

# CONTRAILS AND INDUCED CIRRUS

## Optics and Radiation

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Improving the present understanding of the optical properties of contrails and contrail cirrus and enhancing the global satellite detection and retrieval of these clouds will greatly benefit the evaluation of the radiative impact of aviation-induced cloudiness 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, which constitute a potentially serious long-term environmental issue associated with aviation (Minnis et al. 2004; Wuebbles et al. 2010). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Aviation and the Global Atmosphere (Penner et al. 1999) reported a best estimate of the global mean contrail radiative forcing of approximately  $0.02 \text{ W m}^{-2}$  based on the study of Minnis et al. (1999), albeit a highly uncertain value. 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 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 contrails and contrail cirrus, it is necessary to improve our knowledge about their fundamental optical and radiative properties. This study, based on two subject-specific white papers (Ou and Liou 2008; Yang et al. 2008) for the Aviation Climate Change Research Initiative undertaken by

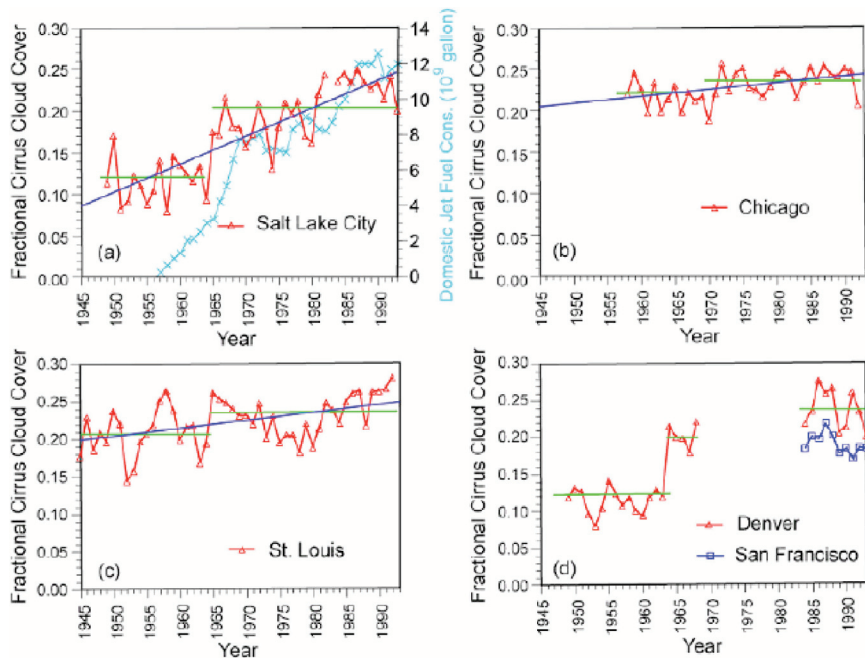
the U.S. Federal Aviation Administration, assesses the present state of knowledge and identifies areas of uncertainty with recommendations for future action.

Contrails and contrail cirrus consist mainly of nonspherical ice crystals. The aircraft-generated ice crystal habits (i.e., shapes) may be similar to those in natural cirrus, but their distributions (i.e., the percentage of various habits) may be different from those in natural ice clouds. For example, in situ samples of contrail ice crystals taken at  $-61^\circ\text{C}$  revealed several ice habits: hexagonal plates (75%), columns (20%), and a few triangular plates ( $<5\%$ ; see Goodman et al. 1998), whereas quite a different habit distribution, inferred from in situ observations, has been reported for natural ice clouds (Baum et al. 2005) that have been assumed to consist of droxtals (100%) for  $D_{\text{max}} < 60 \mu\text{m}$ , where  $D_{\text{max}}$  denotes the maximum dimensions of the ice particles; 3D bullet rosettes (15%), solid columns (50%), and hexagonal plates (35%) for  $60 < D_{\text{max}} < 1000 \mu\text{m}$ ; hollow columns (45%), solid columns (45%), and aggregates (10%) for  $1000 < D_{\text{max}} < 2000 \mu\text{m}$ ; and 3D bullet rosettes (97%) and aggregates (3%) for  $D_{\text{max}} > 2000 \mu\text{m}$ . The nonsphericity of

these crystals must be taken into account when parameterizing the bulk contrail single-scattering properties for climate model applications and when simulating contrails and contrail cirrus radiative forcing. Moreover, to infer correctly the microphysical and optical properties of contrails or contrail cirrus from remote sensing techniques, single-scattering properties associated with realistic ice crystal morphologies must be used.

### SCIENTIFIC CONTEXT.

Because of substantial increases in air traffic over the globe, it is likely that large amounts of soot particles, sulfur compounds, and water vapor have been emitted by jet aircraft into the upper atmosphere, which are directly responsible for the occurrence of contrails and contrail cirrus (Liou et al. 1990; Minnis et al. 2004). Based on surface observations and satellite data, Fig. 1 shows an upward trend of cirrus cloud cover over the past 50 yr near U.S. flight corridors, and this increase appears to correspond to the rising trend of jet fuel consumption. Although the



**FIG. 1.** Mean annual high cloud cover over Salt Lake City, Utah, from 1948 to 1992 and domestic jet fuel consumption (after Liou et al. 1990). Statistical fitting curves for high cloud cover for 1948–64 and 1965–92 (solid lines). The statistical fitting curve for the entire period is denoted by the heavy line. Also shown are cirrus cloud covers for several midlatitude cities from 1945 to 1992.

overall coverage of contrails and contrail cirrus is much less than that of naturally formed cirrus, their radiative effects are not negligible near the flight corridors where they occur most frequently. The assessment of the impact of increased cloud cover resulting from contrails requires the continuous characterization of contrails and their environment over their entire lifetimes. Moreover, it is difficult to estimate the radiative forcing of contrails and contrail cirrus from a global perspective because the global coverage and optical properties of these clouds are not well quantified.

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, which are parameters that vary with time. The radiative forcing of contrails and contrail cirrus is sensitive to the optical depths of these clouds. The optical depths of contrails measured from passive satellite imagers are typically between 0.1 and 0.5 (Minnis et al. 2005), but they can be much smaller, and values larger than 1 are not uncommon. Different values of the mean contrail optical depth have been used to study the global and regional contrail radiative forcing, leading to uncertainties in the current understanding of contrail forcing. Furthermore, few field campaigns have been designed to study contrails

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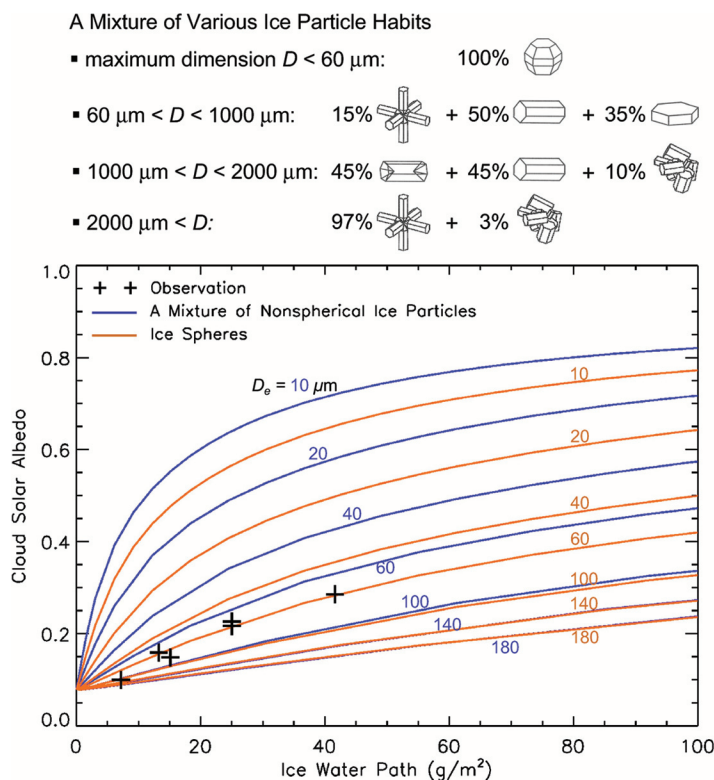
from formation to dissipation, and the temporal variation of contrail ice crystal shape during a contrail's lifetime is unknown. Figure 2 illustrates the importance of ice crystal shape for characterizing radiative processes. Specifically, the solar albedos for ice clouds, calculated by assuming mixtures of various ice particle habits (Baum et al. 2005), and spherical ice particles are compared with in situ measurements (Stackhouse and Stephens 1991) from a field campaign. For ice clouds with effective particle sizes less than  $100\ \mu\text{m}$ , the assumption of ice spheres leads to an underestimation of solar albedos, particularly for effective particle sizes less than  $60\ \mu\text{m}$ , which is a range that overlaps the range of ice crystal sizes for contrails (see Heymsfield et al. 2010).

While differences in radiative properties between various nonspherical particles are likely to be smaller than those shown in Fig. 2, it is clear that ice crystal shape is an important component in determining the contrail radiative impact, similar to the case for natural ice clouds (Zhang et al. 1999). Figure 3 shows the scattering phase function, which describes 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  $0.65\ \mu\text{m}$  and for a maximum particle dimension of  $50\ \mu\text{m}$ . All habits except ice crystal aggregates display pronounced halos in the forward-scattering direction of their phase functions. In the case of aggregates, the prescribed surface roughness smooths out halo peaks. The shape of the phase function in backscattering directions also differs from one habit to another, implying that representative ice crystal habit distribution models are needed for accurate determination of contrails from remote sensing and simulation of the contrail radiative properties.

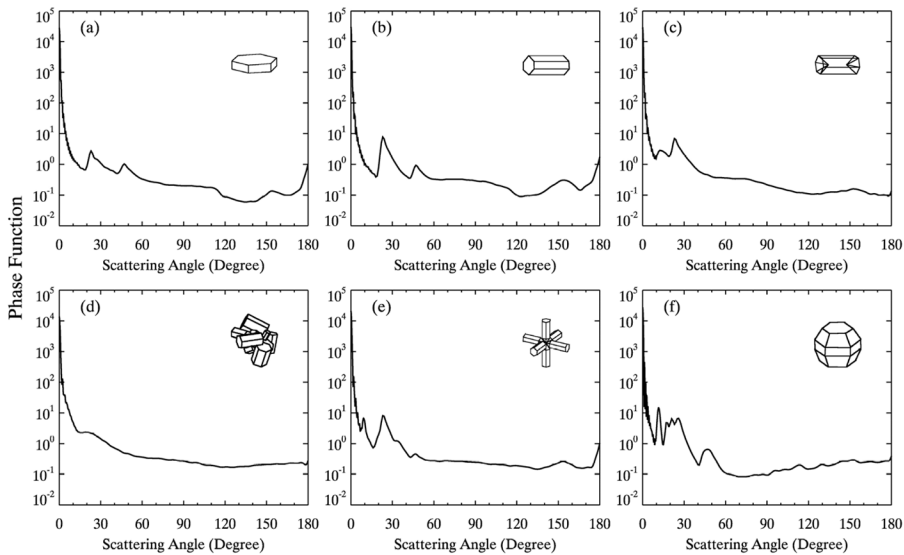
Ice crystal size is also a key factor governing the spectral variation of ice crystal single-scattering properties. Figure 4 shows the mass extinction coefficient, single-scattering albedo, and asymmetry factor for the solar spectral region from  $0.2$  to  $4\ \mu\text{m}$  and for four different effective ice particle sizes based on the same mixture of ice particle habits as those in Fig. 2. It is noted that the bulk optical properties of ice crystals vary substantially with 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, have been developed for scattering and absorption computations involving nonspherical particles. The applicability of each method depends significantly on particle shape and size. Thus, a suite of the existing state-of-the-art scattering computational methods is now available for computing the single-scattering properties of ice particles in contrails, provided that sufficient computational resources are available.

However, there is no established method for estimating the radiative forcing of contrail cirrus (Burkhardt et al. 2010), and accounting for the ice particle optical properties is important for determining the radiative effects of contrails and contrail cirrus clouds. Variations in ice water path and the particle shape and size distributions determine the spectral optical depths and, hence, the amount of shortwave radiation that is either reflected or ab-



**FIG. 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 First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment, Wisconsin, Nov–Dec 1986 (Stackhouse and Stephens 1991). Theoretical results computed with a mixture of various ice habits (blue lines; see Baum et al. 2005), and the results with an assumption of ice spheres (red lines).



**FIG. 3. Scattering phase functions at  $0.65\text{-}\mu\text{m}$  wavelength for a maximum dimension of  $50\ \mu\text{m}$  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.**

sorbed and the amount of longwave radiation that is absorbed. Additionally, the shortwave radiative forcing is further governed by the solar zenith angle and the underlying surface albedo. The total albedo will not increase significantly for a contrail occurring over a highly reflective surface, such as snow or an optically thick cloud; however, it can rise substantially over dark surfaces such as forests and water. Both contrail temperature and the temperature of the background affect contrail longwave radiative forcing. Thus, a contrail over a high cloud or a cold surface will have a minimal impact on outgoing longwave radiation, while a substantial reduction will result from the same contrail over a relatively warm surface or a low cloud. Thus, if a contrail occurs above or within an optically thick high cloud, it will have virtually no radiative impact in either the day or night; however, if it develops over a warm, clear tropical ocean, it will have a significant impact at all wavelengths. Furthermore, the overall effect of the contrails on a regional or the global radiation budget depends on their fractional coverage.

**UNKNOWN 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 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 cirrus for applications to climate models and the retrieval of contrail properties from satellite observations. Although laboratory measurements of the optical properties of ice crystals have provided very useful information, they are quite limited in terms of the spectral coverage and the angular range that is necessary for measurements of the scattering phase function. Moreover, these measurements usually lack a complete set of the single-scattering properties; that is, the

phase function, the extinction cross section, and the single-scattering albedo have not been 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. Thus far, however, a suitable scattering and absorption database specified for studies involving contrails and contrail cirrus is still lacking.

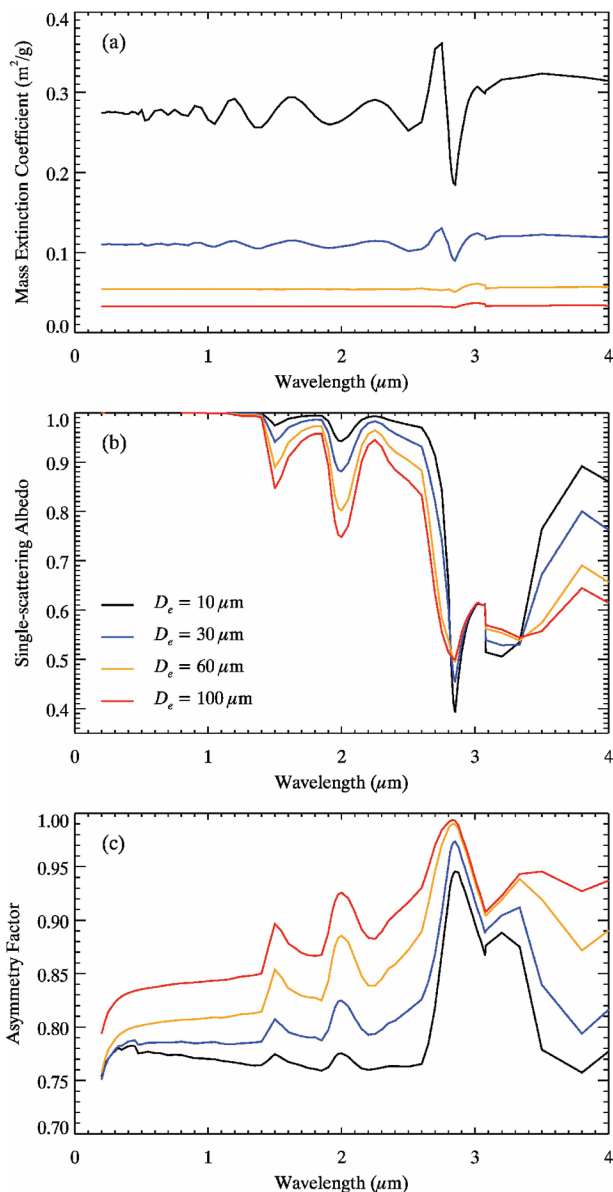
Essentially all climate models contain radiation parameterizations that have been developed for natural cirrus. Thus, it is necessary to develop new parameterizations for the bulk single-scattering properties of contrail and contrail cirrus for incorporation in radiative transfer and climate models. Building new radiation parameterizations suitable for contrails and contrail cirrus would reduce uncertainties in the estimation of their radiative forcing and provide an efficient way to understand the differences between the radiative forcings of contrails, contrail cirrus, and natural ice clouds. Development of reliable parameterizations of the radiative properties of contrails and contrail cirrus 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 microphysics of contrail and contrail cirrus.

Satellite remote sensing can complement theoretical and in situ studies by providing information on both 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 concerning the radiative background; this approach has limitations, however. In essence, contrail cirrus that no longer has the characteristic linear shape is indistinguishable from natural cirrus. For this reason, most existing contrail radiative forcing studies have focused on 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 contrail cirrus 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 have been 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 a pressing 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 depth and particle sizes along with their radiative environment.

Existing and past satellite sensors—such as interferometers with high spectral resolutions; imagers that measure narrowband, broadband, and polarized radiances; imagers with multiple-viewing-angle capabilities; and spaceborne lidars—provide an unprecedented means of observing contrails and contrail cirrus. While it is clear that 1.375- $\mu\text{m}$  reflectances and 8.55-, 11-, and 12- $\mu\text{m}$  brightness temperatures are effective for detecting thin and high clouds, including contrails, separating natural and anthropogenic 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 climatologically on both global and regional scales. Field campaigns with various instruments (e.g., a lidar, upper-air radiosonde, and radiometer) can be valuable for both validating satellite retrieval products and improving our understanding of the optical and microphysical properties of contrails and contrail cirrus.



**FIG. 4.** (a) Mass extinction coefficient, (b) single-scattering albedo, and (c) asymmetry factor as functions of wavelength from 0.2 to 4  $\mu\text{m}$ . The minima/maxima located at 2.85  $\mu\text{m}$  are the well-known Christiansen effect. Ice clouds are assumed to have a mixture of various habits, as shown in Fig. 2.

**THE WAY FORWARD.** An adequate evaluation of the radiative forcing of contrails and contrail cirrus hinges on improving our knowledge of the microphysical, macrophysical, and chemical properties and coverage 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. Specifically, it is recommended that we 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 that we 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 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 the aerosol indirect effect on ice cloud formation on the basis of satellite data in order to estimate the extent and impact of soot cirrus (Heymsfield et al. 2010).

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