solar zenith angle and the albedo of the underlying surface. The total albedo will increase negligibly for a contrail occurring over a highly reflective surface such as snow or an optically thick cloud, but can rise significantly over dark surfaces such as forests and water. Contrail longwave radiative forcing is affected by the temperature of the contrail and the temperature of the background. Thus, a contrail over a high

cloud or a cold surface may minimally alter the outgoing longwave radiation, while a substantial reduction will result from the same contrail over a relatively warm surface or low cloud. Thus, if a contrail occurs above or within an optically thick high cloud, it will have virtually no radiative impact day or night, but if it develops over a warm, clear tropical ocean, it will have a significant impact at all wavelengths. Finally, the overall effect of the contrails on a regional or the global radiation budget depends on their fractional coverage.

Unknowns and Problems to Be Addressed

A variety of issues must be addressed to reduce uncertainties in the assessment of radiative forcing of contrails and contrail-induced cirrus clouds. The single-scattering properties for at least the predominant particle habits in these clouds must be determined. These optical properties should serve as the basis for parameterizations of the radiative properties of contrails and contrail-induced cirrus clouds for applications to climate models and the retrieval of contrail properties from satellite observations. Although laboratory measurements of the optical properties of ice crystals provide very useful information, they are quite limited in terms of the spectral coverage and in angular range necessary for the measurements of the scattering phase function, and they usually lack a complete set of the single-scattering properties; that is, the phase function, extinction cross sections, and single-scattering albedo are not measured simultaneously. Thus, for many practical applications, a theoretical approach is generally used to infer the single-scattering properties for a wide variety of ice crystal habits. So far, however, there is not a suitable scattering database specified for studies involving contrails and contrail-cirrus clouds.

Since most, if not all, climate models contain radiation parameterizations that were developed essentially for natural cirrus clouds, development of new parameterizations of contrail and contrail-cirrus bulk radiative properties may be necessary to represent contrails realistically in the radiative transfer schemes. Building new radiation parameterizations suitable for contrails and contrail-cirrus clouds will bring more accurate estimates of radiative forcing and provide an efficient way to understand the differences between the radiative forcings of contrails, contrail-induced cirrus clouds, and natural cirrus clouds. Development of reliable parameterizations of the radiative properties of aircraft-induced clouds using the aforementioned database of ice crystal optical properties must be guided by a suitable number of in situ measurements of ice particle habit and size distributions, requiring additional aircraft measurements of contrail and contrail-cirrus cloud microphysics.

Satellite remote sensing can complement the theoretical and in situ studies by providing information about where and when contrails occur over the globe; by estimating their bulk radiative properties, such as optical depth, particle size, and temperature; and by providing essential information about the radiative background. But this approach also has limitations. In essence, very young contrails and older contrails that no longer have the characteristic linear shapes are quite difficult to detect. For this reason, most existing contrail radiative forcing studies have focused on linear contrails that are distinguishable from natural cirrus. Although very young contrails are expected to have a negligible effect, their impact has never been estimated. Only a few case studies have directly evaluated the radiative forcing of older contrail-cirrus clouds by tracking the growth and dissipation of contrails (e.g., Duda et al. 2001).

Moreover, the split-window technique typically used to detect and interpret linear contrails often misidentifies natural cirrus clouds as contrails (Minnis et al. 2005), and the retrievals are limited by inadequate knowledge of the contrail ice crystal habits and size distributions. Current estimates of contrail coverage and retrievals of contrail bulk radiative properties are confined to only a few locations, years, and times of day, limiting their utility for validating parameterizations or establishing firm global statistics. Obviously, there is an urgent need to improve the satellite detection of all types of contrails and contrail-cirrus over the globe and to develop more effective algorithms to infer contrail optical thickness and particle sizes along with their radiative environment.

Existing and past satellite sensors, such as interferometers with high-resolutions, imagers that measure narrowband, broadband and polarized radiances, imagers with multiple-viewing-angle capability, and spaceborne lidars, provide an unprecedented opportunity to observe contrails and contrail-cirrus clouds. While it is clear that 1.375 μm reflectances, and 8.55 μm, 11 μm, and 12 μm brightness temperatures are effective for detecting thin and high clouds, including contrails, separating natural and aircraft-generated ice clouds remains a large source of uncertainty. Thus, additional study of the spectral properties of contrails is required to determine the potential for distinguishing contrails from nearly linear cirrus clouds in current and future satellite imagers. It is highly recommended that existing and ongoing satellite datasets should be used synergistically to quantify the extent of contrails and contrail-cirrus clouds climatologically on both global and regional scales.

The Way Forward

An adequate evaluation of the radiative forcing of contrails and contrail-cirrus clouds hinges on improving our knowledge of the microphysical, macrophysical, and chemical properties of these clouds. To this end, four near-term priorities have been identified for the best use of the currently available tools to reduce uncertainties in assessing the climate impact of contrails and contrail-cirrus clouds. Specifically, it is recommended to (1) develop datasets representing contrail particle single-scattering properties from existing light scattering models, which will use realistic shapes and sizes of ice crystals observed in these clouds; (2) parameterize the radiative properties of contrails and contrail-cirrus for use in global and regional climate models; (3) accurately determine contrail coverage, optical properties, and radiative forcing from a variety of satellite datasets; and (4) carry out a small-to-medium scale contrail/contrail-cirrus field experiment in an air traffic corridor to support optical property and radiative forcing calculations and remote sensing validation.

As longer-term priorities, it is recommended to (1) use coupled meteorology and chemistry models with ice microphysical and spectral radiative transfer modules to study the predictive capabilities and radiative forcing effects of contrails and contrail-cirrus; (2) understand the development of contrail-cirrus clouds on the basis of numerical models with supersaturation capability, while exploring the use of sensors on commercial aircraft to improve water-vapor/contrail relationships; and (3) study aerosol indirect effect on ice clouds on the basis of satellite data in order to estimate the extent and impacts of aircraft-aerosol induced cirrus.

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Figure 1. Mean annual high cloud cover over Salt Lake City from 1948 to 1992 and domestic jet

fuel consumption (after Liou et al. 1990). The two solid lines are the statistical fitting curves for

high cloud cover for 1948–1964 and 1965–1992. The statistical fitting curve for the entire period

is denoted by the heavy line. Also shown are cirrus cloud covers for several mid-latitude cities

from 1945 to 1992.

Figure 2. Solar albedo as a function of ice water path determined from broadband flux

observations (cross dots) from aircraft for cirrus clouds that occurred during the FIRE

experiment, Wisconsin, November-December, 1986 (Stackhouse and Stephens 1991). The blue

lines represent the theoretical results computed from DISORT with a mixture of various ice

habits used in MODIS Collection 5 of ice cloud retrieval products. The red lines represent the

results with an assumption of ice spheres.

Figure 3. Scattering phase functions at 0.65 μm wavelength for a maximum dimension of 50 μm

computed by an improved geometric optics method (Yang and Liou 1996), for six ice crystal

habits: (a) plate, (b) hexagonal solid column, (c) hollow column, (d) aggregate, (e) bullet rosette,

and (f) droxtal.

Figure 4. Mass extinction coefficient (a), single-scattering albedo (b), and asymmetry factor (c)

as functions of wavelength from 0.2 to 4 μm. The minima/maxima located at 2.85 μm are the

well-known Christiansen effect. Ice clouds are assumed have a mixture of various habits as
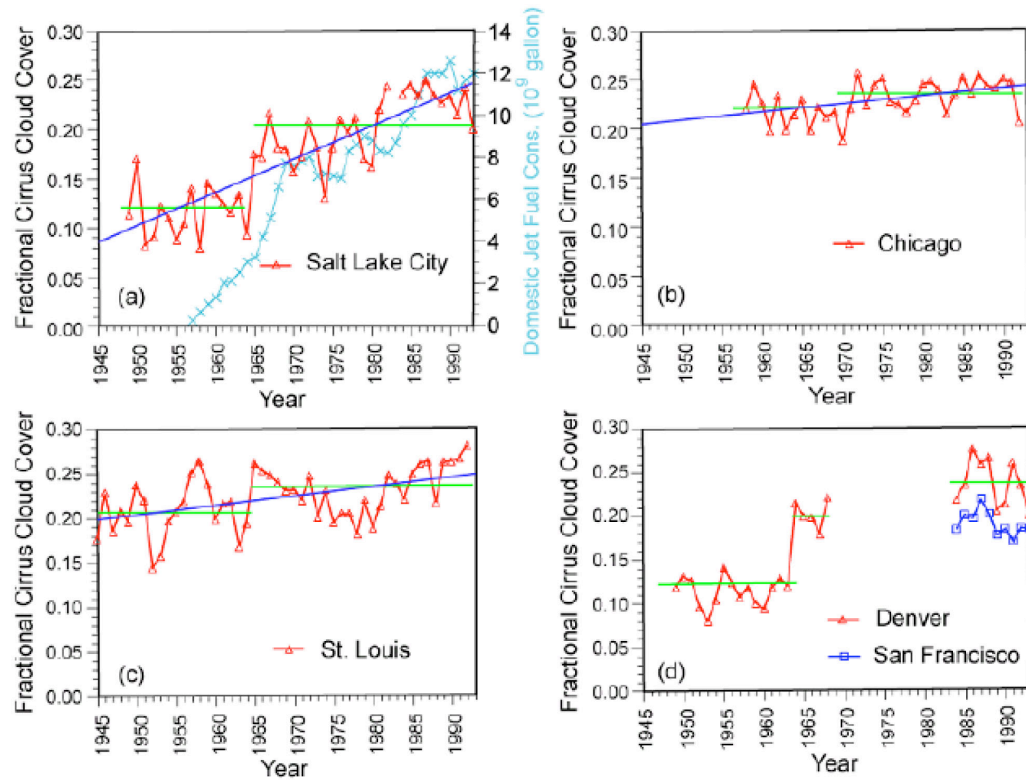
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FIGURE 2

A Mixture of Various Ice Particle Habits

- maximum dimension D < 60 μm: 100%
- 60 μm < D < 1000 μm: 15%   + 50%   + 35%
- 1000 μm < D < 2500 μm: 45%   + 45%   + 10%
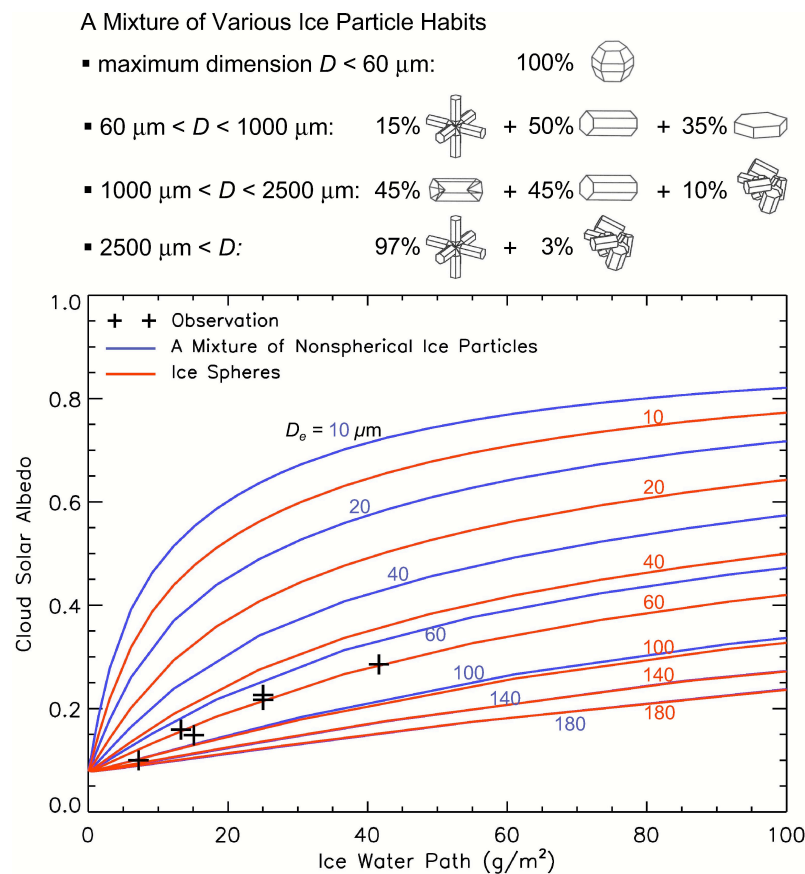- 2500 μm < D: 97%   +   3%

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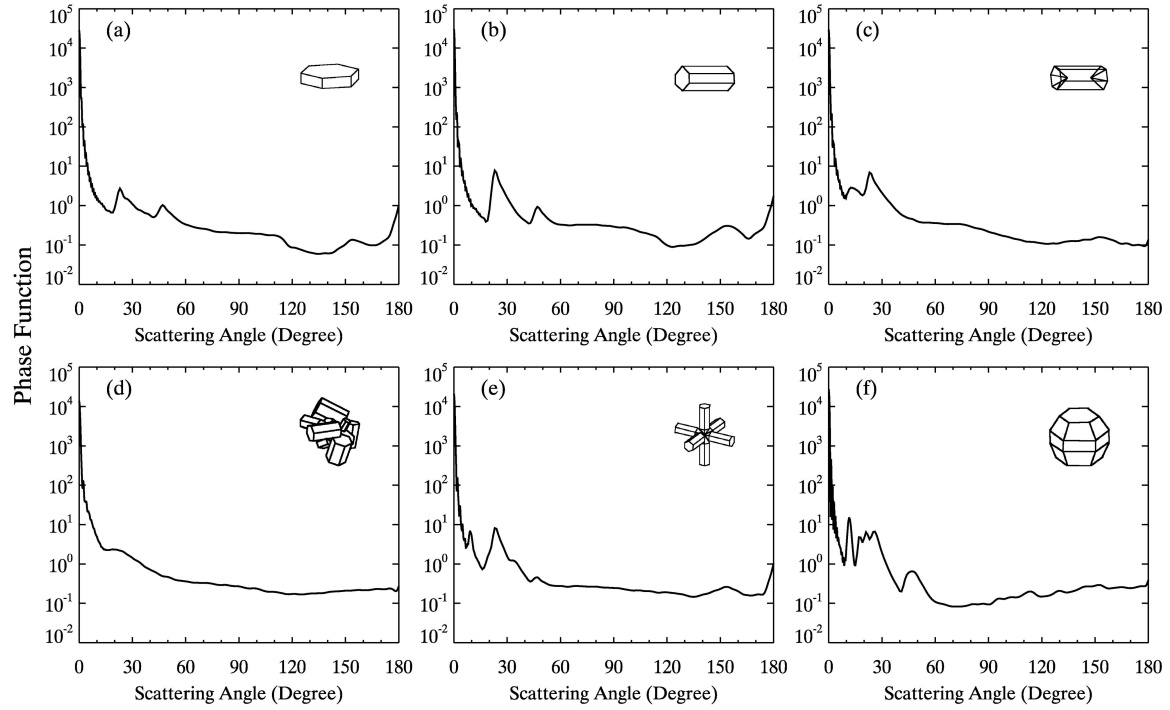
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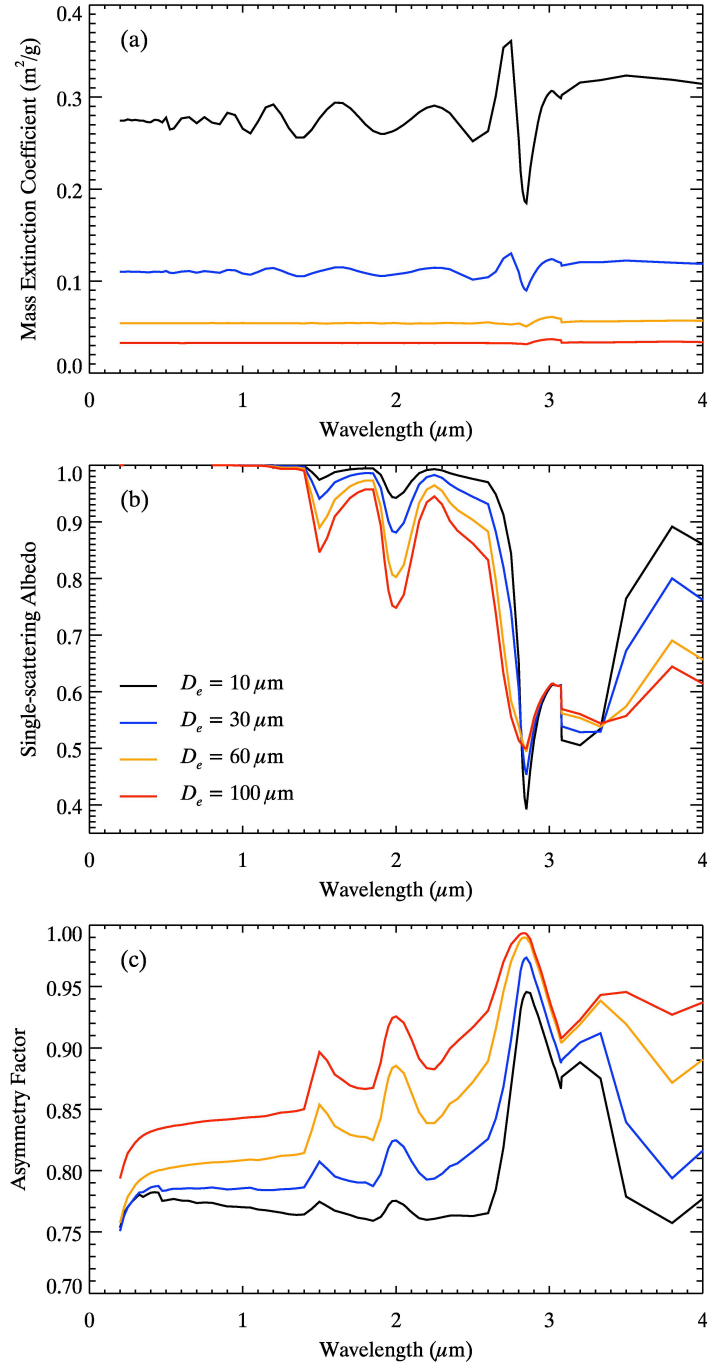
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