A STUDY OF THE MICROPHYSICAL AND MACROPHYSICAL PROPERTIES OF CIRRUS: AN INTERCOMPARISON BETWEEN CLOUDSAT, IN SITU MEASUREMENTS, A GCM AND AN ICE CRYSTAL MODEL

Anthony J. Baran¹, Clare Lee², Richard Cotton³, Alejandro Bodas-Salcedo⁴, Jorge Bornemann⁵, Edwin Hirst⁶, Richard T. Austin⁷, John G. Haynes⁸, Graeme L. Stephens⁹, and Paul Connolly¹⁰

¹-⁵ Met Office, Exeter, UK
⁶ University of Hertfordshire, Hatfield, UK
⁷-⁹ Colorado State University, Fort Collins, USA
¹⁰ University of Manchester, UK

1. INTRODUCTION

Cirrus (ice crystal cloud) is now well known to be an important component of the earth-atmosphere radiation balance as well as the hydrological cycle (Liou and Takano 1994; Stephens et al., 2002; Edwards et al. 2007). This balance depends not only on the vertical extent and position of the cloud within the earth’s atmosphere but also on its macrophysical and microphysical properties. It is therefore important to characterise cirrus in terms of the vertical distribution of IWC, ice crystal size, shape and how the particle size distribution function (PSD) evolves within the cloud. These characterizations are essential if parameterizations are to be further improved in general circulation models. Moreover, characterizing cirrus is also important in order to test theoretical models of cirrus and space-based measurements of IWC and ice crystal size. Since April 2006 there is now a complete series of space-based instruments (called A-train) able to measure the radiative and hydrological contributions of cirrus to the climate system (Stephens et al., 2007). In this extended abstract we report on a number of field campaigns that attempt to characterise semi-transparent cirrus in terms of its macrophysical and microphysical composition. The in situ measurements of IWC and ice crystal effective dimension are compared against CloudSat retrievals as well as the Met Office Global and Mesoscale operational NWP model products. The in situ measurements are also used to test a theoretical ensemble model of cirrus described in Baran and Labonnote (2007) in terms of its prediction of IWC, ice crystal effective dimension and extinction profiles.

2. THE CAMPAIGNS AND INSTRUMENTATION

During the Winter and Autumn of 2007 the FAAM (Facility for Airborne Atmospheric Measurements) BAE-146 G-LUXE aircraft flew a number of flights as part of the CAESAR (Cirrus and Anvils: European Satellite and Airborne Radiation measurements project) campaign of flying in, above and below cirrus around the United Kingdom located over the sea. The goal of CAESAR is to understand the radiative properties of cirrus over a wide range of wavelengths in combination with airborne in situ measurements of cirrus microphysical properties. Flights observed semi-transparent frontal cirrus co-incident with the CloudSat Aqua-train. In total there were six flights three of which were coincident with CloudSat on the 16th and 25th of January 2007 and on 20th September 2007. For the CloudSat co-incidences the aircraft sampled the cirrus as a series of profiles from cloud-top, which was penetrated in all three cases, to cloud-bottom and as a series of saw-tooth manoeuvres. These manoeuvres were performed in order to obtain a good statistical sample of the macrophysical and microphysical state of the cirrus with which to compare against CloudSat and the Met Office NWP models. The other three
CAESAR flights took place on the 14th November 2005, 1st December 2005 and on the 9th May 2006. These flights are used to test the ensemble model of cirrus briefly mentioned in the introduction. Table 1 summarises each flight in terms of its location and the suite of cloud physics instrumentation that was onboard.

Table 1. Flight Summary

<table>
<thead>
<tr>
<th>Flight No</th>
<th>Date</th>
<th>Lat/Long°</th>
<th>SID II</th>
<th>2DC</th>
<th>CPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>B258</td>
<td>16/01/07</td>
<td>54.8-56.4N;2-3E</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>B262</td>
<td>25/01/07</td>
<td>56.2-58.3N;3.5E</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>B327</td>
<td>20/09/07</td>
<td>53.4-55.2N;8W-3E</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>B138</td>
<td>14/11/05</td>
<td>49.9-50.8N;8-6W</td>
<td>X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B143</td>
<td>1/12/05</td>
<td>50.5-51.6N;7.2-5W</td>
<td>X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B195</td>
<td>9/04/06</td>
<td>49.3-50.8N;8-8.3W</td>
<td>X X X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The crosses in the table indicate that the instrument was operational during the flight. Unfortunately, although the 2DP was onboard it was not operational and so ice crystals greater than 800 µm were not measured. Other instrumentation included the new Small Ice particle Detector (SID II) described in Hirst et al. (2001) (although the Hirst et al paper is concerned with SID I its principal of operation is similar to SID II). This instrument can measure the PSD between 3 µm and 100 µm, the particle number concentration, particle phase, and particle size. The SID II instrument given the measurement of ice crystal size can also be used to estimate the IWC by assuming spheres of density 0.92 g cm⁻³. The error in the SID II estimate of IWC is likely to be ±50% given uncertainties in sampling volume and sizing. The 2D-C overlaps with SID II. The Cloud Particle Imager (CPI) instrument described in Lawson et al. (2001) was available for three of the flights which occurred before the launch of CloudSat. An algorithm developed by Connolly et al. (2007) has been applied to the CPI to correct for over sizing and particle rejection. The 2D-C probe was also used to estimate the IWC and ice crystal effective dimension, $D_e$. The 2DC IWC was derived assuming the mass-dimensional relationships given in Brown and Francis (1995) and the ice crystal $D_e$ is derived as follows (Foot 1988; Francis et al. 1999);

$$D_e = \frac{3IWC}{2\rho \sum n_j A_j}$$

where IWC is the ice water content, $n_j$ is the ice crystal number concentration in the $j$th size bin and $A_j$ is the mean cross-sectional area of the $j$th bin so $\Sigma n_j A_j$ is the cross-sectional area density of the integrated size distribution function. The density $\rho$ is a reference density assumed to be unity in order to keep the units of Eq. (1) consistent. The definition of $D_e$ used in Eq. (1) was also applied to the CPI. The error in determining the IWC from the 2DC and CPI is likely to be ±50% (Heymsfield et al. 2002). The mean cross-sectional area is likely to be a similar error to the 2DC being unable to measure ice crystals less than 100 µm in size. This error will be further compounded by shattering on the inlet of the probe (Field et al. 2003). Therefore, given the definition of $D_e$ from Eq. (1) the uncertainty in $D_e$ is likely to be ±70%. The mean cross-sectional area as measured by the CPI is also likely to be a similar error to that of the 2DC due to sampling volume and ice crystal shattering. Therefore, the CPI error in determining $D_e$ will also be of the order ±70%.

From the measured aircraft or CloudSat IWC vertical profile the Ice Water Path (IWP) can be found from;
\[ \text{IWP} = \int_{z_1}^{z_2} \text{IWC}(z) \, dz \]  
\[ \text{(2)} \]

where \( z_1 \) and \( z_2 \) correspond to the aircraft measured cloud-bottom and cloud-top, respectively.

From the IWP given by Eq. (2) and assuming the geometric optics approximation, in which the volume extinction coefficient is just twice the area density, the optical depth of the cloud, \( \tau \), is then related to IWP and \( D_e \) via:

\[ \tau = \frac{3 \text{IWP}}{\rho D_e} \]  
\[ \text{(3)} \]

Equations (1), (2), and (3) are used to compare aircraft derived values with those retrieved from CloudSat, predicted by the Met Office NWP models and the ensemble model of cirrus. The \( D_e \) derived in the Met Office NWP models is based on cloud temperature relationships described in Edwards et al. (2007).

3. CLOUDSAT RETRIEVALS

The CloudSat retrieved IWC and \( D_e \), based on the 94 GHz radar reflectivities, are obtained from the level 2B radar-only algorithm which is described in Austin et al. (2008). In this algorithm the IWC is derived from the 1-dvar retrieved particle number density and the geometric mean diameter of ice crystals and by assuming a constant density for ice. Since retrievals are based on a 1-dvar scheme there are uncertainties associated with the retrievals, which are given in the level 2B product. There is an implicit assumption in the radar reflectivities at 94 GHz being dominated by Rayleigh scattering; however, there is a correction for non-Rayleigh scattering which is based on Mie-Lorenz theory. A further point is that there are no retrievals of IWC below a threshold of approximately 2 mgm\(^{-3}\) (determined by the cloud mask algorithm in the 2B-GEOPROF product). The ice crystal effective dimension, \( D_e \), can be related to the retrieved geometric mean diameter via an assumed lognormal size distribution function. The IWP can be derived via Eq. (2) as defined by the aircraft and the \( D_e \) related to Eq. (1) via a factor 1.5. Although the definitions of \( D_e \) are not exactly the same they are sufficiently close for the purposes of the present study. Moreover, the 2DC probe has not been corrected for ice crystals less than 100 \( \mu \)m in size so that the in situ measurements of \( D_e \) are more relatable to the radar-only retrievals of \( D_e \).

4. CLOUDSAT AND NWP MODEL CASE STUDIES

In this section results obtained for B262 are presented in detail, results for the other two cases are similar but are not presented here for reasons of brevity. Results are shown in the form of PDF’s for the in situ measurements, CloudSat retrievals and NWP models. For B262 the cloud-top according to the aircraft measured ice particle number concentrations was situated at 10.80 km whilst the cloud-bottom was situated at 6.0 km. Figure 1 (a-c) shows PDF’s of the measured in situ IWC obtained from the 2DC and SID II instruments, the corresponding NWP model predictions and the CloudSat retrievals, respectively. The X-axis of Figure 1 is transformed into Log10 (IWC) space so that results for each set are directly comparable.

From Fig. 1 the range of in situ measured binned IWC goes from 0.120 - 126 mgm\(^{-3}\) for the 2DC and between 0.21 - 316 mgm\(^{-3}\) for SID II. This range of measured IWC is not surprising since SID II is biased to smaller ice crystals and the 2DC is biased to the larger ice crystals. Moreover, the SID II estimate of IWC might be considered an overestimate due to the assumption of solid ice spheres in converting size to an IWC. Therefore, SID II gives the upper range of measured IWC whereas the 2DC can be considered as the lower range of IWC. The mean IWC as measured by the 2DC and SID II are 18.013 mgm\(^{-3}\) and 35.65 mgm\(^{-3}\), respectively. The mean of the estimated
IWC from the two instruments are within a factor two of each other which is a good result given the uncertainties.

The modes of the two distributions are 9.33–52.48 mgm\(^{-3}\) and 21.88–52.48 mgm\(^{-3}\) for the 2DC and SID II instruments, respectively.

The median of the 2DC and SID II IWC distributions are 15.93 mgm\(^{-3}\) and 26.32 mgm\(^{-3}\), respectively, and it is around the medians of the two distributions that most of the in situ estimated IWC is concentrated.

(a)

![Graph](image)

(b)

![Graph](image)

Figure 1. The normalized frequency plotted against Log10 (IWC) for (a) in situ measurements (b) NWP models (40 km and 4 km are the global and mesoscale models, respectively) (c) CloudSat

The NWP distribution of IWC is fairly well distributed in relation to the in situ measurements but IWC’s greater than 52.48 mgm\(^{-3}\) are not produced by the models. Although both models have the same cloud scheme their distribution of IWC about the cloud is slightly different. This could be due to the models having differing horizontal and/or vertical resolutions. As a result of the models not producing higher IWC’s their mean values will be lower than the in situ measured values and so will be biased to the lower end of IWC as indicated by Fig. 1 (b). Indeed, the models produce IWC’s lower than it is possible to measure by the in situ probes though this occurrence is about 1% for the Global model and much less than 1% for the Mesoscale model. The mean IWC produced by the Global model is 7.9 mgm\(^{-3}\) and 5.0 mgm\(^{-3}\) for the Mesoscale model. The mean values for the NWP models are a factor 2-4 less than the in situ mean estimated IWC values. The modal values of the NWP distributions are 3.8–9.12 mgm\(^{-3}\) and 0.69–1.62 mgm\(^{-3}\) for the Global and Mesoscale models, respectively. There
is a tendency for the Mesoscale model to produce less IWC than the Global model. Though, essentially both models underpredict the higher IWC end of the in situ measurements.

The CloudSat results are shown in Figure 1 (c) together with the retrieved uncertainties shown as +U and –U in the figure, respectively. Since CloudSat is a 94 GHz radar it is not expected to estimate IWC less than 2 mgm\(^{-3}\) as stated in Section 3. The interesting point to note in Fig. 1 (c) is the lack of retrievals greater than 52.48 mgm\(^{-3}\) and the drop off in IWC is sharper than in the NWP models. The mean of the CloudSat distribution is 7.2 mgm\(^{-3}\) with the mode centred between 3.8-9.12 mgm\(^{-3}\). These mean results and modal values are not dissimilar from the NWP model results. A possible explanation for the CloudSat behaviour of retrieved IWC is shown in Fig. 2.

Figure 2 shows the vertical distribution of the in situ estimated SID II IWC together with all the CloudSat retrieved vertical IWC uncertainty profiles for B262. SID II is shown in Fig. 2 to highlight the vertical variation of IWC compared to the CloudSat retrievals.

The SID II Profile 9 (profiles are vertical descents/ascents from cloud-top/bottom to cloud bottom/top) shows a bulge in IWC around the centre of the cloud then a further bulge in IWC towards the cloud-bottom, together with Profile 8. Profile 10 shows consistently high IWC towards cloud-top when compared to profiles 8 and 9. The distance between profiles 8 and 9 towards cloud-top was of the order of 68 km and about 100 km between profiles 8 and 10. Clearly, there are significant variations in IWC both in the vertical and horizontal. The CloudSat vertical profiles also show a bulge in IWC towards the higher regions of IWC shown by Profiles 9 and 8 but the CloudSat retrievals decrease towards cloud-bottom. The reason for this decrease in retrieved CloudSat IWC could be due to much larger volume sampling at cloud-top and bottom compared to the aircraft volume sampling both vertically and horizontally. Moreover, the vertical resolution of CloudSat is of the order of 500 m so towards cloud-bottom CloudSat would be sampling below the cloud as well as within the cloud thus resulting in significantly lower IWC retrievals relative to the aircraft measurements.

Figure 3 shows the distribution of in situ measured 2DC \(D_e\) together with the UM predicted \(D_e\) based on temperature, and the CloudSat retrieved \(D_e\) with the uncertainties associated with those retrievals.

**Figure 2.** Profiles of retrieved IWC plotted as a function of altitude showing the in situ derived SID II IWC with all the CloudSat retrieved IWC uncertainty profiles for B262.

**Figure 3.** The normalized frequency plotted against \(D_e\) for B262 showing the 2DC derived \(D_e\), CloudSat retrieved \(D_e\) with its range of uncertainty shown as +U and –U and the NWP model (UM) derived \(D_e\).
Not surprisingly Figure 3 shows distinct differences between the NWP model and in situ measurements as well as the retrievals. As regards $D_e$ agreement is not expected since the NWP model parameterization is biased towards the small particle end of the PSD due to this parameterization being based on Ivanova et al. (2001). The 2DC does not measure ice crystal sizes greater than 800 $\mu$m whereas the CloudSat radar-only retrievals will be most sensitive to the largest ice crystals. The mean in situ measured $D_e$ is 114.63 $\mu$m compared to 140.32 $\mu$m for CloudSat. The modal value of the 2DC measurements is 110-120 $\mu$m, this compares to 120-130 $\mu$m for CloudSat. Given the uncertainties the mean $D_e$ and modal values between the in situ measurements and CloudSat are in fairly good agreement. The NWP model mean $D_e$ is 47.25 $\mu$m, it is not known if this cirrus case was populated by very small ice crystals.

The other two cases B327 and B258 give very similar results to those described above.

Given the differences in retrieved IWC and $D_e$ it is interesting to compare if there are significant differences in the derived IWP and cloud optical depth.

5. COMPARISONS BETWEEN DERIVED IWP AND CLOUD OPTICAL DEPTH FOR THE CASE B262

In this section the IWP is derived using Eq. (2) and from the mean $D_e$ of the vertical profile the optical depth is estimated from Eq. (3). Table 2 shows comparisons between the in situ derived mean IWP, mean $D_e$ and mean $\tau$ based on the profiles 8 and 9 shown in Fig. 2, and the NWP model and CloudSat estimates for these quantities.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>IWP gm$^{-2}$</th>
<th>$D_e$ $\mu$m</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2DC</td>
<td>31.8±12.4</td>
<td>116.3±2.2</td>
<td>0.82±0.3</td>
</tr>
<tr>
<td>SID II</td>
<td>74.4±31.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CloudSat</td>
<td>16.0±8.3</td>
<td>137.5±8.6</td>
<td>0.35±0.2</td>
</tr>
<tr>
<td>NWP 40</td>
<td>22.72±17</td>
<td>47.32±3</td>
<td>1.41±0.9</td>
</tr>
<tr>
<td>NWP 4</td>
<td>16.95±9.0</td>
<td>47.32±3</td>
<td>1.05±0.5</td>
</tr>
</tbody>
</table>

It is instructive to see from Table 2 how NWP models from compensating errors may still predict reasonable solar radiative properties which are within experimental error. This compensating error in models could mean that if the predicted ice crystal size is too small then the clouds would appear brighter than measurements. However, due to the IWC being smaller relative to the measurements this would act to darken the clouds – this competition between too low IWC and ice crystal size might cancel giving reasonable solar cloud brightness when compared against measurements. CloudSat on the other hand would estimate darker clouds relative to the in situ measurements and NWP models due to the very large $D_e$ retrieved relative to the IWP.

6. FURTHER EXAMINATION OF THE CLOUDSAT RETRIEVED IWC

In section 4 it was argued, using Figure 2, that the CloudSat retrievals of IWC could be smaller than in situ measurements due to volume sampling issues and its vertical resolution. In this section evidence is presented which highlights a differing argument recently put forward by Heymsfield et al. (2007). In this paper it was shown that CloudSat could potentially underestimate IWC due to aggregating ice crystals not taken into account in the retrieval algorithm. Such aggregating ice crystals could be sufficiently large enough to violate the Rayleigh assumption. Moreover, the applied Mie-Lorenz correction to take account of this potential violation may further diminish the estimate of IWC. In Heymsfield et. al. (2007) it is concluded that
due to ice crystal aggregation and non-Rayleigh scattering the CloudSat retrieval could underestimate IWC by as much as 60%.

For this section the case of B327 is used to illustrate this potential problem. B327 is the deepest of all the cirrus cases and has an estimated in situ solar bulk optical depth of 2.82. Figure 4 shows a comparison between the deepest CloudSat retrieved IWC profile and the deepest in situ 2DC derived IWC profiles. The CloudSat profile shown in Figure 4 also gave the largest IWP of 72.94 gm\(^{-2}\). As indicated in Figure 4 the deepest 2DC IWC profiles were vertically averaged over a distance of about 500 m and for Profiles 8, 9 and 10 the derived IWP values were 69.98, 75.77 and 77.57 gm\(^{-2}\). These in situ derivations of IWP compare reasonably well with the CloudSat derivation.

![Graph showing IWC profiles](image)

**Figure 4.** The deepest CloudSat retrieved IWC profile plotted with the deepest 2DC derived IWC profiles as a function of altitude for B327.

From Figure 4 it is interesting to note that towards the cloud-top and cloud-bottom the in situ measurements of IWC are well within the uncertainty of the CloudSat retrieved IWC. However, at about the centre of the cloud the in situ measurements of IWC, even when substantially vertically averaged, can reach nearly 100 mgm\(^{-3}\).

Figure 5 shows the 2DC images that were collected from the region of highest IWC shown in Figure 4.

![Image of 2DC images](image)

**Figure 5.** Samples of 2DC images collected in the highest region of IWC for B327.

Figure 5 shows evidence of ice crystals larger than 800 µm since a number of 2DC bins are either full or nearly full; moreover, the figure also shows evidence of ice crystal aggregation in a number of the bins. Given the vertical depth of the cloud being 3.5 km aggregation should certainly be expected. Figure 5 can be contrasted with Figure 6 which shows 2DC images collected near the cloud-bottom.
Figure 6. 2DC images collected near cloud-bottom of B327 between an altitude of 7500-8500 m shown in Figure 4.

From Figure 6 it is clear that there are no ice crystals nearly filling the 2DC bins and this image is representative of others near cloud-top and bottom. The reason for the appearance of smaller ice crystals near cloud-bottom is probably due to sublimation.

Given Figure 5 with the evidence of aggregation and the likelihood of the existence of non-Rayleigh scattering then the possibility of CloudSat retrievals being biased towards lower IWC in the central regions of the cloud as demonstrated in Heymsfield et al. (2007) cannot be ruled out for this case.

6. USING CPI DATA TO TEST AN ENSEMBLE MODEL OF CIRRUS

In this section an ensemble model of cirrus described in Baran and Labonnote (2007) is tested against CPI in situ measurements for the other three cases described in Table 1. The ensemble model of cirrus is an attempt to couple cirrus microphysical and macrophysical properties with the radiative properties of the cloud. This requires a prior PSD from which the ensemble model predicts the IWC, volume extinction coefficient and \( D_e \). In the paper by Baran and Labonnote (2007) it was shown that the ensemble model was reasonably able to predict IWC and volume extinction coefficient given the PSD. The PSD was generated from a parameterization of the PSD shape given an IWC and in-cloud temperature (Field et al. 2005; 2007). The Field et al. (2005; 2007) parameterization is independent of particle geometric shape, area density and \( D_e \).

The ensemble model shown in Figure 1 of Baran and Labonnote (2007) consists of six shapes which increase in complexity as a function of maximum dimension. The basic shape of the ensemble model is the hexagonal geometry, which with increasing maximum dimension are aggregated together to form more complex crystals. The smallest ice crystal consists of the hexagonal ice column and the most complex consists of a ten-branched ice aggregate, representing the smallest and largest ice crystal maximum dimension, respectively. From the geometric volume of the ensemble the IWC can be computed by:

\[
IWC = \rho \int V(\epsilon) n(\epsilon) d\epsilon
\]  

where in Eq. (4) \( \rho \) is the bulk density for ice assumed to be 0.92 g cm\(^{-3}\), \( V(\epsilon) \) is the geometric volume of the ice crystals. The vector \( \epsilon \) represents the various sizes and shapes of ice crystals in the size distribution function.

The \( D_e \) of the ensemble is defined by Eq. (1) and the volume extinction coefficient has been previously defined in section 2 as twice the area density in the limit of geometric optics.

To test the ensemble model prediction of IWC, volume extinction coefficient and \( D_e \) the particle size distribution function is generated from the CPI measured IWC and in-flight cloud temperature profiles using the parameterization due to Field et al. (2005; 2007). The ensemble model is then integrated over the generated particle size distribution function to predict IWC given by Eq. (4). From the ensemble model
predicted IWC and volume extinction profiles the IWP can also be predicted from Eq. (2) as well as the cirrus optical depth, given by:

$$\tau = 2 \int_{z_1}^{z_2} \sigma(z) dz$$  \hspace{1cm} (5)$$

where $z_1$ and $z_2$ are the cloud-bottom and top defined by the aircraft and $\sigma(z)$ is the volume extinction profile.

In Figure 7 (a) –(c) results are presented for the ensemble model predictions of the vertical profile of IWC, volume extinction coefficient and $D_e$. The figure shows results for the case B138 profile 3.

The figure shows that the ensemble model is able to predict the CPI measured IWC, volume extinction and $D_e$ vertical profiles well within experimental uncertainty for this particular case. The measured CPI IWP from Figure 7 is $31.74 \pm 15.87$ mgm$^{-2}$, and $\tau=1.04 \pm 0.52$. The corresponding ensemble model predictions are $34.95$ mgm$^{-2}$ and $\tau=0.730$. The ensemble model predictions of IWP and $\tau$ are also well within experimental uncertainty. Results for the other cases also demonstrate that the ensemble model predictions of these quantities are also within experimental uncertainty.

CPI images of the ice crystal shapes for B138 profile 3 are shown in Figure 8.
Figure 8. Various CPI images obtained during from B138 of profile 3 from cloud-top, middle and bottom.

Figure 8 shows the variety of ice crystal shapes that were most commonly observed during profile 3. The ice crystals appear to be irregulars with evidence of aggregation as well as rosettes and elongated hexagonal columns. The ensemble model as demonstrated from Figure 7 appears able to predict the fundamental parameters required to compute solar radiative transfer through cirrus to within experimental uncertainty.

7. SUMMARY

In this extended abstract results have been presented from the CAESAR field campaign which took place during the Winter and Autumn 2007. In situ measurements of IWC, $D_e$, and ice crystal area densities were collected using 2DC, SID II, and CPI probes. Three missions were flown that coincided with CloudSat overpasses and the corresponding Met Office Global and Mesoscale model products were extracted. The in situ measurements were compared to the CloudSat retrievals and NWP predictions of IWC and $D_e$.

In general it was found that relative to the in situ measurements higher IWC’s were not predicted by the NWP models nor retrieved by CloudSat. Though, in the case of the NWP models the distribution of IWC throughout the cloud replicated the measured distribution fairly well. It was noted that in the case of the CloudSat IWC distribution the higher IWC’s rapidly decreased after the modal value.

It was hypothesized that this decrease could be due to volume sampling of thin cirrus and the low vertical resolution around the cloud-bottom. However, a further reason, which would add to compound the problem, could be due to very large aggregating ice crystals which would become non-Rayleigh scattering. It was recently reported in the literature that the aggregation of ice crystals could depress CloudSat IWC estimates by as much as 60%. We find that, for a particular case, in the presence of ice aggregation the CloudSat estimates are depressed relative to the in situ 2DC measurements. Moreover, the 2DC measurements could themselves be underestimates as ice crystals greater than 800 $\mu$m were not accounted for.

As regards $D_e$ the NWP models prediction were much smaller than either the in situ measurements or CloudSat retrievals. Though this should not be very surprising since the 2DC does not measure ice crystals less than 100 $\mu$m in size and CloudSat retrievals of $D_e$ are currently based on the radar-only algorithm.

The Met office NWP model prediction of the solar radiative properties was shown to be consistent with in situ measurements based on the 2DC. Though this was due to the
models possibly predicting too small $D_e$ and too low IWC, this compensation may produce solar radiative properties that are consistent with independent measurements.

An ensemble model of cirrus was tested against CPI measurements of IWC, $D_e$, volume extinction coefficient, IWP and optical depth. The ensemble model was shown to be able to predict these quantities well within the experimental uncertainty for the case shown. Moreover, the ensemble model, which represents, aggregating ice crystals could be used to correct CloudSat retrievals for ice aggregation.

8. BIBLIOGRAPHY


ACKNOWLEDGEMENTS

We would like to thank FAAM for providing the flights and necessary aircraft data that made this analysis possible. The CloudSat team at CSU for providing the CloudSat products.