A COMPARISON BETWEEN AIRBORNE LIDAR DEPOLARIZATION AND IN-SITU ICE CRYSTAL MEASUREMENTS FROM CIRRUS CLOUDS.

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ABSTRACT

Results are presented from the EMERALD measurement campaigns. By using two aircraft simultaneous measurements of the lidar depolarization ratio and in-situ measurements of ice crystals were unambiguously compared.

It was found that a direct relationship between the depolarization ratio and the ice microphysics measurements did not exist. Instead the depolarization ratio was found to be sensitive to ensembles of ice crystals. This is primarily an effect of the large variability in the ice crystal habit that was observed within cirrus cloud sample volumes.

1. INTRODUCTION

The EMERALD field campaigns [1] measured cirrus clouds associated with large scale frontal systems and cirrus outflow from tropical convection (EMERALD 1 and 2 respectively). The aircraft and instrumentation used enabled a direct, unambiguous comparison to be made between airborne lidar and in-situ ice microphysics measurements. Two aircraft were used during each flight, one flew below the cirrus clouds with an upward pointing lidar and the second was equipped with instrumentation for in-situ measurements of the ice crystals. At all times an effort was made to insure that the two aircraft flew in close formation so that a direct comparison could be made between the measurements.

2. INSTRUMENTATION

The King Air aircraft was equipped with lidar system based on an Nd:YAG laser. The Egrett and was fitted out with a complementary suit of instruments for in-situ cloud measurements. Furthers details of these instruments are presented in [1].

The beam from the lidar was guided up through a port in the ceiling of the aircraft and a small 10 cm diameter telescope with a 1 mrad field of view was used to collect the scattered beam. The beam was pulsed at 20 Hz, with a power of 30 mJ. An interference filter with a 1 nm bandwidth, a polarizing beam splitter and two photomultiplier tubes with photon counting data acquisition were used in the receiver.

This lidar system was capable of making atmospheric measurements up to 13 km above the aircraft at a vertical resolution of 30 m and a time resolution of 2 seconds. The lidar measurements presented in this paper were averaged over 10 seconds in the horizontal extent and 90 m in the vertical extent.

In-situ measurements of the ice microphysics are presented from the cloud particle imager (CPI) [2] installed onboard the Egrett. It recorded high resolution digital images of cloud ice crystals, as well as measuring ice crystal size, shape and concentration.

3. MEASUREMENTS

Fig. 1 shows an example of the extreme difference between EMERALD 1 and 2 depolarization ratios with representative examples of the ice crystals included. The same depolarization scale is used for both plots to indicate the difference in the depolarization ratio observed in mid-latitude and outflow cirrus. The flight track of the Egrett is superimposed over the top of each plot. The Y-axis is the height above the ground (km) and the X-axis is the distance of the aircraft from the beginning of the flight leg (km).

Examples of the ice crystals are included for both the EMERALD 1 and EMERALD 2 measurements presented in fig. 1. These are indicative of the types of ice crystals observed during the two campaigns. In the mid-latitude clouds of EMERALD 1, the ice crystals were mostly small and irregular in shape. However regions of pristine ice crystals such as rosettes or columns were found. In comparison EMERALD 2 cirrus outflow was dominated by larger pristine and aggregated ice crystals.

Fig. 2 plots the ratio of aggregated ice crystals to single ice crystal concentrations against depolarization

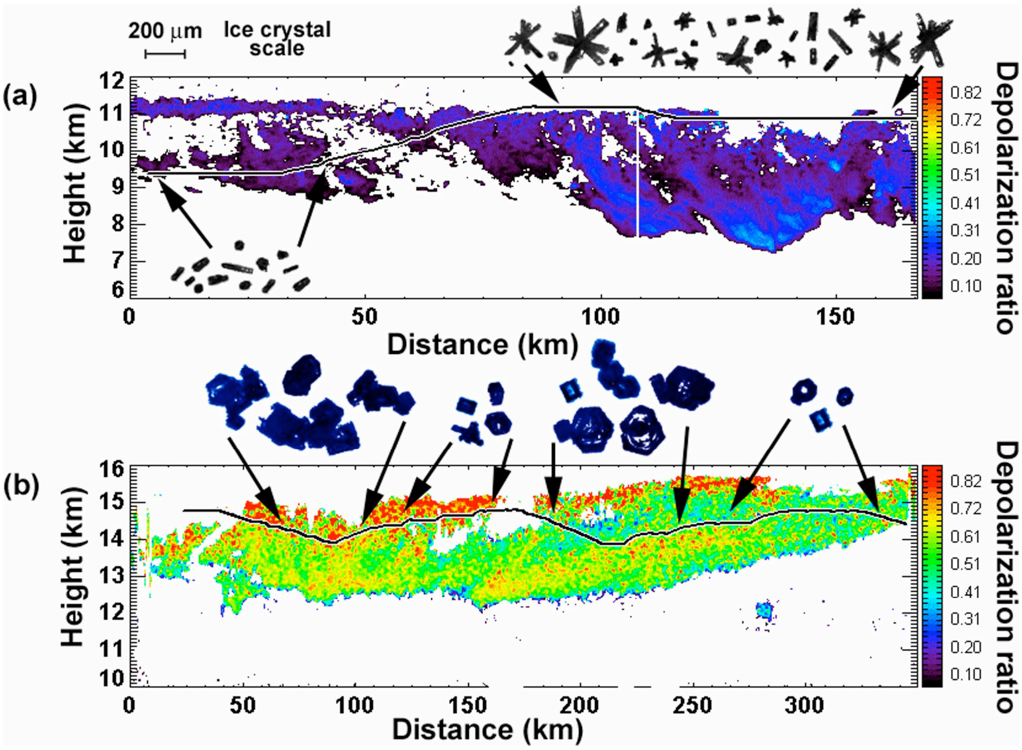

Fig. 1. Depolarization measurements and examples of the ice crystals imaged by the CPI obtained from both EMERALD 1 and 2. (a) Flight leg 4 from the 19th September 2001; (b) Flight leg 3 from the 23*rd* November 2002.

ratio at the height of the Egrett for the 23rd November from EMERALD 2. This figure clearly demonstrates as the ratio of aggregated to single ice crystals increases so does the depolarization ratio.

4. DISCUSSIONS AND CONCLUSIONS

The difference between EMERALD 1 and EMERALD 2 depolarization measurements indicates that the depolarization ratio is sensitive to different collections of ice crystals. The low depolarization ratios from EMERALD 1 are as a result of small irregular shaped ice crystals and the high depolarization ratios from EMERALD 2 are produced by the high abundance of pristine ice crystals such as columns and plates, and the numerous occurrences of ice aggregation. Furthermore, there are occasions when you can see various regions within the clouds that have different water phases (liquid and ice, although not in the two examples given here).

Depolarization ratio can provide an unambiguous means of discriminating between the ice and water phases of clouds [3]. However as a practical tool for distinguishing between ice crystal habit, it is hindered by the fact that typically the depolarization ratio is obtained from a variety of ice crystal habits contained within the sample volume. During the EMERALD campaigns the clouds measured contained ice crystals with multiple habits and different sizes. As a result using depolarization ratio as a means of determining the precise type of ice crystal was very difficult. More typically the depolarization ratio indicates the possible mixture of ice crystal habits present.

Typical for EMERALD 1 the average depolarization ratio was 0.21, with a standard deviation of 0.05 for the flight shown in figure 1(a). The depolarization ratio for these clouds ranged from 0.1 to 0.3. Depolarization measurements of mid-latitude cirrus clouds have been conducted from the ground using the same cloud lidar at Aberystwyth and Chilbolton in the UK. Cirrus clouds were observed up to 14 km with the average depolarization ratio varying from 0.13 to 0.48. Compared with EMERALD 1 measurements, a greater diversity in depolarization was observed, with ratios of up to 0.8 measured, the mean values, however were not dissimilar to EMERALD 1. Other measurements have been made in both the southern and northern hemisphere described by [4], who calculated averages of approximately 0.25 in both hemispheres, but with larger values measured in the southern hemisphere. In fact they measured depolarization ratios of up to 0.85 on several occasions, however almost no values above 0.45 were seen in the northern hemisphere. Reference [5] describe measurements of mid-latitude cirrus in Florence, Italy and Dumont d'Urville, Antarctica. They recorded depolarization ratios in the cirrus over Italy with an average of 0.46 (standard deviation 0.18), compared with 0.37 (standard deviation 0.16) in Antarctica. Reference [6] based on observations of cirrus clouds from the University of Utah Facility for Atmospheric Remote Sensing (FARS) measured typical depolarization ratios ranging from 0.2 to 0.4.

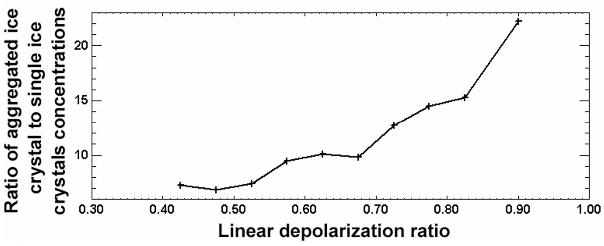

Fig. 2. Ratio of complex aggregates to simple aggregates versus depolarization ratio for EMERALD 2.

Low depolarization ratios and small standard deviations in EMERALD 1 measurements were primarily due to the high number concentration of small particles detected by the FSSP and CPI [1]. As a result of the relatively unpolluted skies in southern Australia, large concentrations of smaller ice crystals were commonly measured. The lack of pollution along with high supersaturated humidity's (with respect to ice) and cold temperatures resulted in homogeneous freezing being the most likely source of ice crystal nucleation. Homogeneous nucleation is capable of producing high concentrations [7] of ice crystals. Large numbers of ice crystals, along with further ice nucleation's, results in strong competition for the available water vapour. This produces many smaller ice crystals, where cold temperatures further limit the ability of the crystals to grow [8]. This results in a cloud with a reduced diversity in ice habit, dominated by small irregular or spheroidal like ice crystals. This explains the lack of diversity in depolarization ratios measured for EMERALD 1, as the smaller ice crystals produce lower depolarization ratios [9] and dominate any depolarization ratio measured.

Another possible mechanism for the lower depolarization was the frequent occurrence of ice crystals with signs of sublimation. Sublimating crystals tend to form rounded, smoothed shapes [10] which can generate lower depolarization ratios [6]. A good example of this can be seen at the beginning of the flight leg shown in fig. 2(a) from the 19th September. During the first 50 km of this flight the Egrett passes through the lower region of the cloud with a depolarization ratio less than 0.15. Closer inspection of the ice crystal images revealed that the columns in particular showed signs of sublimation (the relative humidity with respect to ice was less than 100 %). By contrast the ice crystals imaged during the EMERALD 2 flights were in the highly supersaturated air of the outflow and very rarely showed signs of sublimation.

EMERALD 2 depolarization ratios were quite different. For the 23rd November (fig. 2(b)) the mean depolarization ratio was 0.64 and the standard deviation was 0.12. Typical values ranged from 0.4 to 0.8. Other EMERALD 2 flights showed similar depolarization ratio ranges. Unlike mid-latitude cirrus clouds, there have been very few lidar measurements of thunderstorm outflow. Reference [11] conducted ground based measurements at Mahe on the Seychelle Islands. They reported a mean depolarization ratio of approximately 0.6. Reference [12] conducted airborne measurements of outflow cirrus during the Tropical Ocean and Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Regional Experiment (COARE). They reported depolarization ratios ranging from 0.3 to 0.6, with a steady increase in ratio with height. Both the previous ground based and airborne measurements of outflow cirrus reported similar values to those observed during EMERALD 2.

Very different values of depolarization ratio were observed during EMERALD 1 and 2. This reflects the type of ice crystals and consequently their source of production. The ice crystals recorded during the EMERALD 1 case were generated within the cirrus cloud. Due to the somewhat cold temperature and high relative humidity's (~ 120%) large numbers of small irregular (spheroidal) crystals were common. The cold temperatures limit the growth of the crystals. Conditions were ideal for homogenous nucleation which leads to high concentrations of ice particles. The ice crystals seen within the cirrus outflow during EMERALD 2 were mainly large aggregates and pristine ice crystals. These were formed within the updraft of the thunderstorm, in regions of warmer temperatures and higher relative humidity. These enabled the ice crystals to grow much larger. The updraft then carried the ice crystals high up and into the outflow regions, where the extremely low temperatures then reduces further growth and high relative humidity's prevent the ice crystals from evaporating.

EMERALD 1 cirrus was dominated by small ice crystals which can produce low depolarization ratios, in contrast the EMERALD 2 cirrus outflow is dominated by high concentrations of large aggregates and pristine crystals. Ray-tracing theory predicts that the amount of depolarization is controlled by the ice crystal shape and its internal structure [6]. The more complex a crystal the more opportunities an incoming photon has for changing its polarization. Reference [13] also showed through ray-tracing theory that for hollow columns the depolarization ratio decreased as the size of an interior hollow cone increased. However, [6] have suggested that in fact the depolarization ratio would increase if more realistic internal hollow structures were used, resulting in increased shape complexity. Many of the crystals imaged revealed a complex internal structure. Reference [6] also suggest that complexly aggregated ice crystals can produce high depolarization. These combinations of effects lead to the much higher depolarization values observed during EMERALD 2.

The EMERALD campaigns showed that it is difficult to use depolarization alone in a quantitative sense and trying to assign a certain depolarization ratio to a certain ice crystal habit a difficult exercise. In an idealized cloud with areas made up of distinct crystal types then depolarization ratio to ice habit could be possible. The preponderance of small ice crystals recorded during EMERALD 1 led to a diluting of the depolarization ratio. The small crystals had less of an effect during EMERALD 2, as the cirrus outflow was generally dominated by large pristine single and aggregated ice crystals. The complex structures of these crystals produced higher depolarization ratios. However, within the outflow any one volume of cloud contained many different crystal types and sizes, so trying to assign a ratio to them was somewhat pointless. This indicates that depolarization used along with in-situ measurements, can reveal the microphysical structure of cirrus clouds. That is regions of the cloud can be identified to contain certain collections of ice crystals or at least certain habits can perhaps be ruled out. Regions of high depolarization ratio are likely made up of pristine ice crystals whereas regions of lower depolarization result from small ice crystals of undetermined habit. The most powerful use for depolarization is in distinguishing between cloud phase. Assuming the lidar is offset from the perpendicular to avoid specular reflections liquid water and ice phase are easily differentiated

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