INTERPRETING HIRS LEVEL 1b OBSERVATIONS OF CIRRUS USING THE 8 μm CHANNEL: MIE OR ADT ?

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1. INTRODUCTION

In order to understand the influence of cirrus on the earth-atmosphere radiation balance, it is important to determine and quantify cirrus properties. The cirrus properties to be quantified from the point of view of climate modelling are crystal dimension and shape, ice water path, optical thickness and altitude. The importance of some of these cirrus properties and their role in climate have been highlighted by *Stephens and Webster* (1981), *Liou* (1986), *Takano and Liou* (1989; 1994), *Mitchell et al* (1994). The importance of tropical cirrus has been recently highlighted by *Ramanathan and Collins* (1991), where deep convective clouds can be persistent and extensive producing very high anvils.

In-situ measurements of ice particle size distributions in tropical anvils have recently been made by *Knollenberg et al* (1993) and *Heymsfield and McFarquhar* (1994). Heymsfield and McFarquhar measured median mass diameters (D_{mm}) of between 30 and 90 μm at cloud top with columns and plates being the dominant crystal habit. Whilst Knollenberg et al measured median mass diameters of between 20 and 40 μm near cloud top in the anvils they studied. In general, in-situ measurements of particle size in cirrus are difficult to reconcile with satellite retrieved particle sizes and aircraft radiative measurements, interpretation of which is mostly based on Mie theory (see for example *Ackerman et al* (1990), *Wielicki et al* (1990), *Heymsfield et al* (1990), *Stackhouse and Stephens* (1991) and *Francis et al* (1994)). One of the difficulties in interpreting remotely sensed data is knowing which theory to apply, be it Mie theory, Ray Tracing or Anomalous Diffraction Theory (ADT). It is common practice to apply Mie theory under the assumption of area or volume equivalent spheres. Alternatively, ray tracing can be applied if the particle size parameters are greater than about 30. This maybe suitable for solar radiation, but not for terrestrial radiation, where size parameters are often < 30 for crystal sizes common in cirrus.

In this paper, we use the sensitivity of the 8 μm and 11 μm HIRS channels to determine the near cloud top crystal size for two cases: (i) optically thick mid-latitude frontal cirrus and (ii) optically thick tropical cyclones. The crystal sizes were derived using Mie theory (spheres) and ADT assuming hexagonal columns, plates and planar polycrystals. If Mie theory is assumed, we show that small crystal sizes, which are smaller than observed, are needed to explain the brightness temperatures at 8 and 11 μm. However, ADT can explain the brightness temperature differences between 8 and 11 μm using mean crystal sizes typical of those measured by in-situ particle probes and replicator devices (*Heymsfield and McFarquhar* (1994, 1995); *Knollenberg et al* (1993)). This suggests that the evidence for very small particles could be the results of applying Mie theory inappropriately.

2. MIE THEORY AND ADT

In general, satellite remote sensing of cirrus properties for the purpose of climate data programmes is usually based upon Mie theory, an example being the ISCCP (International Satellite Cloud Climatology Project). However, recent work by *Mitchell* (1995 a,b) has shown shortcomings in applying Mie theory to the irregular shaped particles that occur in cirrus. The essential difficulties arise from differences in how spheres and irregular shaped crystals interact with radiation. *Mitchell and Arnott* (1994) have shown that the effective distance (particle volume divided by projected area) over which radiation is absorbed is much greater for spheres than it is for ice crystals having the same projected area. Since area equivalent spheres are often assumed in the thermal IR, this will result in an overestimation of the absorption, with the absorption coefficient being primarily dependent on the projected area. However, if ice crystals were properly represented, the absorption coefficient would exhibit varying degrees of dependence on mass (volume) and area, as shown in *Mitchell and Arnott* (1994). For small ice crystals, ADT will predict more of a mass dependence which lowers emissivity, whilst large ice crystals will have more of an area dependence which increases emissivity. The imaginary part of the index of refraction has a minimum at 8.3 μm, which is the reason why this channel on HIRS is particularly valuable in determining ice crystal sizes less than 100 μm. That is, absorption changes from being volume to area dependent as the size increases.

Fig 1 shows the difference in predicted absorption and extinction efficiencies between Mie theory and ADT. ADT underestimates absorption relative to Mie theory for particle diameters less than about 100 microns at 8.3 and 11 μm. The fundamental reason for this difference has recently been hypothesised by *Mitchell* (1995b) to be due to the capture of grazing or tangential photons by spheres, a process which is not likely to occur for irregular shaped crystals. By capturing grazing photons with tangential, but non-colliding, trajectories, the absorption cross-section of a sphere can be greater than its physical cross-section. This phenomena causes emissivities predicted by Mie theory to be greater than those predicted by ADT.

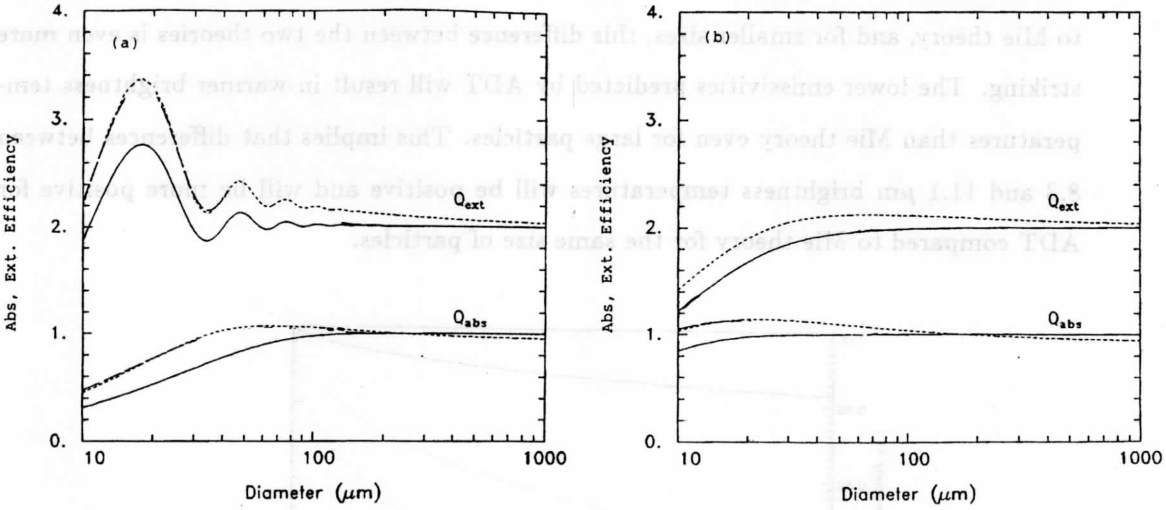

Fig. 1 The difference between Mie and ADT in predicting extinction and absorption efficiencies at (a) 8.3 and (b) 11 μm. ADT (Solid Line), Mie (Dashed Line).

3. MODEL

The irradiance arriving at the satellite detector from a cloud layer, assuming a plane parallel homogenous cloud layer, isotropic surface irradiances, and the zero scattering approximation, is given by;

$$\mathrm{I_m(T)} = (1 - \epsilon)\mathrm{I_s(T_s)} + \epsilon \mathrm{I_c(T_c)} \tag{1}$$

Where $\mathrm{I_m}$, $\mathrm{I_s}$ and $\mathrm{I_c}$ are the measured, surface and cloud irradiances respectively. The emissivity ϵ, is given by

$$\epsilon = 1 - \exp(\mathrm{F_d}\tau_{\mathrm{abs}}) \tag{2}$$

Where $\mathrm{F_d}$ is the diffusivity factor ($\mathrm{F_d}$=1.66), τ_{abs} is the absorption optical depth. Differences in predicted emissivity between ADT and Mie theory are shown in Fig. 2 for two different sizes of hexagonal columns. The ratio of emissivities between 8.3 and 11.1 μm show that for large columns, ADT predicts lower emissivities at 8.3 μm relative to Mie theory, and for smaller sizes, this difference between the two theories is even more striking. The lower emissivities predicted by ADT will result in warmer brightness temperatures than Mie theory even for large particles. This implies that differences between 8.3 and 11.1 μm brightness temperatures will be positive and will be more positive for ADT compared to Mie theory for the same size of particles.

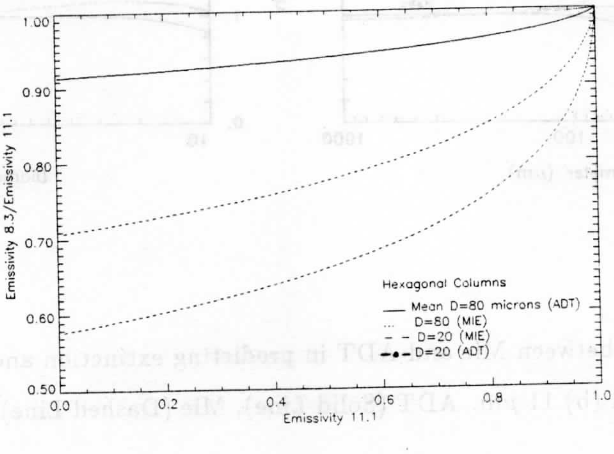

Fig.2 Emissivity ratio between 8.3 and 11.1 μm for hexagonal columns of mean size 20 and 80 μm respectively.

The assumption of isotropic surface brightness temperatures has been tested by using RTTOV (*Eyre* (1991)) to calculate clear sky brightness temperatures as a function of scan position. The calculations show that for tropical atmospheres the variation is at most 5 K for the 8.3 μm channel and less than 1 K for the 11.1 μm channel.

In-situ measurements of ice particle size are often reported in terms of median mass dimension, where the dimension is the maximum distance across the particle. To compare our results with the literature, we converted model predicted mean dimensions to median mass dimensions using the method described in *Mitchell* (1991), where $\nu = 1$ and the beta value for hexagonal columns, plates and polycrystals was 2.91, 2.45, and 2.45, respectively (beta = 1.91 for columns > 100 μm). It is noteworthy that median mass dimensions are typically 2 to 3 times larger than mean dimensions, depending on ice particle size distribution shape.

4. CASE 1. OPTICALLY THICK MID-LATITUDE FRONTAL CIRRUS

For the case of optically thick mid-latitude cirrus, we examine the brightness temperature response at 8.3 and 11.1 μm using HIRS onboard NOAA-10 for mid-latitude frontal cirrus, and then simulate these brightness temperatures using equation (1). Both Mie theory (spheres) and ADT (columns and polycrystals) are used for particular sphere diameters or mean crystal dimensions to fit the data points. A frontal cirrus case was found using HIRS level 1b data on February 4th 1990 at 1900 GMT located 50-64°N, 7°W-15°W. The temperature of the cloud T_c was estimated by finding the intercept of a polynomial on a brightness temperature difference diagram (3.7-11 against 11 microns) at y=0, which yielded T_c=200 K. The parabolic shape for this case is shown in Fig. 3.

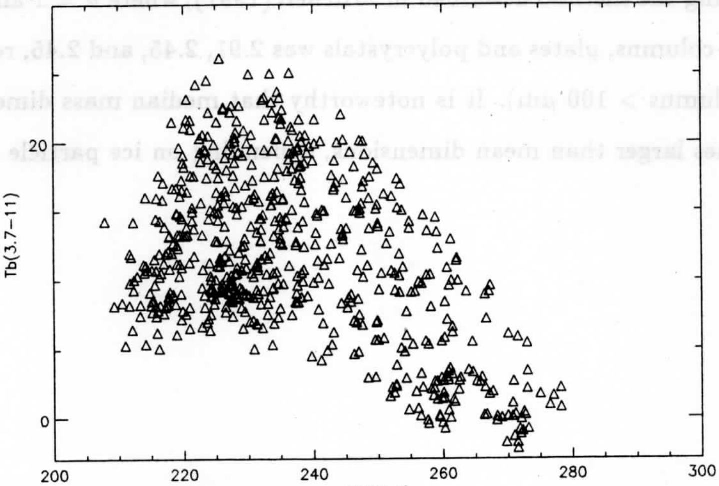

Fig. 3 Diagram showing the classic parabola shape for the frontal cirrus case using a bispectral technique (3.7-11 against 11 microns) used to estimate a cloud temperature.

Fig. 4 shows the brightness temperature in the 8.3 μm channel plotted against the brightness temperature in the 11.1 μm channel. The solid line represents the model calculation with increasing optical depth. ADT using hexagonal columns and planar polycrystals fits through the data points assuming D_{mm} values of 137 and 195 μm, respectively. Whilst Mie theory and spheres, because of the overestimation of absorption, predicts a D_{mm} of 49 μm, at least three times smaller than ADT. Clearly, if Mie theory is used in estimation of ice crystal size, it may reduce retrieved crystal sizes by almost one third. Median mass diameters of 195 μm assuming polycrstals obtained for the frontal cirrus case using the

HIRS 8.3 and 11.1 μm channels are not unlike the sizes reported from the 28th October 1986 FIRE I case study *Heymsfield et al* (1990). Mie theory and spheres require a D_{mm} of 49 μm to explain the brightness temperatures for the frontal cirrus case. Such sizes were not observed using in-situ measurements during FIRE I case studies.

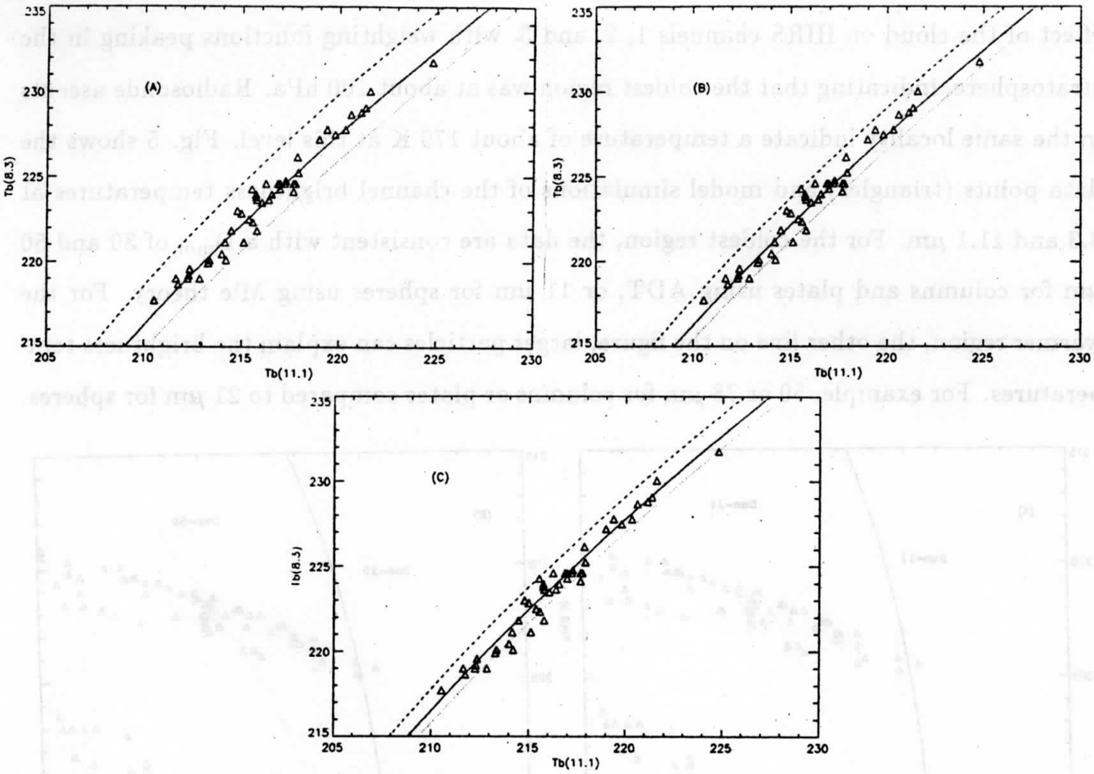

Fig. 4 Channel brightness temperature responses at 8.3 and 11.1 μm for the frontal cirrus case (triangles) and model calculations using Mie theory and ADT. The best fit particle size and sizes ±20% are shown. (A) D_{mm}=49 μm Sphere using Mie theory. (B) D_{mm}=137 μm Hexagonal column using ADT and (C) D_{mm}=195 μm Polycrystal using ADT.

5. CASE 2. OPTICALLY THICK TROPICAL CYCLONE

A tropical cyclone from NOAA-10 HIRS data was observed at 1900 GMT 1 February 1990 located at 15°S, 180-165°W. The same procedure was used as in case 1 for the analysis. To estimate cloud temperature, the coldest spots were chosen. These were at about 179 K. Supporting evidence for this temperature was obtained from a study of the effect of the cloud on HIRS channels 1, 2, and 3, with weighting functions peaking in the stratosphere, indicating that the coldest region was at about 100 hPa. Radiosonde ascents in the same locality indicate a temperature of about 179 K at this level. Fig. 5 shows the data points (triangles) and model simulations of the channel brightness temperatures at 8.3 and 11.1 μm. For the coldest region, the data are consistent with a D_{mm} of 30 and 50 μm for columns and plates using ADT, or 11 μm for spheres using Mie theory. For the warmer region, the other line on the figure, larger particles can explain the brightness temperatures. For example, 50 or 78 μm for columns or plates compared to 21 μm for spheres.

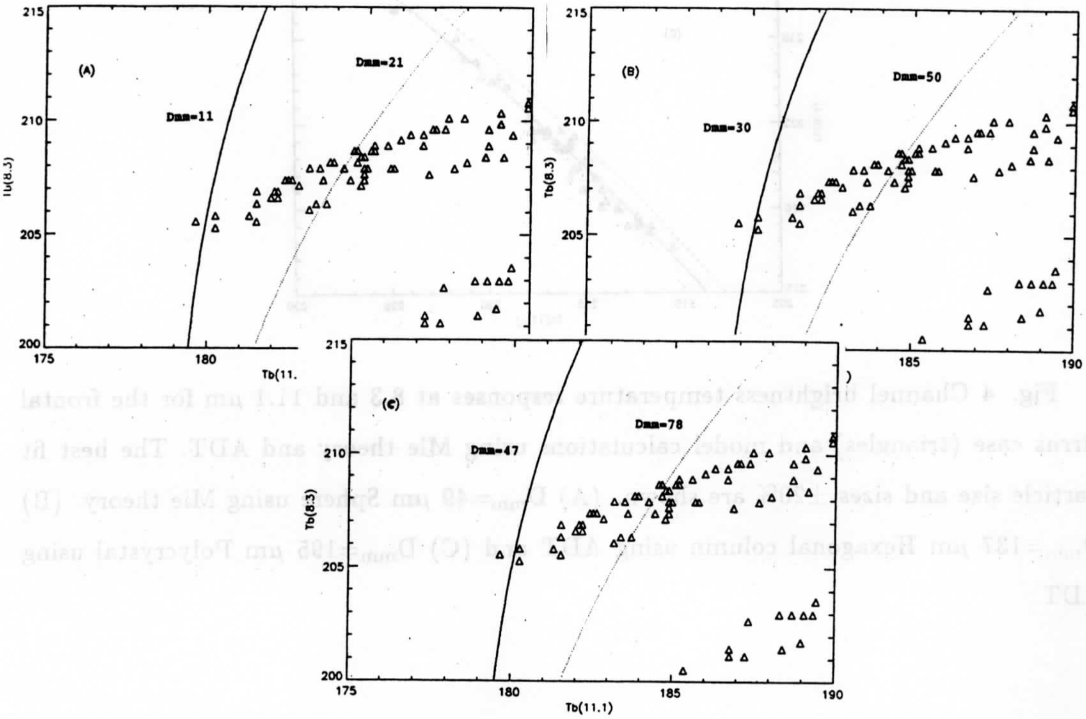

Fig.5 Tropical cyclone case study. Triangles are the data points and the full lines are the model simulations. (A) Sphere using Mie theory, (B) Hexagonal column using ADT and (C) Plates using ADT.

For plates and hexagonal columns the D_{mm} values generated using ADT are similar to the in-situ measurements of *Knollenberg et al* (1993) (D_{mm}=20-40 μm) and *Heymsfield and McFarquhar* (1994) (D_{mm}=30-90 μm). However, Mie theory requires much smaller sizes. Mie theory and spheres would seem to indicate the presence of very small particles undetectable by in-situ measurement probes.

In the above analysis, an isothermal cloud layer was assumed with a contribution from the surface. In reality, thick cirrus sytems will have radiation originating from some level within the cloud, and the cloud emission will be sensitive to the cloud temperature profile. The assumption of an isothermal cloud layer for deriving particle size needs further investigation.

6. CONCLUSIONS

- The sensitivity of the 8.3 μm channel to particle size has been demonstrated.

- Using ADT, the infered particle sizes for the frontal cirrus layered cloud tended to have large crystal median mass diameters of 195 μm if polycrystals are assumed (or 137 μm if hexagonal columns are assumed), whereas tropical cyclones representing deep convective cloud have median mass diameters of around 30-47 μm in the coldest regions if hexagonal columns or plates are assumed.

- Validation from in-situ observations of other frontal and tropical cirrus suggests that the derivations using ADT provides a more realistic retrieval compared to Mie theory based on spheres.

- If the last conclusion is correct, then it follows that if Mie theory is used in satellite remote sensing, this may result in a preponderance of small crystals in conflict with in-situ measurements. ADT appears to better represent real crystals that appear in cirrus.

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ADDENDUM

Some concern regarding the calibration of the 8.3 μm channel was raised at ITSC VIII, which could be affected by the dielectric coating used on the scan mirror. This effect could modulate gain and might cause large differences at cold temperatures between 8.3 and 11 μm. To test this effect, 61 cases of tropical anvil cirrus have been studied. The brightness temperature differences at cold temperatures (11 μm brightness temperature in range 180-200 K) were compared. The brightness temperature differences varied by about 5-25 K over this range in temperature. This suggests that any instrument problem may not be significant. Future missions should ensure that a coating is chosen that will minimise the problem (if any) and that the complete system is rigorously tested.

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