Anatomy of cirrus clouds: Results from the Emerald airborne campaigns

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[1] The Emerald airborne measurement campaigns have provided a view of the anatomy of cirrus clouds in both the tropics and mid-latitudes. These experiments have involved two aircraft that combine remote sensing and in-situ measurements. Results are presented here from two separate flights: one in frontal cirrus above Adelaide, Australia, the other in the cirrus outflow from convection above Darwin. Recorded images of ice crystals are shown in relation to the cloud structure measured simultaneously by an airborne lidar. In mid-latitude frontal cirrus, columnar and irregular ice crystals were observed throughout the cloud while rosettes were found only at the top. The cirrus outflow from a tropical thunderstorm extended for hundreds of kilometres between the heights of 12.2 and 15.8 km. This was composed mainly of hexagonal plates, columns, and large crystal aggregates that originated from within the main core region of the convection. A small number of bullet rosettes were found at the top of the outflow cirrus and this is interpreted as an indication of in-situ crystal formation. It was found that the largest aggregates fell to the lower regions of the outflow cirrus cloud while the single crystals and small aggregates remained at the top. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Whiteway, J., et al. (2004), Anatomy of cirrus clouds: Results from the Emerald airborne campaigns, *Geophys. Res. Lett.*, *31*, L24102, doi:10.1029/2004GL021201.

1. Introduction

[2] Cirrus clouds exist in the upper troposphere where the earth's climate is especially sensitive to absorption and emission of infrared radiation [*Harries*, 1996]. If changes in climate alter the distribution of cirrus clouds, perturbing the balance between scattered sunlight and absorbed terrestrial infrared radiation, this can result in a climate feedback mechanism [e.g., *Ramanathan and Collins*, 1991; *Heymsfield and Miloshevich*, 1991]. Accurate climate change prediction requires a realistic accounting for cirrus ice crystal formation and evolution, and the interactions between microphysics, dynamics and radiation [e.g., *Stephens et al.*, 1990]. This challenge requires knowledge that can only be obtained from advancements in the technology of remote sensing and airborne in-situ measurements. A step forward has recently been made in a project called EMERALD (Egrett microphysics experiment with radiation, lidar, and dynamics). Two aircraft were involved. One, called the Egrett, was equipped with instruments to probe inside cirrus clouds. Another aircraft, a King Air, flew below the clouds with a laser-radar (lidar) to map the cloud structure and to guide the Egrett. This combination of remote sensing and in-situ measurements has provided a unique view of the anatomy of cirrus clouds. Observations of the microphysical structure in mid-latitude and tropical cirrus are presented here.

2. Airborne Measurements

[3] The Egrett aircraft is capable of flying to a height of 15 km at relatively slow airspeeds of 80 to 100 m/s. It carried a variety of instruments in the Emerald campaigns that measured cloud particles, humidity, turbulence, radiative spectra and ozone. The main focus of this letter is on the sampling of cloud ice crystals with a SPEC Cloud Particle Imager (CPI) [*Lawson et al.*, 2001]. This study will concentrate only on the crystal images provided by the CPI, while research is ongoing for the derivation of particle concentrations. The CPI is sensitive only to particles with maximum dimension larger than about 10 μm. Humidity was measured with two separate instruments: one a Frost Point Hygrometer (FPH) [*Busen and Buck*, 1995], the other a Tunable Diode Laser (TDL) spectrometer [*May*, 1998].

[4] The second aircraft, a King Air, carried an upward viewing laser-radar (lidar). The lidar transmitted pulsed light at a wavelength of 532 nm (Nd:YAG laser) and detected the backscatter as a function of time (or height), employing photon counting data acquisition with a vertical resolution of 30 m. The lidar measurements provided a map of the cloud structure, which was displayed in real time to aid scientists on-board the aircraft in making decisions on flight patterns. The two aircraft were in constant radio

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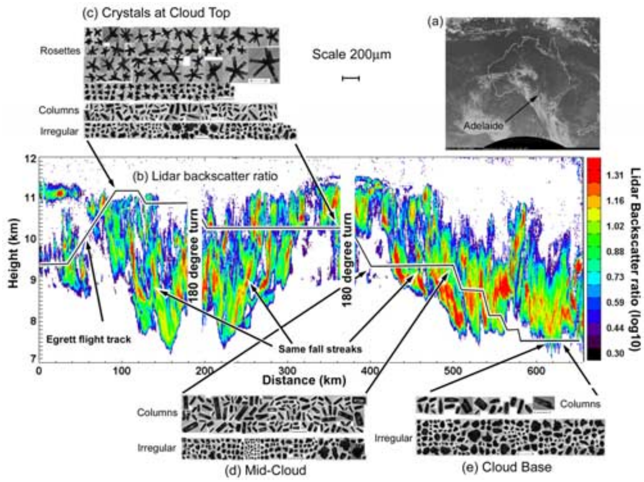

Figure 1. a) Satellite IR image showing the cirrus cloud system above southern Australia. (b) Lidar measurements on-board the King Air while flying directly below the Egrett. Ratio of total backscatter to that expected for molecular backscatter only. (c, d, e) Images of crystals recorded by the CPI on-board the Egrett.

contact and the Egrett was flying directly above the King Air for all of the measurements presented here.

3. Frontal Cirrus

[5] The first Emerald campaign was conducted from Adelaide, Australia, during September 2001 and the focus was on measuring the properties of mid-latitude cirrus clouds. There were ten scientific flights and most were within cirrus clouds associated with cold fronts. Figure 1a shows the satellite infrared image of the cirrus clouds forming behind a cold front that was passing over South Australia on 19 September 2001. The measurements shown in the remainder of Figure 1 were obtained within this cloud.

[6] Figure 1b shows the lidar backscatter signal measured while the King Air was flying below a section of the cirrus clouds with well-defined fall streaks. The goal of this flight was to observe how the cloud particles evolved as they fell by sampling at various heights within the same fall streaks. Both aircraft flew back and forth with the Egrett starting from the top of the cloud and descending for each new flight leg. The thick black line in Figure 1b indicates the path of the Egrett. The flight direction was along the wind direction, so that the same fall streaks were sampled in each flight leg.

[7] Throughout this flight the humidity was measured with the FPH. Within the cloud the relative humidity with respect to ice had an average of 102% with a standard deviation of 9%. The temperature was in the range of $-57°C$, in the crystal formation region at cloud top (height 11 km), to $-30°C$ where the crystals were sublimating near cloud base (height 7.5 km).

[8] Figure 1c shows a sample of ice crystal images recorded by the Cloud Particle Imager (CPI) as the Egrett flew along the top of the cloud. There were three main crystal types in this cloud and at the top the relative proportions by number were 21% bullet rosettes, 26% columns, and 53% irregular. The classification of crystal type was done by viewing each individual crystal image.

[9] After completing the flight leg at cloud top, the Egrett descended to a lower altitude, turned 180 degrees, and flew back through the same cloud system. This pattern was repeated with the Egrett intersecting the same fall-streaks at successively lower heights. Figure 1d shows the ice crystals sampled by the CPI as the Egrett flew through the middle of the cloud at a height of 9.3 km. There is a marked change in crystal composition in comparison with the top of the cloud in that there are no longer any bullet rosettes. The relative proportions in the middle of the cloud are 14% columns and 86% irregular.

[10] Figure 1e shows a sample of crystal images recorded as the Egrett skimmed along the bottom of the cloud at a height of 7.5 km. These are mainly of irregular shape and they are also somewhat more blunt in appearance. This is likely an indication that the crystals are sublimating where there is reduced humidity due to mixing with the dry air below the cloud base. The measured RHi had an average value of 50% along the flight track through the cloud base (620 km). The cooling due to sublimation of ice crystals at the bottom of the cloud would lead to unstable downward buoyant forces that cause downdrafts and turbulence. The lidar signal (600–640 km) reveals that the cloud base was deformed into downward extending columns that are likely caused by the downdrafts.

[11] Previous field experiments have provided evidence that ice crystal generation occurs at the top of cirrus clouds [*Heymsfield and Miloshevich*, 1995]. The crystals grow and fall until completely sublimating at the base of the cloud. In the case presented here, many crystals are growing as rosettes in the cold ice-supersaturated regions at the top of the cloud. Recent laboratory experiments by *Bailey and Hallett* [2002] have found that the columnar arms of the Rosettes grow outward from small ice particles that were formed by homogeneous freezing of supercooled water droplets. Rosettes were not found more than 1 km below the top of the cloud, even though crystals were descending through the fall streaks. It could be the case that the columnar arms of the rosettes had broken off and were being detected as single columns in the lower regions of the cloud. An alternative explanation could be that rosettes were not generated in the previous stages of cloud formation. It is more difficult to speculate on the initial evolution of the irregular crystals. These could be the result of a cycle of sublimation and deposition within the turbulence that was observed throughout the cloud. It could also be that a portion of the irregular crystals are in an early phase of growth and not yet developed into a defined habit [*Bacon et al.*, 2003].

4. Cirrus Outflow From Tropical Thunderstorms

[12] The second Emerald campaign was conducted at Darwin Australia and ten separate flights obtained measurements in the cirrus outflow from deep tropical convection. The Darwin area is a natural laboratory for investigating convection. During November, in the transition between the dry and wet seasons, an isolated system of thunderstorms occurs over the Tiwi Islands (100 km north of Darwin) nearly every day. Such a case is illustrated in the satellite infrared images in Figure 2. On 23 November 2002 an isolated convective cell formed above Bathurst Island.

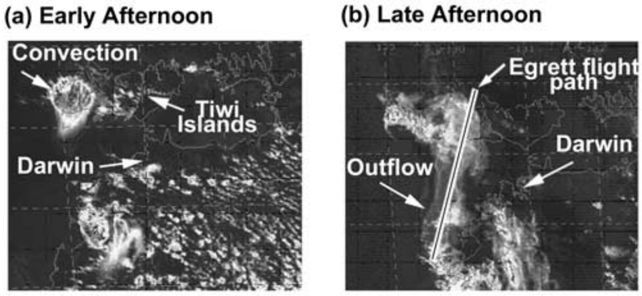

Figure 2. Satellite IR images showing the development of deep convection above the Tiwi Islands (100 km north of Darwin) on 23 November 2002.

Radar reflectivity measurements showed that the top of this convection reached above a height of 17 km – penetrating into the stratosphere. By late afternoon this convection produced a well-defined outflow cirrus cloud as seen in Figure 2b. Both the Egrett and King Air were operated on this day in the same manner as illustrated in Figure 1. The flight legs were aligned across the outflow cirrus and along the length of it.

[13] Figure 3 shows the lidar measurements along the flight path shown in Figure 2b. This starts from behind the original convection (0 km), into the remnants of the storm (50–100 km) and along the outflow cirrus (100–350 km). The thickest part of the outflow (optically) forms a layer that is tilted upward by the action of horizontal wind shear: from a height of 12.2 km at 150 km along the flight-track up to a height of 15.5 km at 350 km. The Egrett flew in a saw-tooth pattern between heights of 13.9 km and 14.8 km. The crystal images that were recorded at various positions along this flight path are also displayed in Figure 3. It can be seen that different regions of the cloud have distinctive ice crystal characteristics.

[14] As the Egrett approached the top of the outflow from upwind a thin cloud with low particle number density was encountered (region 1: x = 30–50 km; z = 14.7 km). The sample of crystal images that was obtained consisted mainly of rosettes. The Egrett then descended into the remnants of the convection (region 2: x = 50–100 km; z = 13.9 km) where most of the cloud particles were aggregates of hexagonal plates and columnar crystals. Next the Egrett ascended down-wind of the convection (region 3: x = 130–150 km; z = 14.7 km) and again, at the top of the cloud, many of the crystals were rosettes. When the Egrett descended into the outflow (region 4a: x = 210–280 km; z = 13.9–14.4 km) a mixture of hexagonal plates, columns, and aggregates was sampled. A similar mixture of crystal shapes was recorded as the Egrett continued to ascend along the outflow. The aggregates were less common and smaller as the Egrett climbed to greater heights and moved further away from the original convection (region 4b: x = 280–340 km; z = 14.4–14.9 km).

[15] The humidity was measured throughout this flight by both the FPH and the TDL and these separate measurements were in close agreement. In the outflow cirrus (x = 120–350 km) the measured relative humidity with respect to ice was maintained near saturation with a mean of 97% (standard deviation of 16%) as the temperature ranged from −67 to −61°C along the flight track.

[16] The flight leg in Figure 3 can be separated into four distinct regions. In regions 1 and 3 the Egrett was sampling at the greatest heights and coldest temperatures (−67°C). Here the presence of rosettes, which were not found in the convective remnants, suggests in-situ formation of crystals at these heights from the humidity provided by the storm outflow. In region 2 the remnants of the convection contained a mixture with plates, columns, and aggregates that could have been formed within updrafts in the core of the storm at lower altitudes and greater temperatures. *Bailey and Hallett* [2002, 2004] have found that plate crystals form at higher temperatures than bullet rosettes. There is no obvious evidence of riming on the sampled crystals, so the plates and aggregates were likely formed near the top of the convection in fully glaciated regions. (Although, it is possible that much larger crystals having riming existed but were not detected within the sample volume of the CPI.) Region 4 is the outflow cloud that had drifted away from the original convection over Bathurst Island. This contained a similar mixture of plates, columns, and aggregates to that which was sampled within the remnants of the storm. The larger aggregates would fall more rapidly and these are found at the lower heights (region 4a) sampled within the outflow cloud. It was also observed by *McFarquhar and Heymsfield* [1996] that sedimentation was an important process in determining the distribution of crystal size within anvils.

[17] The mixtures of crystals sampled on this flight can be divided into two types: rosettes and related crystals forming at heights of 14 km and above; hexagonal plates, columns, and aggregates that formed within the convection (likely below 14 km) either remained with the remnants of the storm or drifted away in the outflow cloud. It should be noted that the CPI detected only large crystals with maximum dimension greater than 95 μm in the outflow cirrus during this flight. This is in contrast with the crystal images from the frontal cirrus (Figure 1) which included a broad spectrum of crystal sizes that extended to the minimum resolution of the CPI (about 10 μm).

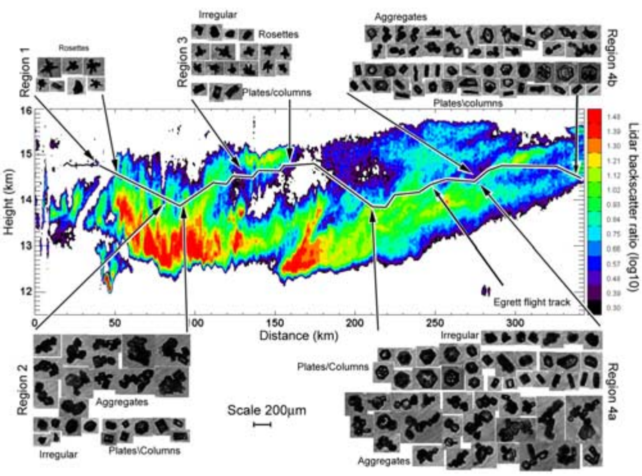

Figure 3. Lidar backscatter (ratio of total to molecular) measurements of the outflow cirrus cloud along the track shown in Figure 2. Crystal images are shown within various sections of the cloud along the Egrett flight path (solid black line).

[18] A unique feature of the ice microphysical measurements in the outflow cirrus was the common observation of aggregates that formed long chains of hexagonal plates and columns. Similar crystal formations found within the upper regions of tropical convection have been reported by *Stith et al.* [2004]. Such results were anticipated from laboratory experiments that demonstrated how strong electric fields enhance crystal aggregation into long chain formations [*Saunders and Wahab*, 1975]. We interpret the similarity of the aggregates sampled in the convective outflow cirrus with those produced in the laboratory as a signature of the process of electric field enhancement of ice crystal aggregation. The chain aggregates are very likely formed in the core updraft region under high electric field strengths and, despite their apparently fragile appearance, persist for long distances downwind of the anvil core.

5. Conclusions

[19] The two campaigns of the Emerald project have provided a unique view of the anatomy of cirrus clouds. The case studies shown here illustrate that the cirrus clouds produced by frontal systems and tropical convection have vastly different microphysical content due to the different conditions of crystal formation and aggregation. This demonstrates how an accurate accounting for the radiative impact of cirrus clouds in climate change must involve the small-scale interactions between dynamics, humidity and microphysics.

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