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MULTI-SPECTRAL THERMAL RETRIEVALS OF ICE WATER PATH, EFFECTIVE SIZE AND PHOTON TUNNELING

David L. Mitchell[1], Daniel H. DeSlover[3], Robert P. d'Entremont[2], W.Patrick Arnott[1],
1. Desert Research Institute, Reno, Nevada
2. Atmospheric and Environmental Research, Inc., Lexington, Massachusetts
3. Cooperative Institute for Meteorological Satellite Studies, Madison, Wisconsin

1. INTRODUCTION

Satellite and ground-based retrievals of effective diameter (D_{eff}) and ice water path (IWP) are needed in cirrus clouds to describe their radiative properties, and to evaluate their effect on climate. Unfortunately these properties are not sufficient for describing the radiative role of cirrus at terrestrial wavelengths. This is because a process referred to as photon tunneling often contributes 15-42% of the absorption at terrestrial wavelengths (λ), as shown in Fig. 1. Contributions are greatest when particle size and λ are comparable. Photon tunneling accounts for radiation beyond the area cross-section of a particle that is either absorbed or scattered. Baran et al. (2001) have shown that tunneling contributions decrease as ice particle shape becomes more complex. As ice particle shapes in natural cirrus tend to be complex relative to the pristine shapes assumed in single scattering calculations, the contribution of the tunneling process to absorption in ice clouds represents a large uncertainty in terrestrial radiation transfer.

The tunneling process has been parameterized for ice clouds (Mitchell 2002), and this ice cloud radiation scheme was found to be accurate within 15% relative to T-matrix calculations of absorption efficiency (mean error = 5%) over a λ range of 2-18 µm (Mitchell and Baran, these preprints). Mean extinction efficiency (Q_{ext}) errors for a hexagonal column ice cloud were $\leq$ 3% relative to measured Q_{ext} over the same λ range (Mitchell et al. 2001). Hence, it appears justifiable to use the tunneling parameterization in this radiation scheme to quantify the tunneling process in ice clouds, and to retrieve a tunneling factor, T_f. The value of T_f ranges from 1.0 (ice spheres) to 0 (no tunneling).

This study provides the first estimates of tunneling and T_f found in natural cirrus clouds, and provides a means of retrieving D_{eff} and IWP based on the 2nd and 3rd moments (area and mass) of the size distribution, SD. These retrievals are thus sensitive to the small particle mode of the SD (D < 100 µm), which retrievals using radar may not be sensitive too. The methodology described here may be applied to both ground-based and satellite remote sensing.

2. RETRIEVAL METHODOLOGY

While previous studies (e.g. Platt et al. 2002; DeSlover et al. 1999) have used the ratio of visible extinction to thermal absorption optical depth to infer ice particle size,

Corresponding author: Dr. David Mitchell, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512-1095 Email: mitch@dri.edu

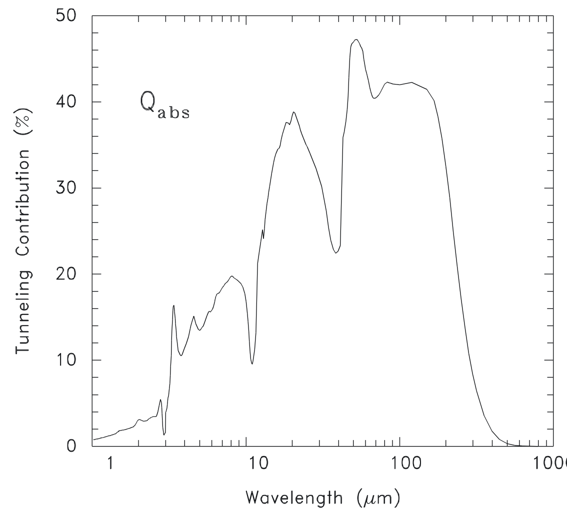

Figure 1. Photon tunneling contribution for a SD of planar polycrystals, large mode mean size = 100 µm.

we find, as pointed out in DeSlover et al., that the mismatch between the the field of view (FOV) between a radiometer (or interferometer) and the lidar may lead to large errors in this ratio, referred to as α. But by using one instrument with one FOV, this error is eliminated. Rather than use the α ratio, we use ratios of absorption optical depth, τ_{abs}. Cloud emissivities, and hence τ_{abs} (assuming zero scattering), can be obtained spectrally from the Atmospheric Emitted Radiance Interferometer (AERI), as described in DeSlover et al. (1999).

By ratioing τ_{abs} using, for example, the AERI microwindow combinations of 3.9/10.1 µm, or 3.9/11.2 µm, the effective diameter D_{eff} can be retrieved, as shown in Fig. 2. In this work, D_{eff} = (3/2) IWC/(ρ_i P), where ρ_i = density of bulk ice and P = projected area of the size distribution SD. Size information is best retrieved when using a band where absorption is volume or mass dependent, and absorption at 3.9 µm is closest to this condition. In the window region at 10.1 µm, absorption is partially mass and partially area dependent, and is area dependent at 11.2 µm. This causes non-unique solutions for D_{eff} retrievals using the 10.1/11.2 µm ratio, as shown in Fig. 2. Curves were generated using the ice cloud radiation scheme of Mitchell (2002), assuming size distributions parameterized for (1) tropical and (2) mid-latitude cirrus, and assuming 4 ice particle shapes. This provides a measure of expected retrieval accuracy. As described in Mitchell (2002), SDs having different D_{eff} values can have the same radiative properties (i.e. τ_{abs} ratio) due to the behavior of the small and large particle modes relative to each other.

We have examined the feasibility of using AERI bands around 3.9 μm, and found that radiances emitted by most cirrus are above the clear sky background radiance under nighttime conditions.

Figure 2 also has application to satellite retrievals. For instance, the MODIS instrument has channels at 3.7, 8.5 and 11 μm, similar to the bands used in Fig. 2 (note refractive indices at 10.1 and 8.5 μm are very similar). Using a methodology similar to d'Entremont et al. (1990) to obtain τ_{abs}, τ_{abs} was retrieved from MODIS channels for convective generated cirrus over the ocean south of New England. An arbitrary sample of about 800 pixels gave mean τ_{abs} ratios of 3.7/8.5 μm and 3.7/11 μm of 0.655 and 0.550, respectively. These are indicated by the "o" symbols in Fig. 2. The fact that these ratios both correspond to D_{eff} = 55 μm is encouraging. MODIS τ_{abs} ratios may also be used to determine T_f, but unfortunately there was insufficient time to perform that analysis before the deadline of this manuscript. Much analysis needs to be done to validate this approach for satellites.

Once D_{eff} is retrieved, the tunneling factor T_f can be estimated from AERI spectral τ_{abs} where τ_{abs} is normalized by τ_{abs} at λ = 12.93 μm. This is shown for the window region in Fig. 3. The AERI data (x) are for the 10 November 1995 cirrus case described in DeSlover et al. (1999), while the solid curve was predicted by the Mitchell (2002) scheme for T_f = 0.3, D_{eff} = 65 μm. The short dashed curve predicts normalized τ_{abs} for T_f = 0, while the long-dashed curve is for T_f = 1.0 (maximum value). This illustrates how data between 10.5 and 11.7 μm is sensitive to the value of T_f, and can be used to estimate T_f. AERI data at λ ≤ 10.1 μm is much less sensitive to T_f, but is sensitive to D_{eff}, and can be used to estimate D_{eff}. The 5 data points < 10 μm above the predicted curves are unexplained based on our knowledge of ice refractive indices, and these points were persistently high in the AERI samples.

The AERI data from Nov. 10th could be explained using either the mid-latitude SD scheme of Ivanova et al. (2001), but only if one assumes hexagonal columns, or by the tropical SD scheme of Mitchell et al. (2000) assuming planar polycrystals. In this analysis, we used the mid-latitude scheme. Since we were restricted to the window region, dual D_{eff} solutions existed (see Fig. 2). But since the cirrus cloud began thin and steadily deepened, we assume D_{eff} starts off small and grows to larger sizes. This D_{eff} assumption has no impact on the retrievals of T_f.

Knowing D_{eff} and T_f, the radiation scheme gives us the area weighted absorption efficiency of the SD, $\overline{Q}_{abs}$, for each AERI microwindow. This information can now be used to determine ice water path (IWP) using the formula given in Mitchell and d'Entremont (2000):

$$\mathrm{IWP} = \frac{2\,\rho_i\,D_{eff}\,\ln(1-\epsilon)\cos\theta}{3\,\overline{Q}_{abs}} \qquad (1)$$

where ϵ = cloud emissivity and θ = instrument viewing angle (θ = 1 at zenith).

The results of our analysis of the 10 November cirrus case are described in Fig. 4. These represent the first measurements of the contribution of tunneling to ice clouds, quantified using T_f. Since T_f depends on the .

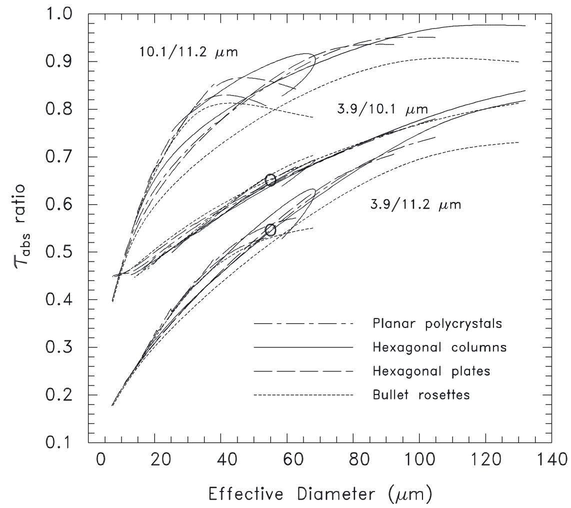

Figure 3. Use of absorption optical depth ratios at various λ for Deff retrievals. Curves are based on two SD parameterizations (tropical and mid-latitude) and four ice crystal shapes to estimate uncertainties.

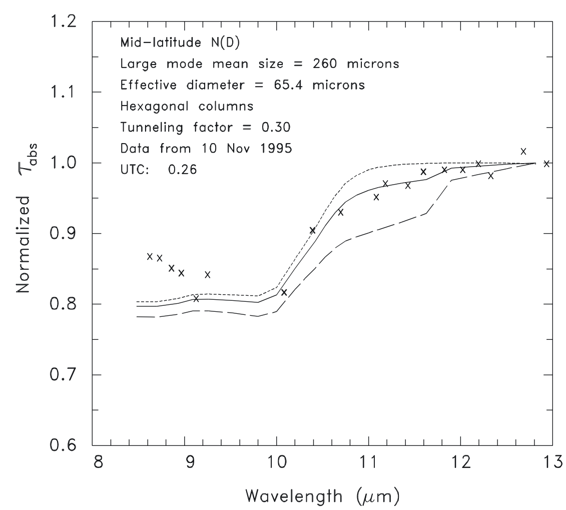

Figure 2. Retrieval of tunneling factor from an AERI sample, with τ_{abs} normalized to the longest λ. Dashed curves indicate range of tunneling contributions.

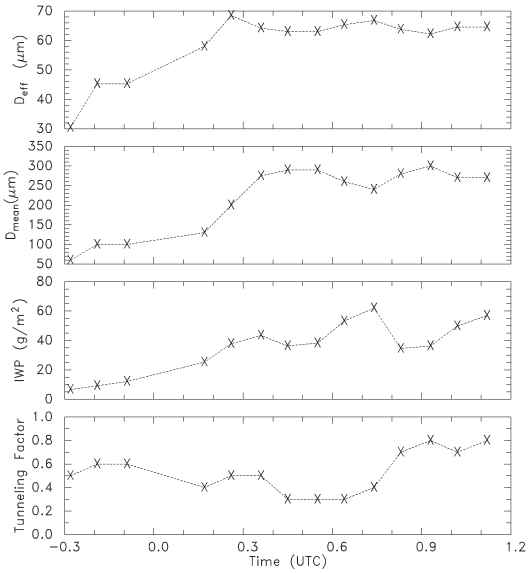

Figure 4. Evolution of cirrus case of 10 Nov. 1995 based on multispectral AERI retrievals

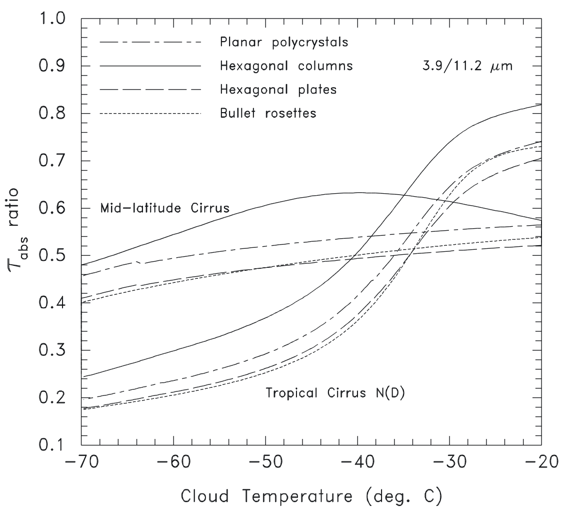

Figure 5. Temperature dependence of τ_{abs} ratio (3.9/11.2) as predicted by SD schemes for tropical and mid-latitude cirrus.

complexity of ice particle shape (Baran et al. 2001), the variation of T_f in Fig. 4 may reflect variations in crystal shape. Clearly T_f is not equal to one, as is true for water clouds (i.e. spheres), and the mean value of T_f in Fig. 4 is 0.53 ±0.18. D_{mean} in Fig. 4 refers to the mean maximum dimension of the large particle mode of the SD, and is comparable to the mean dimension measured by the 2DC probe. Note that when D_{mean} climbs above 200 μm, D_{eff} decreases slightly. This is due to the increase in the concentration of small ice crystals (D < 100 μm) as D_{mean} increases (Ivanova et al. 2001). Whether this increase is real, or is an artifact of the FSSP probe, remains in question.

Finally, the τ_{abs} ratio 3.9/11.2 μm is predicted to behave differently as a function of temperature for tropical vs. mid-latitude cirrus (Ivanova et al. 2001; Mitchell et al. 2000). This is shown in Fig. 5. Either MODIS satellite data or AERI data could be used to evaluate the behavior of this τ_{abs} ratio as a function of cloud temperature for tropical and mid-latitude cirrus, thus testing the validity of these two SD schemes. The reason for the different temperature dependence in Fig. 5 is that the small particle mode in the mid-latitude SD scheme becomes more pronounced (higher concentrations) as the large SD mode broadens. The opposite is true for the tropical SD scheme, since the small mode intensifies as the large mode steepens. Hence, the relative behavior of the large and small SD modes may be evaluated remotely using either AERI data or satellite data.

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