GROUND BASED REMOTE SENSING OF SMALL ICE CRYSTAL CONCENTRATIONS IN ARCTIC CIRRUS CLOUDS

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1. INTRODUCTION

Measurement of small ice crystals (D < 60 \(\mu\)m) remains an unsolved and controversial issue in the cloud physics community. Concentrations of small ice crystals are hard to measure due to shattering of crystals at probe inlets. However, these small ice crystals alter cirrus cloud radiative properties and may affect the cirrus cloud feedback in global climate models. To facilitate better estimation of small ice crystal concentrations in cirrus clouds, a new ground-based remote sensing technique has been used in combination with in situ aircraft measurements. That is, data from the Mixed-Phase Arctic Cloud Experiment (M-PACE) conducted at Barrow on the north slope of Alaska (Fall 2004) is being used to develop an Arctic ice particle size distribution (PSD) scheme, that in combination with the anomalous diffraction approximation (for ice cloud optical properties), serves as the framework of the retrieval algorithm.

2. THEORY

Small ice crystals are evaluated using the properties of photon tunneling or wave resonance. Photon tunneling can be described as the process by which radiation beyond the physical cross-section of a particle is either absorbed or scattered outside the forward diffraction peak (Fig. 1). Tunneling is strongest when:

- The particle is spherical or quasi spherical (an attribute of many small crystals)
- The real index of refraction is relatively large

Tunneling contributions to the absorption efficiency in the window region can reach 20% when particle size is less than 60 \(\mu\)m. Tunneling depends on the real refractive index, which changes abruptly for ice between 12 and 11 \(\mu\)m wavelengths. The corresponding emissivity difference at these wavelengths is only due to tunneling, which makes the tunneling signal an ideal signal for inferring the concentrations of small ice crystals. Historically this emissivity difference was attributed to differences in the imaginary refractive index, but in essence, it is the real refractive index that accounts for this difference in emissivity in ice clouds.

![Figure 1: Depiction of possible trajectories of an incident grazing ray after tunnelling to the drop surface.](image-url)
Better understanding of remote sensing of small crystals by applying the tunneling technique is shown in Fig. 2. The solid curve shows absorption efficiencies ($Q_{abs}$) for a bimodal size distribution of quasi-spheres (droxtals) in the small mode and bullet rosettes in the large mode. Dashed curve is for the large mode, rosettes only. Bimodal PSD are shown in Fig. 3. $Q_{abs}$ for wavelengths > 11 μm are greater for the complete PSD due to tunneling. Tunneling depends strongly on the real index of refraction, $n_r$. The reason $Q_{abs}$ is greater at 12 μm than 11 μm when the full PSD is used is because $n_r$ has a minimum near 11 μm but is substantial at 12 μm. Since tunneling is a measure of the small mode, and the 12 – 11 μm $Q_{abs}$ difference is only from tunneling, this difference serves as a measure of the small mode of the cirrus PSD. These calculations are based on the optical property database given in Yang et al. (2005).

**Figure 2:** Absorption efficiencies ($Q_{abs}$) for a bimodal size distribution.

**Figure 3.** Examples of bimodal size distributions based on measurements from mid-latitude cirrus clouds (Ivanova et al. 2001).

**Figure 4.** Theoretical curves denoting the large mode (dashed) and the complete PSD (solid) corresponding to 3 different temperatures.
3. ESTIMATING SMALL CRYSTAL CONCENTRATIONS

The small mode ice mass content can be estimated by the “arches” in Fig. 4 and also from the absorption optical depth ratio at 12 and 11 μm, referred to as \( \beta \). Several studies have shown that \( \beta \approx 1.08 \) for synoptic and anvil cirrus. The higher the small mode ice mass content (or ice crystal number concentration, \( N_{sm} \)), the higher the arches are. This principle is used to determine \( N_{sm} \) by matching theory with observations, as described below.

1. The first step is to begin with retrievals of cloud temperature and cloud emissivity (\( \epsilon \)) at 11 and 12 μm wavelength channels from the ground based Atmospheric Emitted Radiance Interferometer (AERI), and from a corresponding sounding and cloud radar profile.

2. The cloud temperature can then be used to estimate PSD mean size (D) and dispersion for large and small mode. The difference between the solid and dashed curves results primarily from differences in the contribution of the small PSD mode to the ice water content (IWC). This also determines the effective diameter (\( D_{eff} \)). The dispersion parameter has little influence on the emissivities or emissivity differences.

3. Locate retrieved \( \Delta \epsilon \) (y-axis) and the 11 μm \( \epsilon \) by (1) incrementing the modeled ice water path (IWP) to increase \( \epsilon \) (11 μm) and (2) incrementing the small mode contribution to the cloud IWC, which elevates the curve.

4. If all IWC is in small mode and retrieved \( \Delta \epsilon \) and \( \epsilon \) (11 μm) are still not located, then decrease small mode D to locate them.

5. If retrieved point lies below the “large mode only” curve (e.g. a dashed curve), then systematically increase D for large mode until a match is obtained. Negative \( \Delta \epsilon \) values correspond to maximum allowed D values.

6. This method retrieves IWP, \( D_{eff} \), and the small-to-large mode ice crystal concentration ratio. For a given IWC, it also estimates ice particle number concentration and the complete PSD, even when it is bimodal.

The modified anomalous diffraction approximation (MADA) was used to calculate ice and water cloud optical properties in this AERI retrieval algorithm since it couples explicitly with the cloud microphysics and its analytical formulation makes it computationally efficient (Mitchell et al. 2006; Mitchell 2000).

4. CASE STUDY ANALYSIS

The Ivanova et al. (2001) PSD scheme for mid-latitude synoptic cirrus was used in our retrieval algorithm, but soon we will replace this with a PSD scheme developed from M-PACE PSD data for ice clouds, based on ice water content (IWC) and temperature. Measurements made by the ground-based AERI are used to indicate the concentration of small ice crystals (D < 60 μm) relative to the larger ice particles.

![Figure 5: Ratio of the absorption optical depth between 12 μm and 11 μm as a function of hour of the day (UTC).](image-url)
The absorption optical depth (AOD) of these clouds for three wavelengths (12.19 µm, 11.09 µm and 8.73 µm) are obtained from the AERI and the 12-to-11 µm AOD ratios are plotted in Fig. 5 above. Visible optical depth (OD) is less than 4.5 (to prevent emissivity saturation) and greater than 0.5. An AOD ratio above 1.1 suggests the presence of liquid water in the cloud (Giraud et al. 1997, 2001).

Figure 6 shows that the cloud temperature ranges between -27 °C and -39 °C. According to the homogeneous nucleation theory, super cooled water may be present along with ice in clouds at temperatures above -36 °C. This is supported by AERI AOD values that are higher than 1.1 (Fig. 5).

Combining the small crystal information (from AERI radiances) with the PSD scheme describing the larger particle concentrations yields the retrieved PSD. The products from this AERI retrieval scheme are the PSD and ice particle number concentration for a given IWC, as well as the ice water path, effective diameter and the ratio of the small mode-to-large mode number concentration. However this presumes that the cloud does not contain significant amounts of liquid water.

As noted, the AOD ratios in Fig. 5 and the radiance-weighted cloud temperatures in Fig. 6 suggest the presence of liquid water in the cirrus. In addition, recent findings shown on our website, http://www.dri.edu/Projects/Mitchell/, indicate that the cirrus PSD is either monomodal or weakly bimodal (based on applying our retrieval algorithm to several published remote sensing studies, as well as a case study we recently analyzed). Therefore we have modified our retrieval algorithm to interpret all condensate in the small mode as liquid water. The small mode mean diameter, $D_{sm}$, and the dispersion parameter were assumed to be 7 µm and 9, respectively, which may be representative of droplet spectra in mixed phase conditions. Unfortunately, the cloud retrievals are sensitive to what one assumes for $D_{sm}$, and this is the major limitation of this retrieval method. For example, increasing $D_{sm}$ from 7 to 10 µm

![Figure 6: Plot of the cloud temperature in (deg. C) versus the hour of the day in UTC.](image)

![Figure 7: Retrieval results for M-PACE case study of 17 Oct. 2004.](image)
can increase the retrieved percent liquid water content (LWC) by a factor of 3 and decrease the retrieved water path (WP) and Deff by 40% and 32%, respectively. Results from this analysis are shown in Fig. 7 for the M-PACE cirrus case study of 17 Oct. 2004. T_abs in Fig. 7 is the absorption optical depth at 11 μm multiplied by a factor of 10. Consistent with Figs. 5 and 6, the percentage of liquid condensate is significant from 13 to 14.2 UTC and from 17.6 to 18 UTC. If the mean cloud droplet size was assumed to be 5 μm instead of 7 μm, the %LWC would not exceed 26%. The effective diameter, Deff, is for both liquid and ice fractions combined. Therefore Deff is largest between 14.2 and 15.4 UTC when the cloud is glaciated (LWC is negligible), and these Deff values are typical of the ice phase in general for this case study. At least over this time period, AERI radiances indicate the PSD is generally monomodal with ice particle concentrations of about 4 – 7 liter⁻¹ when the IWC = 10 mg m⁻³ (see Fig. 8). For other time periods having significant liquid water, the cloud droplet number concentration N_d can exceed 30 cm⁻³. When we changed the algorithm to assume the small mode is comprised of ice crystals (based on Ivanova et al. 2001) instead of cloud droplets, N_ice ranged from about 1 to 10 cm⁻³ in the regions where the AOD ratio exceeds 1.08. It seems unlikely that N_ice would change so abruptly, making the mixed phase explanation most reasonable. T_abs in Fig. 7 is minimum between 14.2 and 15.4 UTC, which corresponds to glaciated cloud conditions, lower N and larger Deff.

Finally, Fig. 9 shows lidar depolarization ratios and Millimeter Cloud Radar (MMCR) backscatter for this case study. The high depolarization ratios indicate the dominance of the ice phase, and the MMCR backscatter provides more detail on cloud structure and position. Since we only used AERI data having visible OD between 0.5 and 4.5, the cirrus between 15.4 and 17.6 UTC was not included in this analysis. Note that the low patch of cloud near 18 UTC could be responsible for the higher percent LWC in Fig. 7.

The physics responsible for the differences in AOD at 12 and 11 μm are different for liquid water than for ice. Whereas tunneling produces the AOD differences in small mode ice crystals, the role of tunneling is relatively minor in water droplets since the real refractive index is similar for water at these wavelengths. For

![Figure 8](https://example.com/figure8.png)

**Figure 8.** Retrieved cloud droplet and ice crystal number concentrations assuming a total water content (ice + liquid) of 10 mg m⁻³.

![Figure 9](https://example.com/figure9.png)

**Figure 9.** Lidar depolarization ratios and MMCR backscatter for the M-PACE 17 October case study at Barrow, Alaska, courtesy of Ed Eloranta (Univ. of Madison, WI).
cloud droplets, it is the transition from area dependent absorption to mass dependent absorption (as droplet size decreases for $D < 10 \mu m$) that causes the sudden changes in AOD ratio (see Mitchell and Arnott 1994 for a discussion of area and mass dependent absorption). This is why the retrieval algorithm is so sensitive to $D_{\text{sm}}$.

5. CONCLUDING REMARKS

By applying the principle of photon tunneling or wave resonance to radiances at 11 and 12 $\mu m$, we have found in previous work that the cirrus PSD tends to be monomodal or weakly bimodal, allowing us to infer that the small mode of the retrieved PSD, when present, is mainly comprised of liquid water. When the LWC was negligible, the retrieved ice particle concentrations appear consistent with known ice nucleation processes.

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BIBLIOGRAPHY


