1. INTRODUCTION

Satellite and ground-based retrievals from cirrus clouds of effective diameter ($D_{\text{eff}}$) and ice water path (IWP) are needed to describe cirrus radiative properties and to evaluate the role of cirrus in climate. Unfortunately, $D_{\text{eff}}$ and IWP are not sufficient for describing ice cloud radiative properties at terrestrial wavelengths. Size distribution shape must also be known for terrestrial radiation (Mitchell 2002), since, for example, the absorption optical depth may differ up to 44% for two cirrus size distributions (SD) having the same $D_{\text{eff}}$ and IWP. But even knowing the SD is not sufficient for describing the radiative role of cirrus at terrestrial wavelengths. This is because photon tunneling often contributes 15-42% of the absorption at terrestrial wavelengths ($\lambda$), as shown in Fig. 1. Contributions are greatest when particle size and $\lambda$ are comparable. Photon tunneling accounts for radiation beyond the area cross-section of a particle that is either absorbed or scattered outside of the forward diffraction peak. Baran et al. (2001) have shown that tunneling contributions decrease as ice particle shape becomes more complex. Since ice particle shapes in natural cirrus tend to be complex relative to the pristine shapes assumed in treatments of ice cloud radiative properties based on electrodynamic theory (i.e. at low size parameter), the contribution of the tunneling process to absorption represents a large uncertainty in terrestrial radiation transfer.

In this study we use the modified anomalous diffraction approximation (ADA) for ice clouds (Mitchell 2002), which accurately parameterizes the process of photon tunneling (Mitchell 2000), to quantify the tunneling process in ice clouds by retrieving a tunneling factor, $T_t$. Modified ADA was validated with laboratory measurements in Mitchell et al. (2001) and with T-matrix theory in Mitchell and Baran (2002). The value of $T_t$ ranges from 1.0 (ice or water spheres) to 0 (no tunneling). Shown below are estimates of tunneling (i.e. $T_t$) found in natural cirrus clouds.

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

The proposed methodology provides a means of retrieving $D_{\text{eff}}$ and IWP based on the 2nd and 3rd moments (area and mass) of the size distribution, SD. That is, the cirrus emission a sensor receives is from absorption, which ranges from particle area (strong absorption) to mass (weak absorption) dependence. Moderate absorption in the window region (8.3-12.5 μm) would generally exhibit partial area and partial mass dependence. These retrievals are thus sensitive to the small particle mode of the SD ($D < 100 \mu m$), which retrievals using radar (6th moment dependence) may not be sensitive too. Note that the peak concentration of the small mode is typically 2-3 orders of magnitude greater than the peak concentration in the large SD mode, making $D_{\text{eff}}$ based on only the large mode typically about 45% larger than $D_{\text{eff}}$ based on both modes, based on measurements of the Forward Scattering Spectrometer Probe (FSSP) and the 2DC probe in mid-latitude cirrus (Ivanova et al. 2001). Hence a radar retrieval of $D_{\text{eff}}$ that does not “see” the small mode could seriously overestimate $D_{\text{eff}}$.

Although there is evidence that the FSSP may be accurate in cirrus clouds within a factor of 2-3, a possibility remains that particle shattering at the probe inlet may enhance the numbers of small
crystals. In order to test our ideas concerning ice
crystal nucleation rates, and to accurately describe
ice cloud microphysical and radiative properties, it is
critical to determine whether the small SD mode is
an artifact due to shattering at the FSSP inlet (or
possibly other factors), or whether the high ice
crystal concentrations measured by the FSSP are
real.

The objectives of this study are as follows:

1) Demonstrate the feasibility of retrieving \( D_{\text{eff}} \), IWP,
visible extinction optical depth \( \tau \), and photon
tunneling contributions to absorption \( (T_i) \) for both
ground- and space-based remote sensing.

2) Provide a means of remotely assessing the
magnitude and temperature dependence of the
small SD mode relative to the large particle mode, to
help resolve the role of the small SD mode in
determining cirrus microphysical and radiative
properties. Do this for both satellite and ground-
based remote sensing.

3) Test existing parameterizations of ice particle SDs
using thermal radiances from both ground-based
and satellite remote sensing.

2. GROUND-BASED RETRIEVALS: AERI

This section describes how the Atmospheric
Emitted Radiance Interferometer (AERI; see Smith
et al. 1995) can be used to evaluate SD shape, \( D_{\text{eff}} \),
IWP, \( T_i \), and visible extinction optical depth \( \tau \). This is
shown by way of example, where we have analyzed
a mid-latitude cirrus case study (10 Nov. 1995; see
DeSlover et al. 1999) and a cold tropical cirrus case
study from the CAMEX 3 field program.

Previous studies (e.g. Platt et al. 1989; 1998;
2002; DeSlover et al. 1999; Comstock and Sassen
2001) have used the ratio of visible extinction to
thermal absorption optical depth, known as \( \alpha \), to
infer ice particle size. However, the ratio of the field
of view (FOV) between AERI and the high resolution
lidar (HSRL) is 2000 (Edwin Eloranta, private
communication), and thus may introduce errors in \( \alpha \)
(DeSlover et al. 1999). But by using only the
retrieved cloud emissivity (and not extinction optical
depth), ratios of absorption optical depth, or \( T_{\text{abs}} \) ratios,
may be obtained spectrally from the AERI
(assuming zero scattering). These ratios, often
taken at a moderate and a strongly absorbing
wavelength, exhibit less scatter relative to the \( \alpha \)
ratios, and appear to provide reliable estimates of
\( D_{\text{eff}} \), IWP, \( T_i \), and \( \tau \)

By ratioing \( T_{\text{abs}} \) using, for example, the AERI
microwindow combinations of 3.9/10.1 \( \mu m \), or
3.9/11.2 \( \mu m \), the effective diameter \( D_{\text{eff}} \) can be
retrieved, as shown in Fig. 2. In this work, \( D_{\text{eff}} =
(3/2) \text{IWC}(\rho, P) \), where \( \rho \) = 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 \( \mu m \) is closest to this condition. In
the window region at 10.1 \( \mu m \), absorption is partially
mass and partially area dependent, and is area
dependent at 11.2 \( \mu m \). This causes non-unique
solutions for \( D_{\text{eff}} \) retrievals using the 10.1/11.2 \( \mu m \)
ratio, as shown in Fig. 2. Curves were generated
using the modified ADA, assuming size distributions
parameterized for (1) tropical and (2) mid-latitude
(non-convective) cirrus, and assuming 4 ice particle
shapes. This provides a measure of expected
retrieval uncertainty. As described in Mitchell (2002),
SDs having different \( D_{\text{eff}} \) values can have the same
radiative properties (i.e. \( T_{\text{abs}} \) 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 \( \mu m \), and found that
radiances emitted by most cirrus are above the clear
sky background radiances under nighttime conditions.
Also, when AERI bands around 11 \( \mu m \) become
saturated (emissivity approaches 1.0), one can
switch to the 3.9/10 \( \mu m \) curve for \( D_{\text{eff}} \) estimates.
Sensitivity tests have shown that varying \( T_i \) has little

Figure 2. Use of absorption optical depth ratios at
various \( \lambda \) for Deff retrievals. Curves are based on two
SD parameterizations (tropical and mid-latitude) and
four ice crystal shapes to estimate uncertainties. Circles
 correspond to MODIS retrievals from anvil cirrus using
ratios radiatively similar to those indicated.
effect on the 3.9/11 μm curve, while the 3.9/10 μm curve is moderately sensitive (e.g., ±4 μm). The curves in Fig. 2 assume $T_f = 0.5$.

2.1 Non-convective Case Study

Once $D_{eff}$ is retrieved, the tunneling factor $T_f$ can be estimated from AERI spectral $\tau_{abs}$ where $\tau_{abs}$ is normalized by $\tau_{abs}$ at $\lambda = 12.93$ μm. This is shown for the window region in Fig. 3. The AERI data (x) are for the 10 November 1995 non-convective cirrus case described in DeSlover et al. (1999), while the solid curve was predicted by modified ADA (Mitchell 2002) for $T_f = 0.3$, $D_{eff} = 65$ μm. The short dashed curve predicts normalized $\tau_{abs}$ 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 $\lambda < 10.1$ 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 consistently high in the AERI samples. This issue is currently under investigation. Nonetheless, the microwindow at 10.1 μm was consistently in agreement with predicted values, and may be used with greater confidence.

The AERI data from Nov. 10th could be explained using either the mid-latitude SD scheme of Ivanova et al. (2001), or by the tropical SD scheme of Mitchell et al. (2000), using one or more crystal shapes. In this analysis, we used the mid-latitude scheme and assumed hexagonal columns (or compact high density crystals that would have a similar mass- and area-dimensional relationship). 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. Having two $D_{eff}$ solutions has no impact on the retrievals of $T_f$, since $T_f$ depends on the SD absorption efficiency $Q_{abs}$, and a single $Q_{abs}$ can correspond to more than one value of $D_{eff}$ (Mitchell 2002).

Knowing $D_{eff}$ and $T_f$, the modified ADA gives us the area weighted absorption efficiency of the SD, $Q_{abs}$ ($Q_{abs} = \text{absorption coefficient} \beta_{abs}/P$), for each AERI microwindow. This information can now be used to determine ice water path (IWP) at each wavelength $\lambda$ using the formula given in Mitchell and d’Entremont (2000):

$$\text{IWP} = \frac{2 \rho \cdot D_{eff} \ln(1 - e) \cos \theta}{3Q_{abs}}$$  \hspace{1cm} (1)

where $e = \text{cloud emissivity}$ and $\theta = \text{instrument viewing angle (θ = 1 at zenith)}$. IWPs at each $\lambda$ can be averaged (if $e(\lambda)$ is unsaturated) to produce a mean IWP, and an estimate of precision is obtained from the standard deviation. For this case study, the precision was about ±5%. For optically thick cirrus,
\[ \lambda = 3.9 \, \mu \text{m} \text{ can be used to obtain } \epsilon \text{ and } Q_{\text{abs}}, \text{ so that IWP values at least up to } 100 \, \text{g m}^{-2} \text{ can be retrieved.} \]

Finally, visible optical depth \( \tau \) is estimated from the retrieved IWP and \( D_{\text{eff}} \):

\[ \tau = 3 \, \text{IWP}/(\rho_1 \, D_{\text{eff}}) \]  

which is based on the assumption that at visible wavelengths, extinction efficiency \( Q_{\text{ext}} = 2 \).

The results of our analysis of the 10 November cirrus case are described in Fig. 4. This methodology is the first to estimate the contribution of photon tunneling to natural ice clouds, quantified using \( T_f \). Since \( T_f \) depends on the complexity of ice particle shape (Baran et al. 2001), the variation of \( T_f \) in Fig. 4 may reflect variations in crystal shape. The mean value of \( T_f \) in Fig. 4 is 0.53 ±0.18. In Mitchell et al. (2001), \( T_f \) was found to be about 0.6 for hexagonal columns grown in a cloud chamber. However, a \( T_f \) of 0.8 fit the extinction efficiencies in the window region the best.

2.1.1 Size distribution shape

A major question relevant to the disciplines of cloud physics, atmospheric radiation, and climate prediction is whether the high ice particle concentrations \( N \) measured by the FSSP probe are real. If the answer is yes, then ice particles having maximum dimension \( D < 100 \, \mu \text{m} \) account for a large percentage of the SD projected area \( P \), and thus will have a major impact on cirrus cloud radiative properties. Fortunately, this question can be addressed through AERI measurements, which provide information of SD shape. The mid-latitude SD scheme of Ivanova et al. used FSSP measurements to quantify the small mode, and the 2DC probe to characterize the large SD mode. If small mode \( N \) is orders of magnitude greater than large mode \( N \), then the SD area weighted absorption efficiency, \( Q_{\text{abs}} \), will be considerably less than 1.0 in the window region for \( \lambda \) between 8.3 and 10.2 \( \mu \text{m} \), while \( Q_{\text{abs}} \) for \( \lambda = 11 \, \mu \text{m} \) will be generally be near 1.0. For example, the 10.1/11.2 \( \mu \text{m} \) \( T_{\text{abs}} \) ratio obtained via AERI will be \( \leq 0.93 \) if small mode \( N \) is high. Such AERI data from the 10 November case study is plotted in Fig. 5, along with corresponding \( T_{\text{abs}} \) ratio curves from modified ADA and the mid-latitude SD scheme for various ice particle shapes. The SD temperature dependence in Ivanova et al. allows us to plot the \( T_{\text{abs}} \) ratio against temperature. A sounding released during the AERI case study (Madison Wisconsin) was used to estimate the temperature corresponding to the clouds “radiative center of mass”, as estimated from lidar backscatter (DeSloover et al. 1999). Also plotted are curves (in upper figure) that are based on exponential size spectra. These spectra are calculated from the mean particle size \( D_l \) measured by the 2DC probe and the associated SD slope (SD slope = 1/\( D_l \)), which was parameterized in terms of temperature in Ivanova et al. (2001). These exponential SDs insure that \( N \) increases with decreasing size, but by definition are not bimodal, so that small mode \( N \) is not orders of magnitude higher than large mode \( N \).

Figure 5. Comparison of \( T_{\text{abs}} \) ratios predicted for SI with and without the small mode as measured by 10 FSSP. Measured \( T_{\text{abs}} \) ratios are given by the symbols.

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The difference between the exponential and bimodal SD curves in Fig. 5 demonstrate the impact of the small mode on the \( \tau_{\text{abs}} \) ratio. It is seen that using the small mode based on the FSSP renders good agreement with the measured \( \tau_{\text{abs}} \) ratios (x symbols) for non-convective cirrus. The vertical scatter in the measured ratios could be due to changes in ice crystal shape, or due to changes in small mode D and N. The point for the coldest temperature (lowest \( \tau_{\text{abs}} \) ratio) was obtained when the cloud was thinnest near the beginning of its life cycle.

Finally, the \( \tau_{\text{abs}} \) ratio 10.1/11.2 \( \mu \)m is predicted to behave differently as a function of temperature for tropical convective (Mitchell et al. 2000) vs. non-convective mid-latitude cirrus (Ivanova et al. 2001), based on modified ADA. This is shown in Fig. 6. The temperature dependence of this measured \( \tau_{\text{abs}} \) ratio (x symbols in Fig. 6) reveals the temperature dependence of the small SD mode relative to the large SD mode, and whether this behavior conforms to that predicted for the tropical or mid-latitude cirrus schemes. It is seen that the AERI data conform well with the predicted mid-latitude curves. One reason for the different temperature dependencies in Fig. 6 is that the small particle mode in the mid-latitude SD scheme becomes more pronounced (higher concentrations) as the large SD mode broadens (SD slope decreases). The opposite is true for the tropical SD scheme, where the small mode diminishes as the large mode broadens. These differing behaviors result in a much different temperature dependence regarding \( D_{\text{eff}} \) and SD shape, with \( D_{\text{eff}} \) in the mid-latitude scheme varying much less with temperature than \( D_{\text{eff}} \) for the tropical SD scheme. Both \( D_{\text{eff}} \) and SD shape contribute to the differences between SD schemes in Fig. 6.

Even if the retrieved \( \tau_{\text{abs}} \) ratios did not correspond to either SD scheme, it is possible to modify the tropical or mid-latitude SD parameterization, based on the retrieved \( D_{\text{eff}} \) and \( \tau_{\text{abs}} \) ratios, and the large mode mean length \( D_{l} \) given by the parameterization as a function of temperature. Note that \( D_{l} \) is based on measurements from the 2DC probe, which are fairly reliable. First, it is helpful to note that the \( \tau_{\text{abs}} \) ratio is the same as the corresponding \( Q_{\text{abs}} \) ratio. For both SDs having the same \( D_{\text{eff}} \) and \( Q_{\text{abs}} \) will be lower in the SD having higher ice crystal concentrations N (i.e. steeper slope) in the small particle mode (Mitchell 2002). Thus \( Q_{\text{abs}} \) is both a function of \( D_{\text{eff}} \) and SD shape. By retrieving both \( D_{\text{eff}} \) and the \( \tau_{\text{abs}} \) ratio, the SD shape can be inferred by manipulating the relative contribution of small mode N in our radiation scheme to yield curves conforming with the observed temperature dependence of the \( \tau_{\text{abs}} \) ratios and \( D_{\text{eff}} \) values. To estimate temperatures corresponding to retrieved \( \tau_{\text{abs}} \) ratios and \( D_{\text{eff}} \), a sounding and vertical lidar (or radar) backscatter profile are needed to estimate the temperature of the cloud’s radiative center of mass. With this information, one can modify the existing SD schemes such that they fit the AERI retrievals.

### 2.2 Convective Case Study

During the CAMEX 3 field experiment, cirrus outflow from Hurricane Bonnie was sampled by the AERI on 23 August 1998 near the Bahama Islands, and soundings were taken during the sampling period. The cirrus were several km thick, centered around 14 km altitude with mid-point temperatures around -60 °C. Due to the cold temperatures, cirrus emittance was lower than for the mid-latitude case centered around -40 °C, making the AERI signal noisy relative to the mid-latitude case. But optical depth was more than 1.0, and some periods of sampling contained useful data. For this case, the microwindow at 9.1 \( \mu \)m appeared more stable than the microwindow at 10.1 \( \mu \)m, and \( D_{\text{eff}} \) retrievals were based on the 9.1/11.2 \( \mu \)m \( \tau_{\text{abs}} \) ratio. The curves relating \( D_{\text{eff}} \) to the \( \tau_{\text{abs}} \) ratio were for tropical cirrus, similar to the 10.1/11.2 \( \mu \)m \( \tau_{\text{abs}} \) ratio curves in Fig. 2 for tropical cirrus (i.e. the curves extending to the largest \( D_{\text{eff}} \) values). \( D_{\text{eff}} \) estimates were unique with uncertainties ± 13% for \( D_{\text{eff}} < 60 \mu \)m (due to particle shape). Planar polycrystals were assumed.

\( D_{\text{eff}} \) was also estimated using all window region wavelengths, as illustrated in Fig. 7. The 3 curves correspond to a \( T_{c} \) of 0 (short-dashed), 0.5 (solid) and 1.0 (long-dashed). Both \( D_{\text{eff}} \) and \( T_{c} \) were optimized to produce the best match between theory and observations. Fig. 7 is typical of this case in that \( \tau_{\text{abs}} \) ratios (normalized by \( \tau_{\text{abs}} \) at \( \lambda = 12.93 \mu \)m) appeared anomalously high relative to theory for wavelengths between 8.6 and 10.1 \( \mu \)m. We note that the \( \tau_{\text{abs}} \) ratio at \( \lambda = 9.1 \mu \)m was consistently the lowest, and this point was considered valid when matching theory with observations. It is not clear why other \( \tau_{\text{abs}} \) ratios for \( \lambda < 10.3 \mu \)m appear anomalously high, but the high contribution of background emission and potential ozone emission may be factors.

The analysis illustrated by Fig. 7 was also used to estimate \( T_{c} \). When estimating \( T_{c} \), we used the “least noisy” AERI data, which corresponded to wavelengths at 9.1 \( \mu \)m and 10.3 \( \mu \)m < \( \lambda < 11.9 \mu \)m. Still, the uncertainty in estimating \( T_{c} \) was greater here than in the mid-latitude case. The \( T_{c} \) estimated for
the AERI sample in Fig. 7 was 0.7.

Retrieval results for this tropical cirrus case study are shown in Fig. 8. The 0.8 hour sampling gap between 3.2 and 4.0 hours UTC was actually 3.6 hours, but is shown here as 0.8 h to present the results more clearly. As noted, \( \text{D}_{\text{eff}} \) was determined two ways: using only two wavelengths, and using all \( \lambda \) as illustrated in Fig. 7. The circle symbols correspond to the two \( \lambda \) approach, while the X symbols correspond to the all \( \lambda \) approach. It is seen that the two \( \lambda \) approach, relevant to satellite retrievals, is sufficient for most applications. As noted, IWP was calculated for all 19 \( \lambda \). Mean values and their standard deviations are shown in the IWP panel. Given the challenging operating conditions for the AERI, the IWP uncertainties are quite low. Tunneling factors for this case varied considerably, and were generally larger than in the mid-latitude case (mean \( T_f = 0.74 \pm 0.27 \)).

There is some evidence of periodicity in the results for \( \text{D}_{\text{eff}}, T_f \) and possibly IWP. This might be explained by gravity waves emanating from Hurricane Bonnie, although this is only a guess at this time. If we interpret the data this way, with decreases in \( \text{D}_{\text{eff}} \) corresponding to increases in IWP, there is an implication that ice crystal nucleation rates increase with increasing condensation rates, driving down the mean ice particle size.

2.2.1 Size distribution shape

As noted, the tropical cirrus SD scheme described in Mitchell et al. (2000) predicts that the small and large particle modes in anvil cirrus behave in the opposite manner relative to non-convective mid-latitude cirrus as described in Ivanova et al. (2001). That is, as the large mode (\( D > 100 \mu \text{m} \)) broadens with increasing temperature \( T \) in anvil cirrus, the number concentration \( N \) in the small SD mode diminishes. This may be due to size-sorting by fall speed, with the larger particles descending faster and accumulating preferentially in the mid-to-lower cloud, while the smallest crystals tend to remain aloft at the main detrainment level. Also, aggregation by larger ice particles is likely to deplete the smaller crystals. This physical reasoning supports the above observation in anvil cirrus. In mid-latitude cirrus, the opposite occurs, with small mode \( N \) increasing as the large mode broadens (slope decreases) with increasing \( T \). To understand the microphysics and radiative properties of convective and non-convective cirrus, we need to know whether these differences are real or simply artifacts of the FSSP.

Figure 9 shows the \( \tau_{\text{abs}} \) ratio 9.1/11.2 \( \mu \text{m} \) predicted by modified ADA for mid-latitude and tropical cirrus for 4 different ice crystal shapes, giving an estimate of expected uncertainty. Also shown are the AERI \( \tau_{\text{abs}} \) ratios corresponding to 9.1/11.2 \( \mu \text{m} \) (x symbols). These are plotted at the mid-cloud temperature, which is based on soundings launched during sampling and lidar backscattering returns. The AERI data clearly support the tropical anvil SD scheme, and the implied physics described above. The tropical SD scheme predicts very high
N in the small mode at these temperatures, with the small mode dominating the SD area. The scatter in the AERI data may be due to variations in particle shape or small mode N.

Figure 10 is similar to Fig. 9 except the \( \tau_{\text{abs}} \) ratio is predicted for the tropical scheme with only the large particle mode, which is an exponential function. The absence of the small mode is seen to raise the \( \tau_{\text{abs}} \) ratio considerably. The AERI data support the parameterization of the small mode and the tropical SD scheme in general. Moreover, the AERI data indicate the presence of very high concentrations of small crystals in tropical cirrus, that are generally too small to be detected by the 2DC probe.

3. SATELLITE RETRIEVALS: MODIS

Similar methodology to that above can be used with MODIS satellite data to retrieve \( D_{\text{eff}} \), \( T_{\text{r}} \), IWP and SD shape information. This methodology will be demonstrated using a MODIS satellite scene from the western north Atlantic featuring cirrus of convective origin (associated with the Gulf Stream) during 13 October 2000. Using a methodology similar to d'Entremont et al. (1990), \( \tau_{\text{abs}} \) can be obtained for each MODIS channel. This method solves the equation

\[
I_{\text{obs}} = (1-\epsilon)I_{\text{sfc}} + \epsilon B_{\text{ci}} \tag{3}
\]

at two wavelengths, where \( \epsilon \) is bulk cirrus emissivity, \( I_{\text{obs}} \) is the upwelling thermal radiance from cloud, \( I_{\text{sfc}} \) is the upwelling radiance emitted by the underlying surface (i.e. either the ground or a low level cloud) and clear atmosphere, and \( B_{\text{ci}} \) denotes the cirrus Planck blackbody radiance, which is a known function of the cirrus effective temperature \( T_{\text{ci}} \). The two measured quantities in (2) are \( I_{\text{obs}} \) and \( I_{\text{sfc}} \), corresponding to cloudy or adjacent cloud-free scenes, respectively. This results in two equations (one for each \( \lambda \)) and two unknowns (\( \epsilon \) and \( B_{\text{ci}} \)). Unique solutions for \( \epsilon \) and \( B_{\text{ci}} \) are achieved due to (1) the Planck function dependence on temperature at widely separated wavelengths, and (2) the dependence of \( \epsilon \) on wavelength. The \( \epsilon \) (common to both \( \lambda \)) corresponding to \( T_{\text{ci}} \) is then used in a radiation transfer model incorporating radiances from other MODIS channels, with \( \epsilon \) in each channel forced to be consistent with all observed radiances, the initial \( \epsilon \) retrieval, and radiation transfer theory using modified ADA. From the resulting \( \epsilon \) retrievals, \( \tau_{\text{abs}} \) is obtained assuming zero scattering, provided \( \epsilon \) is significantly < 1.0. While \( \tau_{\text{abs}} \) retrievals are not sensitive to ice particle shape assumptions, there is a weak sensitivity to SD shape (i.e. convective vs. stratiform cirrus), which is diagnosed from retrieved properties like cloud temperature and altitude, and the general appearance of the cloud field in the satellite scene.

The \( D_{\text{eff}} \) retrievals illustrated in Fig. 2 can also be applied to satellite retrievals. For instance, the MODIS instrument has channels at 3.74, 8.55, 11.0 and 12.0 \( \mu \)m, allowing \( \tau_{\text{abs}} \) ratios similar to those used in Fig. 2 to be formed (note refractive indices at 10.1 and 8.5 \( \mu \)m are very similar). As described above, \( \tau_{\text{abs}} \) was retrieved for these MODIS channels. An arbitrary sample of about 800 pixels gave mean \( \tau_{\text{abs}} \) ratios of 3.7/8.5 \( \mu \)m and 3.7/11 \( \mu \)m of 0.655 and
respectively. These are indicated by the “o” symbols in Fig. 2. The fact that these ratios both correspond to $D_{\text{eff}} = 55 \mu m$ is encouraging.

As a proof of concept exercise, we evaluated this anvil cirrus MODIS image, stratifying the emissivity retrievals for each channel into 4 bins based on the 11 $\mu m$ emissivity: 0-0.2, 0.2-0.5, 0.5-0.8, and 0.8-1.0. A $D_{\text{eff}}$ was retrieved for each bin using the predicted $\tau_{\text{abs}}$ 3.74/11.0 $\mu m$ ratio for anvil cirrus, shown in Fig. 11 (essentially the same as the 3.9/11.2 $\mu m$ curves in Fig. 2). Each crystal type in Fig. 11 has two curves: one assuming zero tunneling and one assuming maximum tunneling ($T_f = 1.0$). It is seen that tunneling has little effect on $D_{\text{eff}}$ retrievals, except at the smallest sizes. This is because tunneling is minimal at both wavelengths; due to the large size parameter at 3.7 $\mu m$, and due to the low real refractive index at 11 $\mu m$.

Next, MODIS $\tau_{\text{abs}}$ at 3.74, 4.05, 8.55, 11.0 and 12.0 $\mu m$ were normalized to $\tau_{\text{abs}}$ at 11 $\mu m$ to determine $T_r$ and to confirm the $D_{\text{eff}}$ retrievals. This data is plotted in Fig. 12 for each emissivity bin. The retrieved $D_{\text{eff}}$ values are listed, and predicted $\tau_{\text{abs}}$ curves are shown for each $D_{\text{eff}}$ retrieval. The lowest curve corresponds to the smallest $D_{\text{eff}}$ value, the highest curve to the largest $D_{\text{eff}}$. Since the tunneling process depends on $D_{\text{eff}}$, the use of four retrieved $D_{\text{eff}}$ values to generate four $\tau_{\text{abs}}$ curves provides a more rigorous estimate of $T_f$.

The difference in $\tau_{\text{abs}}$ between 11 and 12 $\mu m$ is a measure of the tunneling contribution and $T_f$. This is because without tunneling, $Q_{\text{abs}}$ would be about 1.0 at both wavelengths in most cirrus. The difference in brightness temperature and $\tau_{\text{abs}}$ at these wavelengths is almost entirely due to differences in tunneling contributions (see Fig. 1). In this 2nd step of the MODIS retrieval, $T_f$ is varied between 0 and 1 in order to find the $T_f$ that best describes the MODIS data.

With these steps complete, modified ADA is then used to determine the SD $Q_{\text{abs}}$ for each of the above MODIS bands. The retrieved $D_{\text{eff}}$, and corresponding emissivities, are then used with $Q_{\text{abs}}$ in Eq. (1) to calculate IWP for each channel, and a mean IWP is determined.

Retrievals of $T_f$ are shown in Fig. 12. Matching between theory and observations at $\lambda = 12$ $\mu m$ depends strongly on $T_r$ with a $T_r$ of 0.8 producing a clear mismatch (not shown). A $T_r$ of 1.0 fits the MODIS data best, as shown in Fig. 12. This was unexpected, as laboratory measurements and electrodynamic theory both indicate $T_r$ should be less than 1.0 for hexagonal columns and plates (Mitchell et al. 2001; Baran et al. 2001). One possible explanation is that convective cirrus, formed through the detrainment of condensed water from the convective updraft column, may be comprised of high concentrations of frozen droplets or quasi-spherical particles that dominate the SD area. While larger crystal shapes are non-spherical, concentrations of quasi-spherical particles with $D < 50 \mu m$ may be high enough to dominate the anvil infrared radiative properties as seen from space. Clearly more satellite scenes and analysis are needed to understand this issue.

Finally, the SD shape can be inferred using MODIS channels, such as those at 3.74 and 11.0 $\mu m$, using the methodology described under AERI.
retrievals and retrievals of $T_d$. This is illustrated in Fig. 14. While more points are needed, the present MODIS data are consistent with the SD scheme for tropical (i.e. anvil) cirrus. This is encouraging, since most of the cirrus in the satellite scene were of convective origin. The low $T_{abs}$ ratios relative to mid-latitude values indicate higher concentrations of smaller crystals in the small mode for anvil cirrus. The points near -50 and -40 °C correspond to the c bins 0-0.2 and 0.8-1.0, respectively. The number of pixels used in each c bin, from lowest to highest c, are 1148, 8100, 8861, and 17474, respectively.

4. SUMMARY

A relatively accurate method of retrieving IWP has been described and implemented for ground-based and satellite remote sensing, with uncertainties (standard deviation) < ± 20%, applicable over an IWP range of at least 1-100 g m⁻³ when using a channel around 3.9 µm. Effective size and optical depth are also retrieved in this process.

Methods were introduced allowing two new cloud properties to be retrieved for the first time: (1) size distribution shape or bimodality, and (2) photon tunneling contribution to absorption, quantified as a tunneling factor $T_t$. Results regarding (1) suggest that the high concentrations of small crystals ($D < 60$ µm) measured by the FSSP are real (not primarily artifacts of ice particle shattering at the probe inlet), and that their radiative impact is important. These results also support existing parameterizations of cirrus size spectra of convective and non-convective origin, providing evidence that the physical processes governing the evolution of size spectra in these two cirrus categories are fundamentally different. Future retrievals regarding (2) may reduce much of the uncertainty that plagues radiation transfer in ice clouds at thermal wavelengths.

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REFERENCES


Figure 13. Temperature dependence of the $T_{abs}$ ratio as predicted by the SD schemes for tropical and mid-latitude cirrus. Corresponding MODIS data are compared.


