Radiative Properties of Ice Clouds

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Introduction

A new treatment of cirrus cloud radiative properties has been developed, based on anomalous diffraction theory (ADT), which does not parameterize size distributions in terms of an effective radius (partially published in Mitchell and Arnott 1994). Rather, it uses the size distribution parameters directly, and explicitly considers the ice particle shapes. There are three fundamental features which characterize this treatment: 1) the ice path radiation experiences as it travels through an ice crystal is parameterized, 2) only the physical cross-section or projected area of the particle determines the amount of radiation scattered and absorbed, and 3) as in other treatments, the projected area of the size distribution is conserved. The first two features are unique to this treatment, since it does not convert the ice particles into equivalent volume or area spheres in order to apply Mie theory.

It may not be obvious that the second feature differs from Mie theory. However, Mie theory predicts that the absorption and extinction cross-section of a sphere can be (and often is) substantially greater than would be predicted from its physical cross-section. This involves the capture of photons which have approximately tangential trajectories to the sphere. Once captured, they can either be scattered or absorbed into the sphere. By capturing photons which do not actually collide with the sphere, the absorption cross-section for a sphere becomes greater than the sphere's physical cross-section. Now, the question is, does this same physics also apply to ice?

Testing the Cirrus Radiation Scheme with Laboratory Measurements

Measurements of extinction efficiency (Q_{ext}) were made in a laboratory ice cloud over wavelengths in the thermal infrared. Mean size parameters ($x = \pi\bar{D}/\lambda$, $\bar{D}$ = mean maximum dimension of size distribution, λ wavelength) corresponding to these measurements ranged from 1.2 to 11.0. Details can be found in Arnott et al. (1995). Figure 1 gives the results of this study for an ice cloud of hexagonal columns. The sizes and concentrations of the ice crystals were measured, and the estimated $\bar{D}$ was 7 to 8 µm. The short-dashed curves depict the laboratory measurements. The solid curve was generated by the new ADT treatment, assuming $\bar{D}$ = 8 µm. The minima shown are extremely sensitive to ice crystal size and only occur when sizes are relatively small and the real index of refraction, n_r, approaches 1. The agreement of the measurements with the ADT curve indicates the ice crystal path of the radiation was well represented (feature 1 above). The long-dashed curve was predicted by Mie theory, based on $\bar{D}$ = 8 µm. Agreement between Mie theory and observations becomes poorer away from the minima where $n_r > 1$.

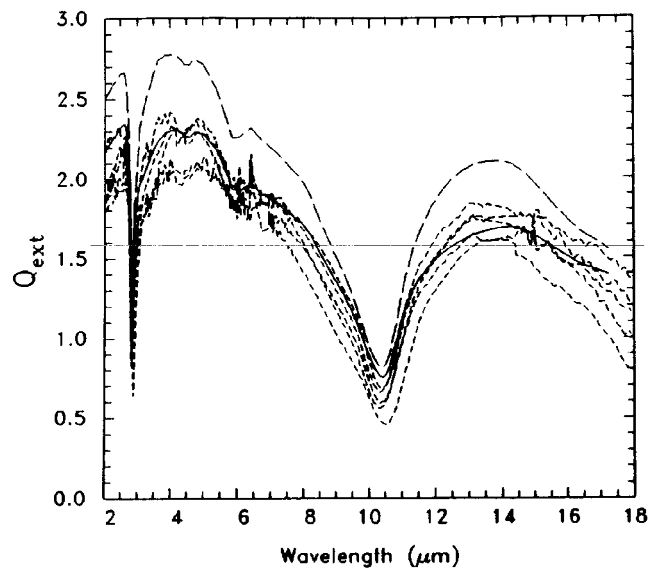

Figure 1. Extinction efficiency measurements (short-dashed curves) for an ice cloud of hexagonal columns, having a mean size ($\bar{D}$) of 7-8 µm. Using $\bar{D}$ = 8 µm, the solid curve was predicted by the new cirrus radiation treatment, while the long-dashed curve was predicted from Mie theory.

To apply Mie theory, column ice crystals were converted to equivalent distance (D_e) spheres, where the distance radiation travels through a crystal and corresponding ice sphere sphere are equal. The size distribution projected area was conserved. These operations allow us to directly compare our treatment with Mie theory.

A similar comparison between lab measurements and theory was made when the ice cloud was composed primarily of hexagonal plates, and $\bar{D}$ was 14 µm. Agreement between ADT and experiment in this case was equally as good as the case with columnar crystals.

Physical Explanation for the Behavior of Q_{ext}

The cause of the extinction minima near 2.8 µm and 10.3 µm is the result of the real part of the refractive index, n_r, approaching a value of 1.00. When $n_r = 1$, scattering due to refraction and reflection is minimized. Thus, the alteration of radiation transmitted through an ice crystal will be reduced, contributing less to extinction. Also, when $n_r = 1$, there is no phase lag for waves passing through the crystal, so there is no wave interference contribution to extinction. This leaves diffraction and absorption to contribute to Q_{ext} at the extinction minima. With just these two processes, $Q_{ext} \approx 2$ when absorption is strong and $D >> \lambda$. But as the particle size becomes comparable to or smaller than the wavelength, the ability of the particle to scatter radiation via diffraction decreases, and absorption becomes the dominant contributor to Q_{ext}. As ice crystal size decreases, absorption changes from an area dependence to a mass dependence (i.e., Beer's Law), and the absorption efficiency, Q_{abs}, decreases. This is why the minima for Q_{ext} can be < 1, even though the *imaginary* index of refraction is substantial at 2.8 and 10.3 µm. This complex dependence of the extinction minima on the above phenomena puts theory to a rigorous test.

Testing the Cirrus Radiation Scheme with Field Measurements

This cirrus radiation treatment was compared against data from a cirrus cloud field study (Paltridge and Platt 1981), where broad-band albedos and emittances from a cirrus deck were measured from an aircraft. These measurements are shown in Figure 2 by the "+" signs. The solar zenith angle was 33 degrees. The mean ice crystal size, based on measurements from a 1-D Knollenberg cloud probe, was estimated as $\bar{D}$ = 6 µm. This size was obtained by extrapolating the measured size distribution to zero size.

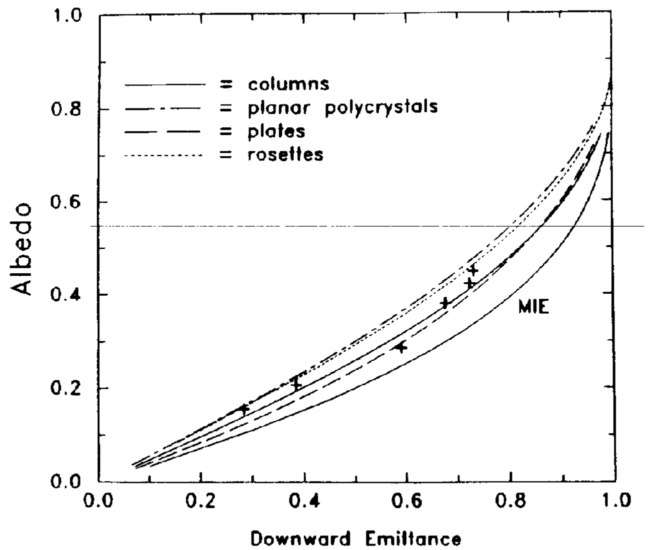

Figure 2. Albedo-emittance data (+) from the cirrus cloud sampled by Paltridge and Platt during Flight 7. Based on measurements, $\bar{D} \approx 6$ µm. This size was used to produce the theoretical curves. The lower curve for hexagonal columns is based on Mie theory.

Theoretical curves are shown for $\bar{D}$ = 6 µm, for various ice crystal shapes. These were predicted from the new ADT treatment. This is the first time these observations have been explained theoretically from the observed microphysics.

Different Physics for Water and Ice?

A method was developed to make ADT "act" like Mie theory. This Mie modified ADT treatment is like the ADT treatment except that the effects of internal reflection/refraction and grazing photon capture have been parameterized to make ADT "act" like Mie theory. This parameterization generally matched the Mie theory result to within 10% for $x \geq 1$, where $x = \pi D/\lambda$. Grazing photon capture causes the absorption cross-section of an ice crystal to be larger than would be predicted from the physical cross-section. This results in greater emittances than evidently occur.

This parameterization was used to help interpret the above results. This modified ADT (short-dashed curve) is compared against Mie theory (solid curve) in Figure 3 for a size distribution of ice spheres having $\bar{D}$ = 15 µm, where Q_{abs} is predicted over a wavelength range from 1.4 µm to 50 µm.

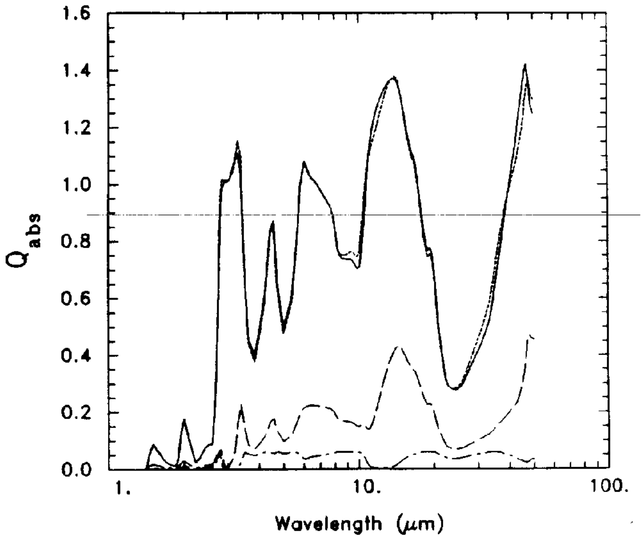

Figure 3. Absorption efficiencies predicted by Mie theory (solid curve) and modified ADT (short-dashed curve), for wavelengths from 1.4 µm to 50 µm and an ice sphere size distribution having $\bar{D}$=15 µm. The long dashed curve is the contribution from grazing photon capture, as predicted by the modified ADT, while the dash-dot curve gives the contribution from internal reflection/refraction.

Also shown is the contribution of grazing photon capture (long-dashed curve) and internal reflection/refraction(dash-dot curve) to Q_{abs}. Grazing photon capture is the dominant of the two processes in the thermal infrared and contributes significantly to Q_{abs}.

The capture of grazing photons contributes to wave resonance phenomena inside a sphere, as discussed in Guimaraes and Nussenzveig (1992). Resonance phenomena may be unique to spheres, although it may occur to a lesser extent in cylinders and some spheroids (Barber and Hill 1990). The above results indicate that grazing photons do not contribute to resonance phenomena in ice crystals, perhaps because the different geometry of ice crystals does not support wave resonance. More laboratory measurements and analytical work are needed to test this hypothesis.

Acknowledgment

This work was funded in part by the U.S. Department of Energy's Atmospheric Radiation Measurement Program (ARM), and by the National Oceanic and Atmospheric Administration Climate and Global Change Program as an aspect of the Global Energy and Water Experiment Cloud Systems Study.

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