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Observations and comparisons of cloud microphysical properties in spring and summertime Arctic stratocumulus clouds during the ACCACIA campaign

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Profiled Ascent A1

During profile A1 the aircraft (travelling south) made a profiled ascent from 300 m above the sea surface, reaching cloud base at 650 m, identified using a Liquid Water Content threshold of LWC > 0.01 g m^{-3}, as derived from CDP data. Below cloud base the 2D-S probe revealed low concentrations (< 0.5 L^{-1}) of irregular snow (Fig. 3d) particles (mean size ~ 530 μm) that had precipitated from the cloud layer above. As the aircraft climbed through cloud base, temperatures decreased to -11 °C. CDP droplet concentrations (N_{drop}) (10 second averaged values) increased to ~ 80 cm^{-3}, LWCs peaked at ~ 0.2 g m^{-3} and mean droplet diameters were ~ 8 μm. Measurements from the 2D-S showed ice crystals with mean size ~ 415 μm in low concentrations, ~ 1 L^{-1}. Images from the 2D-S revealed irregular snow particles with some dendritic habits coexisting with small liquid droplets. As the ascent continued the aircraft encountered a layer containing higher N_{ice} at -14 °C. Ice crystals consisted of snow particles (mean size 350 μm) in concentrations ~ 4 L^{-1}. Probe imagery showed these to be a mixture of large irregular ice crystals, small, more pristine plate-like crystals and some crystals with columnar habits. The highest 10 second mean N_{ice}, reached ~ 6 L^{-1} with peak values ~ 15 L^{-1}. These were observed in a region approximately 500 m below cloud top. Maximum 10 second averaged Ice Water Content (IWC) reached 0.2 g m^{-3} with peaks up to 0.3 g m^{-3} in the same region. Particle images here revealed (Fig 3b) irregular ice crystals together with a few smaller pristine plates. The mid region of this stratocumulus deck also consisted of liquid droplets (mean diameter ~ 13 μm) in concentrations ~ 75 cm^{-3}, and LWC ~ 0.3 g m^{-3}, with some 1 second integration periods being as high as 0.5 g m^{-3}. As the aircraft approached cloud top, where the lowest temperature recorded was -19.5 °C, N_{ice} reduced to ~ 0.5 L^{-1} with mean sizes of 285 μm, however this region was dominated by liquid droplets (mean diameter 17 μm) with N_{drop} up to 95 cm^{-3}, and LWC values peaking at 0.7 g m^{-3}. Imagery from the 2D-S revealed many small droplets together with numerous small irregular ice crystals in this

cloud top region. After measuring the vertical structure of the cloud layer, which was approximately 1 km in depth, the aircraft penetrated cloud top at 1675 m and passed through an inversion layer where the temperature increased to -13 °C.

Profiled Descent A3

Following another ascent, the aircraft performed a profiled descent (A3) from the inversion layer , *T*= -13°C, penetrating cloud top at 1,569 m asl where *T*= -16 °C. As the aircraft descended, LWC increased rapidly to 0.9 g m^{-3} at 30 m below cloud top, the highest LWC recorded at any point during the flight. Mean droplet diameters in this region were ~ 23 μm in concentrations of ~ 90 cm^{-3}. 2D-S images revealed many small liquid droplets with a few small (mean diameter 190 μm) irregular ice crystals (Fig. 3a) with N_{ice} ~ 1 L^{-1}. The region immediately below this cloud top layer, between 1520 and 1275 m, exhibited a steady decline in LWC while droplet concentrations and N_{ice} maintained similar values to those observed in the cloud top region. Mean ice crystal diameters increased markedly to 520 μm before LWCs eventually fell to below the threshold value (0.01 g m^{-3}), marking the base of an upper layer of cloud. A subsequent cloud layer, 750 m below, was then encountered. In the clear air region separating these two cloud layers temperatures rose by around 5 °C to -11 °C and large (~ 760 μm) irregular snow particles, some of which exhibited dendritic growth habits, were observed. Precipitation concentrations were generally < 0.5 L^{-1}. Mean IWCs in this precipitation zone were ~ 0.01 g m^{-3}. The particles observed falling from the higher cloud layer descended into the cloud layer below at 1,275m asl. In the top of this lower cloud layer (T= -11°C) LWCs rose to 0.4 g m^{-3} with N_{drop} (mean diameter 15 μm) increasing to ~ 120 cm^{-3}while N_{ice} increased to ~ 1 L^{-1} , 2D-S probe imagery in this region revealed the presence of larger snow particles (mean diameters ~ 815 μm). As the aircraft descended further, LWCs gradually decreased while N_{drop} remained fairly constant before reaching cloud base at 280 m,

(much closer to sea level than in profiles A1 and A2). Below cloud base precipitating snow (mean particle size ~ 625 μm) was observed.

Profiled Ascent B2

During profiled Ascent B2 (prior to profile descent B1 above) the aircraft climbed from below cloud base at 190 m (T =-5 °C) travelling initially through snow precipitation in concentrations peaking at ~3 L^{-1} (mean diameter 420 μm). Images revealed dendritic ice crystals that had descended from the cloud layer above (fig. 5c). IWCs in this region peaked at 0.025 g m^{-3}. Cloud base during this profile was less well defined than in later ascents with variable LWCs and droplet number concentrations before a more defined cloud base was encountered at 1010 m. N_{drop} then increased rapidly to 270 cm^{-3} (mean diameter ~ 12.5 μm) while LWCs increased more gradually to ~ 0.4 g m^{-3}. N_{ice} through this region showed a decline to < 0.1 L^{-1}, and consisted of precipitating snow particles with a mean diameter of 430 μm. Closer to cloud top (1410 m) ice crystal number concentrations increased, to peak values of ~ 1 L^{-1}. Images (fig. 5b) showed smaller crystals (mean diameter ~ 370 μm) at this higher altitude, with evidence of hexagonal habits and peak values of IWC ~ 0.04 g m^{-3}. Droplet concentrations towards cloud top were similar to lower in the cloud, while LWCs increased to 0.6 g m^{-3} and mean droplet diameter increased to ~ 15 μm. The coldest temperature reached within the cloud layer was -18 °C, but cloud top (at ~ 1530 m) was warmer by 1 ºC. A further increase of 1°C was observed as the aircraft ascended through the inversion layer. The depth of this cloud layer (520 m) was significantly less than that observed during the previous spring case cloud layer penetrations.

Constant Altitude Runs B3 and B4

During straight and level run (SLR) B3 the aircraft flew below cloud base at 390 m asl to characterise precipitation. During B3 the aircraft briefly traversed a region of low cloud with

high N_{drop} (peaking at ~ 520 cm^{-3}) but generally low LWCs (< 0.1 g m^{-3}). These cloud droplets were small (mean diameter ~ 6 μm). 2D-S imagery also revealed small drops were present together with snow crystals (mean diameter ~ 370 μm) that were precipitating into these brief regions of low cloud. During B3 temperatures increased from -12 °C to -10 °C. Crystal habits in the out of cloud regions were dominated by aggregates of dendrites and some pristine ice crystals (~ 0.5 L^{-1}). Here, LWCs were below 0.01 g m^{-3}, although the 2D-S also detected drizzle droplets precipitating from the cloud layer above (mean concentration ~ 0.2 L^{-1}). Later in B3 the aircraft left its constant altitude and descended to 80 m asl (T =-8.5 ˚C). Mean N_{ice} increased to ~ 2 L^{-1} with peaks up to 4 L^{-1}. There was a corresponding increase in 2D-S droplet concentrations to a mean of ~ 1 L^{-1}. 2D-S imagery shows the presence of small columnar shaped ice crystals (similar to those shown in figure 5d), together with larger snow particles and drizzle droplets. CDP LWC was < 0.01 g m^{-3} in this region, since the larger drizzle droplets measured by the 2D-S were outside the CDP size range. In this region of enhanced N_{ice}, just above the sea surface, IWCs, which were generally < 0.01 g m^{-3} in the below cloud base region, increased to peak values of 0.04 g m^{-3}.

At the start of run B4, prior to undertaking a mainly straight and level run (SLR) initially to the NW, the aircraft first descended from the inversion layer (T = ~ -14 °C) into the cloud top (1050 m asl). LWC initially rose sharply to a peak of 0.5 g m^{-3} before gradually falling away to a mean value ~ 0.3 g m^{-3}. Mean droplet concentrations over a ~ 5 minute period were 340 cm^{-3} (mean diameter 11 μm) and the 2D-S imagery revealed the presence of small droplets together with large snow crystals (mean diameter 730 μm) in concentrations < 0.1 L^{-1} and IWCs of 0.03 g m^{-3}. At 1240 UTC a generally cloud free region was encountered and sampled for ~ 4 minutes before re-entering cloud again. During this period the aircraft was turned onto a reciprocal heading at the NW limit of its track. Cloud microphysics measurements revealed this cloud top region to be very similar to the first period during B4.

Mean values of LWC over ~ 4 minute period were 0.2 g m^{-3}, droplet concentrations (mean diameter ~ 9 μm) were ~ 340 cm^{-3}. N_{ice} while generally less than 1 L^{-1} (IWC ~ 0.01 g m^{-3}) showed brief increases (during 1 second integration periods) to 2 L^{-1} and IWC values peaked at 0.1 g m^{-3}. 2D-S imagery showed the presence of dendritic ice particles (mean diameter 750 μm) together with small spherical particles, likely to be liquid droplets. Temperatures in the cloud top regions remained fairly constant throughout B4 (between -15 °C and -16 °C). The aircraft flew above cloud top for the remainder of the SE-bound leg, and found there to be no ice particles falling into cloud top from above.

Stepped Run C1

The BAS aircraft performed a stepped profile (flight segments C1.1 - C1.4) from a cloud top altitude of ~ 3000 m down to 2249 m covering the temperature range -7.5 °C to -2 °C. In total 4 SLRs and 4 profiled descents were carried out during this run. During the first penetration of cloud (run C1.1), N_{drop} over a 2 minute period was 240 cm^{-3}. LWCs rose to ~ 0.1 g m^3 and the droplet mean diameter was 10.5 μm. N_{ice} was generally very low during this period < 0.25 L^{-1} with some peaks up to 0.5 L^{-1}. During C1.1 the aircraft maintained an altitude of ~ 3000 m for several minutes. The cloud microphysics remained predominantly stable, with low N_{ice} (< 0.25 L^{-1}) and LWCs ~ 0.01 g m^{-3}. The only notable change was a slight increase in the mean diameter of droplets measured by the CDP to 11.5 μm and a reduction in number concentration to 185 cm^{-3}. At ~ 0900 UTC the aircraft descended ~ 100 m to start run C1.2 (T= -6˚C), and encountered a cloud sector where N_{ice} increased to 2 L^{-1} with peaks to 5 L^{-1} (and IWC peaks up to 0.03 g m^{-3} observed here). 2D-S imagery (Fig 7a) revealed irregular ice crystals and the presence of columnar ice both of which appeared to be rimed. Many small single pixel (10 μm) particles were also measured. These likely represent the small droplets detected by the CDP in this region (mean diameter 13.5 μm) in concentrations of 125 cm^{-3}. Later during C1.2, N_{ice} fell to values < 0.25 L^{-1}. The aircraft performed a profiled descent at

the start of C1.3, descending 200 m to ~ 2720 m (T= -4˚C). During the descent, LWCs and droplet number concentrations fell to near zero values while N_{ice} increased to peak values of 5 L^{-1} (and IWC peaked at 0.02 g m^{-3}). 2D-S images again revealed the presence of small (mean diameter 255 μm) rimed irregular ice crystals and ice crystals of columnar habit. In the temperature range spanned by this cloud, these observations are consistent with the contribution of secondary ice production (SIP) through rime-splintering. During C1.3 further N_{ice} peaks up to 5 L^{-1} consisting of columnar particles and irregular ice crystals were observed (fig 7b). The liquid phase of the cloud in this region was much more variable than nearer to cloud top. Increases in peak LWCs to 0.01 g m^{-3} were seen together with an increase in droplet number concentrations to ~ 150 cm^{-3} (mean diameter 13.5 μm). These occurred between periods where LWC values were near zero and the cloud was predominantly glaciated.

During C1.4 the aircraft descended 300 m to 2,450 m (T = -3˚C). During this run the time between peaks in N_{drop} increased, while the highest N_{ice} measured during this science flight were observed (peaking at N_{ice} = 35 L^{-1}). IWCs peaked at 0.2 g m^{-3}, which is significantly greater than values observed elsewhere in this cloud system. 2D-S imagery (fig. 7c) reveals that these high ice crystal number concentrations were dominated by columns (mean diameter 260 μm), which at times were seen together with small liquid droplets. These observations are consistent with SIP through the H-M process.

Profiled descent D1

Well into the flight, the BAS aircraft performed a profiled descent from cloud top at 3,700 m to 2,400 m over the temperature range -5.2 °C to 3 °C. At cloud top, LWCs rose to a peak of 0.3 g m^{-3}, with peak N_{drop} (mean diameter 12.5 μm) up to 270 cm^{-3}. N_{ice}, initially close to zero, rose to peaks of 6 L^{-1} with IWCs up to 0.1 g m^{-3}. 2D-S images (fig. 9a) showed

columnar ice crystals (mean diameter 350 μm) in this region, together with liquid droplets. At times swift transitions between predominantly liquid and glaciated conditions were observed. At 3,500 m (T = -3.5 °C) the CDP stopped measuring significant values of LWC (> 0.01 g m^{-3}) and this appeared to mark a gap region in the cloud layer of approximately 100 m in depth. The 2D-S did detect low N_{ice} in this region. These were generally below < 0.5 L^{-1}. When the aircraft descended into the lower cloud layer (T = -2 °C) LWCs increased to peak values of 1 g m^{-3}, where N_{drop} (mean diameter 13.5 μm) increased to values as high as 250 cm^{-3}. 2D-S imagery revealed few ice crystals in this region but high drizzle drop concentrations.

At 2,800 m (T = 0 °C) a further period of drizzle droplets was observed in the 2D-S imagery. These again appeared stretched and made it impossible to separately identify ice in the data set, so there is no reliable ice crystal mass and number concentration data in this region. At this time, CDP LWCs peaked at 0.4 g m^{-3} and droplet concentrations varied from close to zero to up to ~ 350 cm^{-3}. The mean diameter of the droplets measured by the CDP was 10 μm. As the aircraft descended towards its minimum descent altitude large variations in LWCs and droplet concentrations continued to be observed with peaks up to 0.2 g m^{-3} and 420 cm^{-3} respectively.