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OPTICAL CONSTANTS OF ICE IN THE INFRARED ATMOSPHERIC WINDOWS

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1. INTRODUCTION

The optical constants of ice from the ultraviolet through the microwave were recently reviewed by Warren (1984), who presented a consistent set of recommended values for the complex index of refraction over the spectrum. He noted that in several regions there were significant uncertainties in his recommended values and disagreement among the published values from different experimenters.

These regions included the infrared atmospheric windows, where the radiative properties of cirrus clouds are important for the radiation balance and are used in remote sensing to distinguish between ice and water clouds. Because of the significance of these IR windows, the uncertainties of the ice refractive index in this region will be examined more closely. The corresponding optical properties of ice clouds will also be briefly discussed.

2. 8-12 μm ATMOSPHERIC WINDOW

Warren (1984) accepted the measurements of Schaaf and Williams (1973) (SW) for the complex index of refraction in the spectral region 3-33 μm wavelength, because they were made close to the melting point and used reflectance spectroscopy, which is appropriate for ice in this spectral region. However, the imaginary index in the 12 μm absorption band (Figure 1) is a factor of 3.5 larger than that inferred earlier by Irvine and Pollack (1968) (IP). Further confusion is due to a series of misprints in IP's table at the center of the 12 μm band, enhancing the apparent discrepancy by an additional factor of 10 (Liou, 1974). These misprints (also shown in Figure 1) were perpetuated in subsequent reviews of the optical constants by Ray (1972) and Hobbs (1974).

The results of SW are supported by the reflectance measurements of Tsujimoto et al. (1982, their Figure 4) and those of Wood and Roux (1982, their Figure 15). Transmission measurements of Bertie et al (1969) also give a large value of imaginary index at 12 μm in support of SW, but their values are less definitive than the others because they did not take into account the variation of reflectance across the band. These last measurements were all made at temperatures of 180 K or lower, but Tsujimoto et al found little dependence on temperature in the range 77 to 180 K.

Irvine and Pollack used Ockman's transmission measurements at -30°C. Ockman did not measure his sample thickness (a few μm), so IP inferred it by requiring Ockman's absorption coefficient to match that of Fox and Martin (1940) (who did measure sample thickness) at a wavelength they had in common. However, when Carlon (1972) applied the same approach he

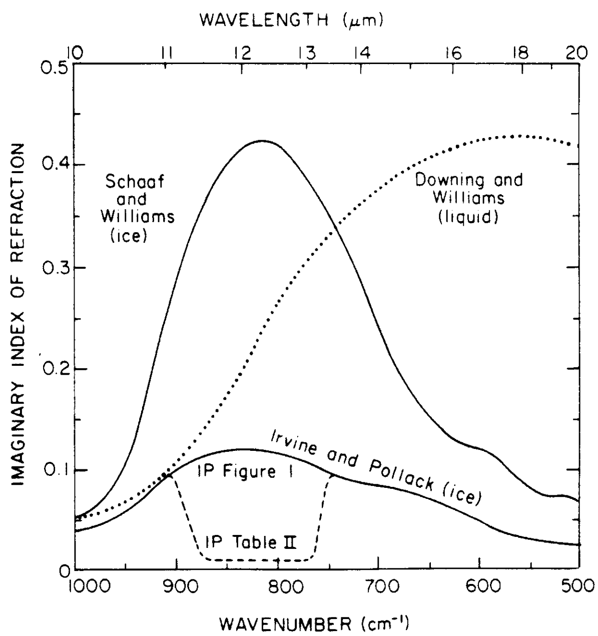

Figure 1. Imaginary index of refraction of ice in the 12-μm absorption band. The values for liquid water (Downing and Williams, 1975) are also shown for comparison.

inferred a much smaller thickness for Ockman's sample, and a peak imaginary index of 0.3, in much better agreement with SW. The difference between IP and Carlon appears to be due largely to different methods of accounting for the loss due to reflection at the AgCl-ice interfaces when the sample was in place between AgCl windows, and the AgCl-air interfaces when the sample was not in place. The error due to inaccurate measurement of sample thickness by Fox and Martin is only 30%, and a possible error due to light leakage by Ockman is probably also small because his transmittance was about 50% at 12 μm wavelength.

Although we cannot completely explain Ockman's measurements, we continue to recommend the results of SW because they are confirmed by essentially all subsequent measurements of the 12 μm band.

3. 3-5 μm ATMOSPHERIC WINDOW

The 3.7-μm channel of AVHRR, which is used for remote sensing of water phase in clouds, is in a spectral region where the optical constants of ice have not been accurately measured. Neither the transmission measurements of Fox and Martin (1940), nor the reflection measurements of SW, are accurate to better than 50% for wavelengths 3.5-4.3 μm. [The imaginary index is too small here to be obtained by the reflection method, and the sample used for the transmission measurements was too thin.] However, the imaginary indices obtained in these two experiments do agree with each other to within 30% (Figure 2). Transmission measurements on a 30-μm-thick sample are needed to establish the imaginary index reliably in this region.

4. THE CLOUD OPTICAL PROPERTIES

To briefly examine the possible effects of the uncertainties in the complex refractive index, as discussed above, on the optical properties of ice clouds a set of Mie scattering calculations were carried out for different size ice spheres. While the simplifying assumption that the ice particles are spherical will affect the details of the scattering properties, the general dependence on size will be reasonably described.

A narrow log normal size distribution was used:

$$\frac{dN(r)}{dr} = \frac{N_o}{\ln 10 . r . \sigma \sqrt{2\pi}} \exp - \left[\frac{(\log r - \log r_o)^2}{2\sigma^2} \right] \quad (1)$$

where $\sigma = 0.1$ and N_o was chosen to be proportional to r_o^{-3}, so that the mass concentration of the ice was constant (ρ ice cloud = 0.487 gm/m^3). This corresponded to $N_o = 10^7$ part/cm^3 for r_o = 0.1 μm and 10^{-2} part/cm^3 for r_o = 100.0 μm.

Figure 3 shows the resulting extinction coefficients for 12.0 μm radiation as a function of particle radius, for the different possible refractive indices. There are significant

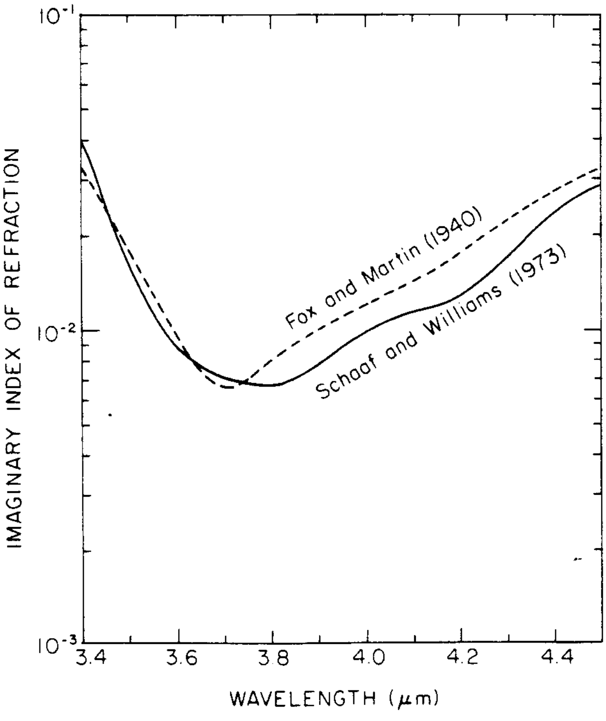

Figure 2. Imaginary index of refraction of ice in the 3.7-μm region.

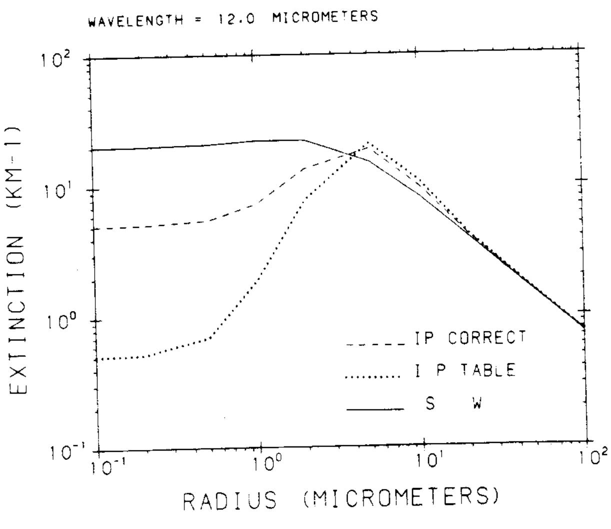

Figure 3. Extinction coefficients versus particle size (r_o in Eq. 1) for different choices for the refractive index of ice, at a wavelength of 12 μm, holding the mass concentration of the ice fixed a ρ_{ice} = 0.0487 gm/m^3. SW - Schaaf and Williams (1973); IP - Irvine & Pollack (1968).

differences for particles with radii less than 3 μm and negligible differences for larger sizes. However for the single scatter albedo (ratio of scattering to total extinction) shown in Figure 4, using the tabulated values of the refractive index from Irvine & Pollack leads to significant differences compared with the other two refractive indices for all sizes calculated. Major differences between using the Schaaf and Williams value and the correct Irvine and Pollack refractive index is limited to radii < 10.0 μm.

Similar results were found for the other wavelengths in the 8-12 μm atmospheric window. Since typical ice particle sizes for cirrus clouds is from 10 μm to larger than 100 μm, there will not be meaningful differences in the radiative properties of cirrus clouds if the either the correct IP refractive index are use or the SW values (this was noted by Liou, 1974). However, if the tabulated IP values or Ray's analytic approximation to these values are used in this spectral region, can result in significant differences compared with either the correct IP values or the SW values.

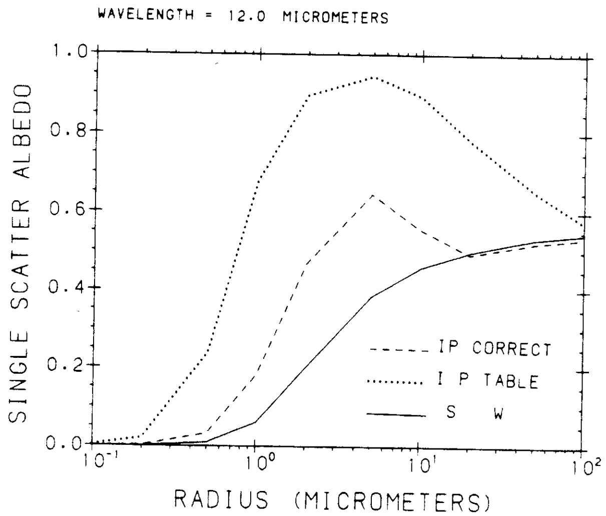

Figure 4. Single scatter albedo versus particle size (r_0 in Eq. 1) for different choices for the refractive index of ice at a wavelength of 12 μm.

5. REMARKS ON THE ULTRAVIOLET REFRACTIVE INDEX

On a related subject, the values of imaginary index recommended by Warren (1984) for the near-ultraviolet, 180-400 nm, are too low. The transmission data of Minton (1971) at 180-185 nm, which were used as a basis for interpolation from 185 to 400 nm, were published by Minton in the form of an extinction coefficent ε. Warren interpreted this as an extinction coefficient defined as base-e, but it was actually defined on base-10 (Hughes, 1952; Minton, personal communication), as:

$$T = T_o \, 10^{-\varepsilon \rho d}, \qquad (2)$$

where T and T_o are respectively the transmittance with and without the ice sample, d is path length, and ρ is concentration (or density).

This means that the values plotted by Warren are a factor of 2.3 too low at 180-185 nm wavelength, and also too low by a smaller factor for the 185-400 nm spectral region.

These topics are discussed in more detail by Warren and Shettle (1986).

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