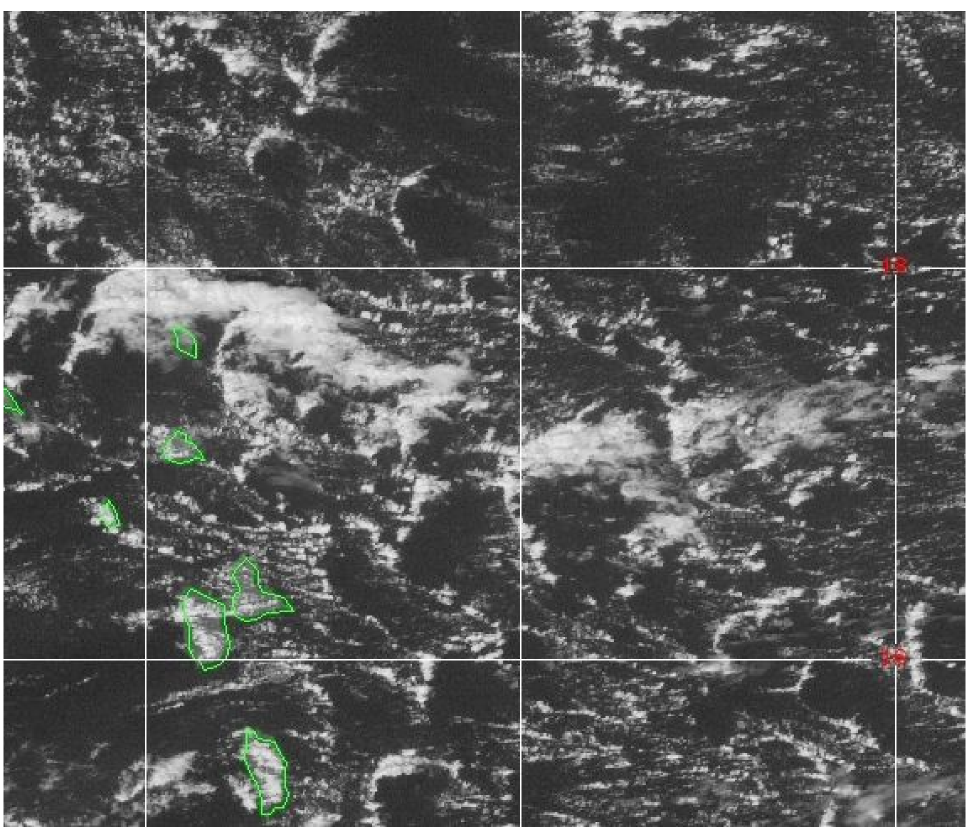
King Air N2UW flight report for January 14, 2005.

Crew: Drew, Vali, Gordon, Wechsler

General: 3-aircraft operation based on plans formulated during yesterday's planning meeting. Basically, block altitudes maintained then shuffling of the deck at fixed times. Top a/c to make cloud selection.

Strong and moist easterlies to about 700 mb; windshift and some drying from there to weak 550 mb inversion.

Cloud development is characterized by distinctly stronger growth on the west sides of large mesocells. Some of this development reached well beyond the inversion and produced anvils sheared, and at times drifting off, to the East. Most intense development took place in a broad band running ESE to WNW, made up of patches on the west sides of the cells. This formation moved toward the west and had its peak intensity at around 18:00 when Barbuda was just under the line. To the north of this line, clouds were somewhat less deep and formed arcs (i.e. the western portions of cells). On he south side of the line the picture was similar but clouds were deeper and formed less clear a pattern.



Detail of GOES 17:42 1-km VIS image

In the large echoes, reflectivities near the surface ranged to 50 dBZ, and echoes reached to 7 km height. The variety of cloud intensities made the day somewhat confusing to study, specially for the coordinated flights envisioned in the plan.

Narrative: The King Air flight was made up of four segments. **A**. 16:50-17:20; deep convection was sampled to the ESE of SPol. The BAE 146 was probing the same cluster at about 1000 m, but no coordination was attempted. **B**. ~17:20-18:20; first phase of 3-a/c pattern, with KA at 1340 m, 146 at higher altitudes, and the C130 lower. **C**. ~18:20-19:20 Smaller Cu were sampled at 1685 m along long flight lines in the region N of the broad band of major echoes. Other a/c lower. **D**. ~19:20- 20:20; cloud base and precipitation was sampled while chasing the other two aircraft.

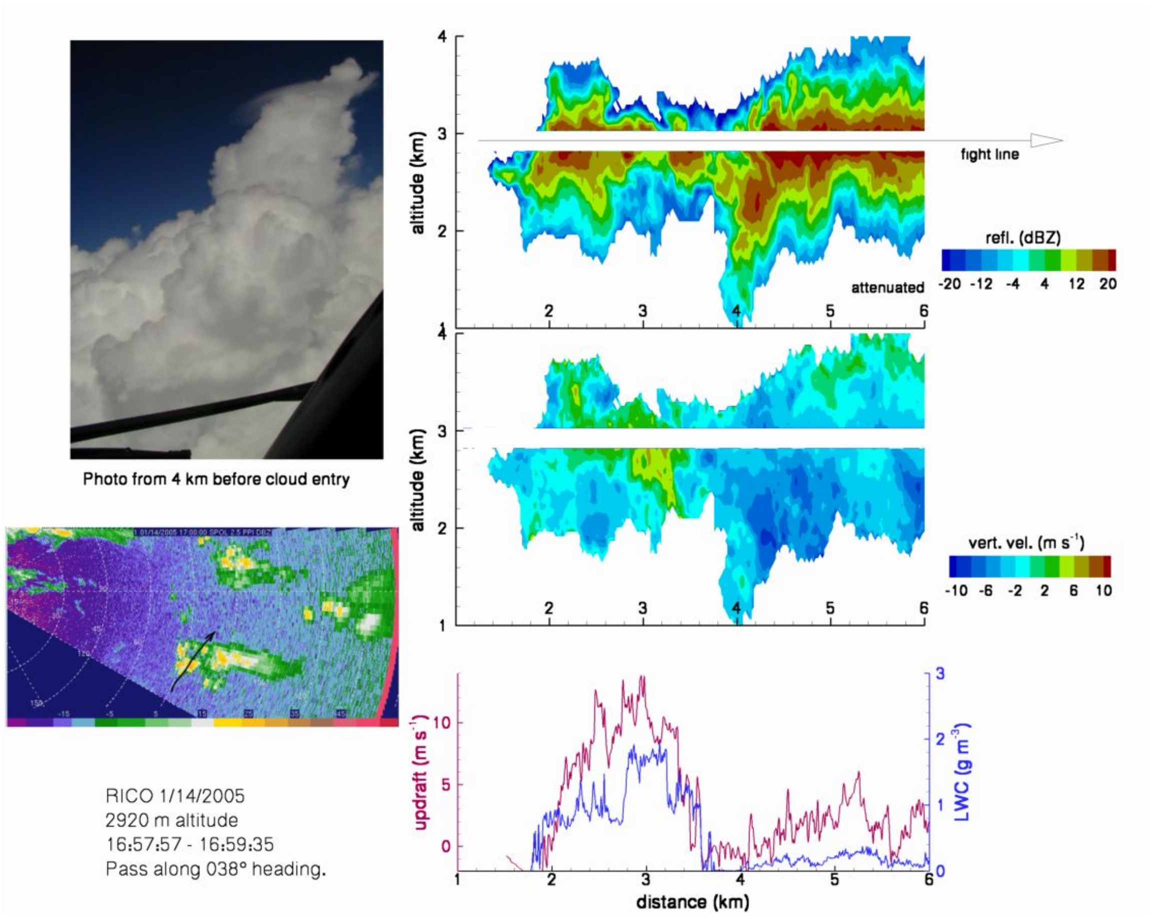
A. Growing turrets were sampled on the west side of a larger cloud mass, first near 3600 m altitude, then near 3000 m. During this time the BAE 146 was at 1000 m.

The locations of new turrets in the period of sampling moved toward the East at nearly 20 m s^{-1}, which corresponds to winds at about 500 m above the ocean surface and is almost double of the wind speed at the sampling level. I surmise, that this is an important characteristic of this day, and that it goes with the observations mentioned earlier about the general appearance of deep clouds on the west sides of the mesocells in the sense that two tendencies reinforce each other there, while they are in opposition on the east sides of cells.

As a consequence of the wind shear, new turrets were fairly well separated from previous ones. Perhaps the most vigorous updrafts of the project were seen on this occasion.

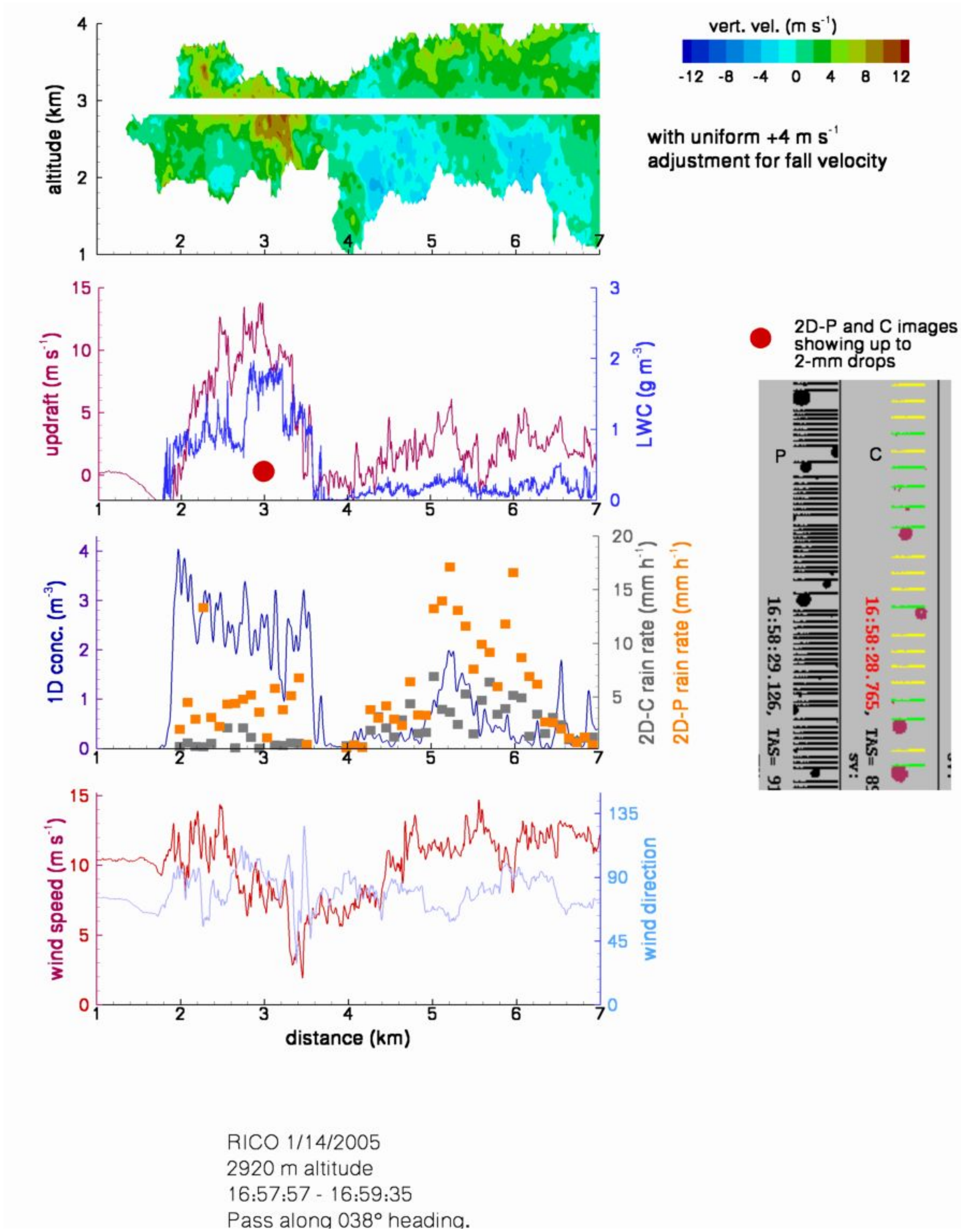
Data from the third penetration is shown on the next two pages. The radar reflectivities are strongly attenuated; this accounts for finding the highest values close to the flight path. Neither the upper, nor the lower boundaries of the echo can be trusted to depict real boundaries of cloud or of precipitation. Also, have to remember that the vertical Doppler velocities represent the sum of air velocity and fall velocity, so that the values are lower than the in situ measurements. Coupled with the fact, that there were millimeter sized drops essentially everywhere in the region sampled, as evidenced by the in situ particle probe data, the Doppler velocities are 4 to 5 m s^{-1} lower. To see the effect of this in some rough way, a +4 m s^{-1} correction is added to the velocities shown in the second diagram.

Without the correction, the velocity image shows the strongest updrafts, which exhibit a pattern consistent with the pulsating nature on new turret development. The core of the updraft above the flight level is at about 2.2 km on the abscissa, while the next pulse from below the flight level is near 3 km. That places this pulse a little closer to the older echo, off toward the north, but as the photograph shows there were in fact several new turrets rising toward the flight level, the strongest one to the left of the flight line.



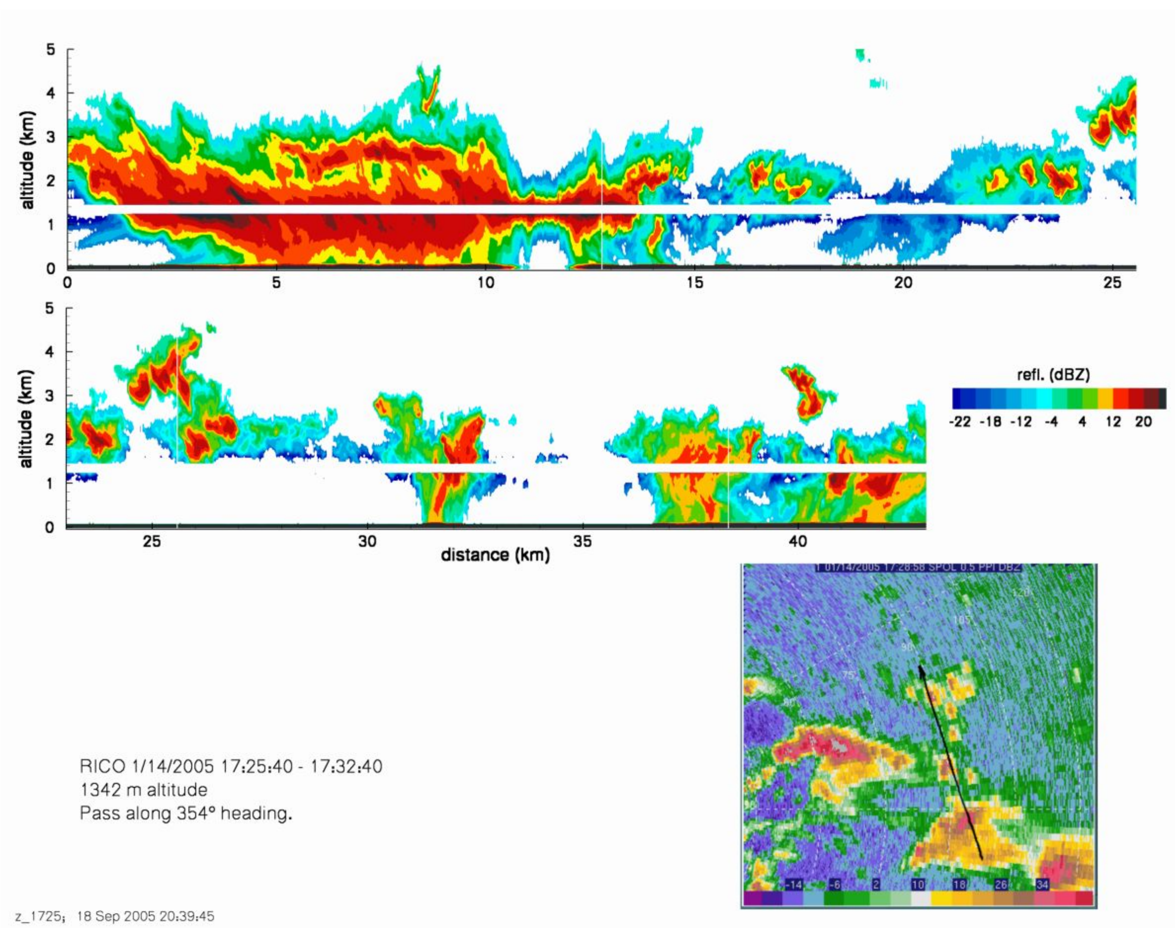
The LWC maxima approached about half the adiabatic value; mixing being also evident in that the variability in LWC in the main updraft zone. The new turret – between 2 and 3.5 km – contained a large concentration of drops in the 100-400 μm size range, and also drops of millimeter size (as shown in the 2D images in the second figure). The proportions of smaller drops (1D range) to larger ones changed in the older part of the cloud, between 4 and 7 km.

The horizontal winds in the updraft show some evidence of the low level momentum being carried aloft, but that seems to have been quickly reduced by the influence of the weaker and more northerly upper level winds, even leading to the minimum near 3.4 km.



The two previous passes were at 3580 m altitude, and even in updrafts of 10 - 12 m s^{-1} LWC values reached only 0.5 – 0.7 g m^{-3}. Compared to the values seen in the pass at 2920 m, this demonstrates the rapid conversion to larger drops. Indeed, drops up to 3 mm in diameter were present in these passes. Figures, with in situ and radar data, similar to those shown above, are available on request for these passes too.

B. During this first of the three periods of 3-a/c patterns (roughly 17:20-18:20), the KA was to be at fixed 4000' and 146 at higher altitude calling out directions. Didn't work real well, in part due to heavy radio traffic with center. Clouds sampled were still on the N flank of the deep convection. Nonetheless, the WCR images for the period show an interesting variety, with echoes of varying depth and with small turrets/bubbles shooting up to 4.5 km or more. A sample segment is shown below; in this case, poor visibility prevented visual adjustment of where the clouds were penetrated.

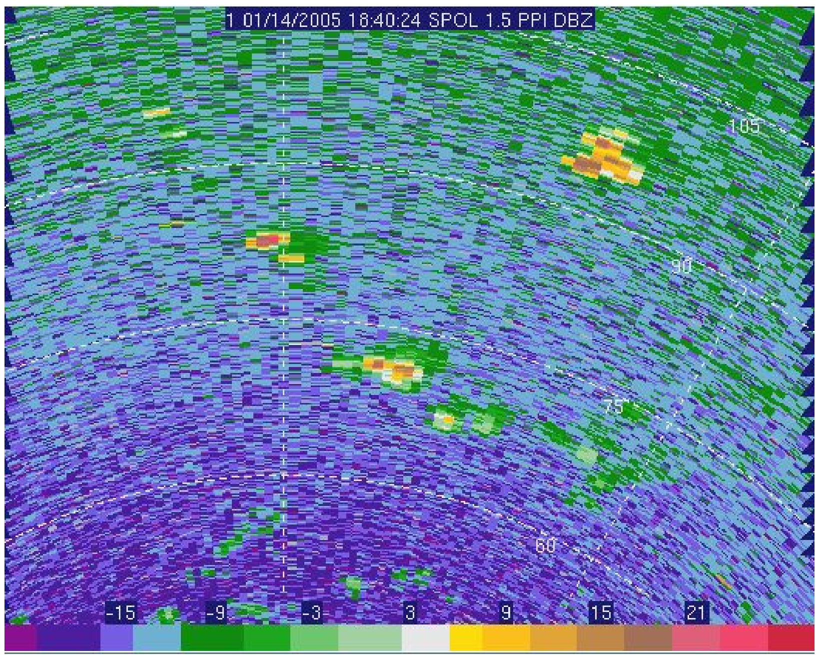


C. This segment of the flight (roughly 18:20 to 19:20) consisted of long passes with minor deviations to maximize cloud intercepts. Changed to area further N, away from the anvil shadow; coordinated legs started about 18:33.

Small to medium Cu were in the region, with WCR echo tops to 3 km, but mostly less than that. Sampling was at 1685 m altitude.

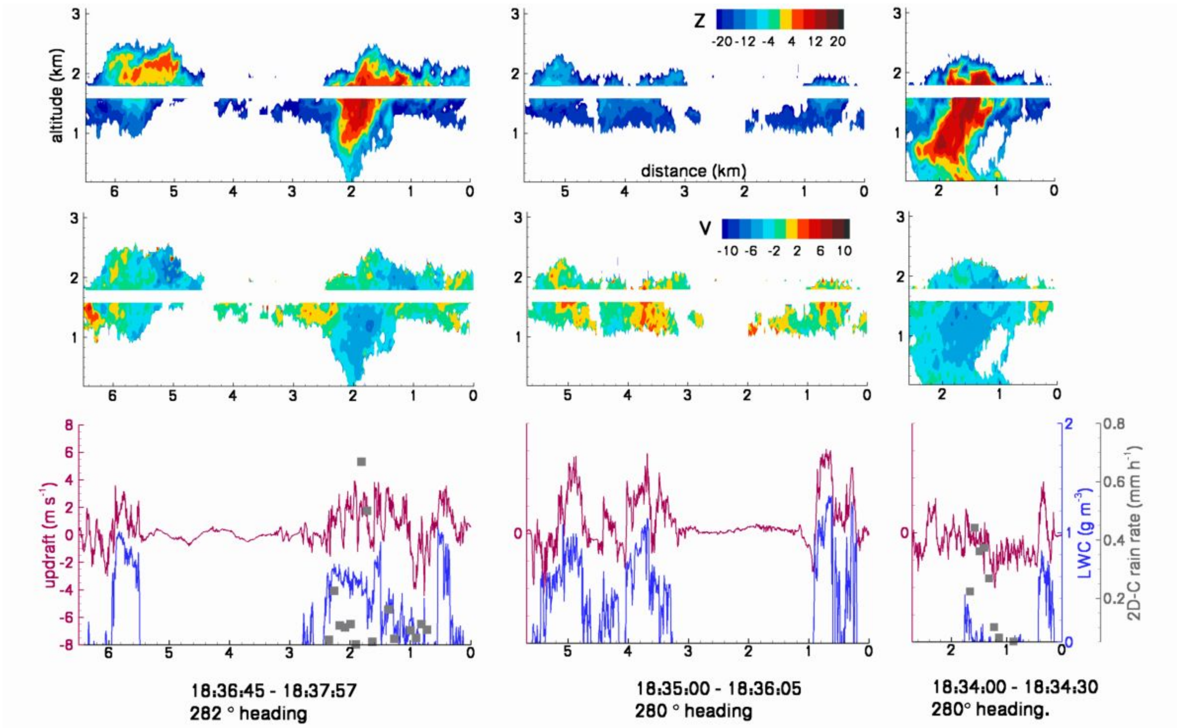
Four legs made up this segment, with the sampled region spanning -10 to 50 km E and 30 to 70 km N of SPol. In total, 30 clouds were sampled, with a modal size of about 1.5 km, i.e. with width to depth aspect ratios of roughly 1.5 to 2. The total length of the run was 237 km, of which 33 km (14%) was in cloud, defined as LWC>0,03 g m^{-3}.

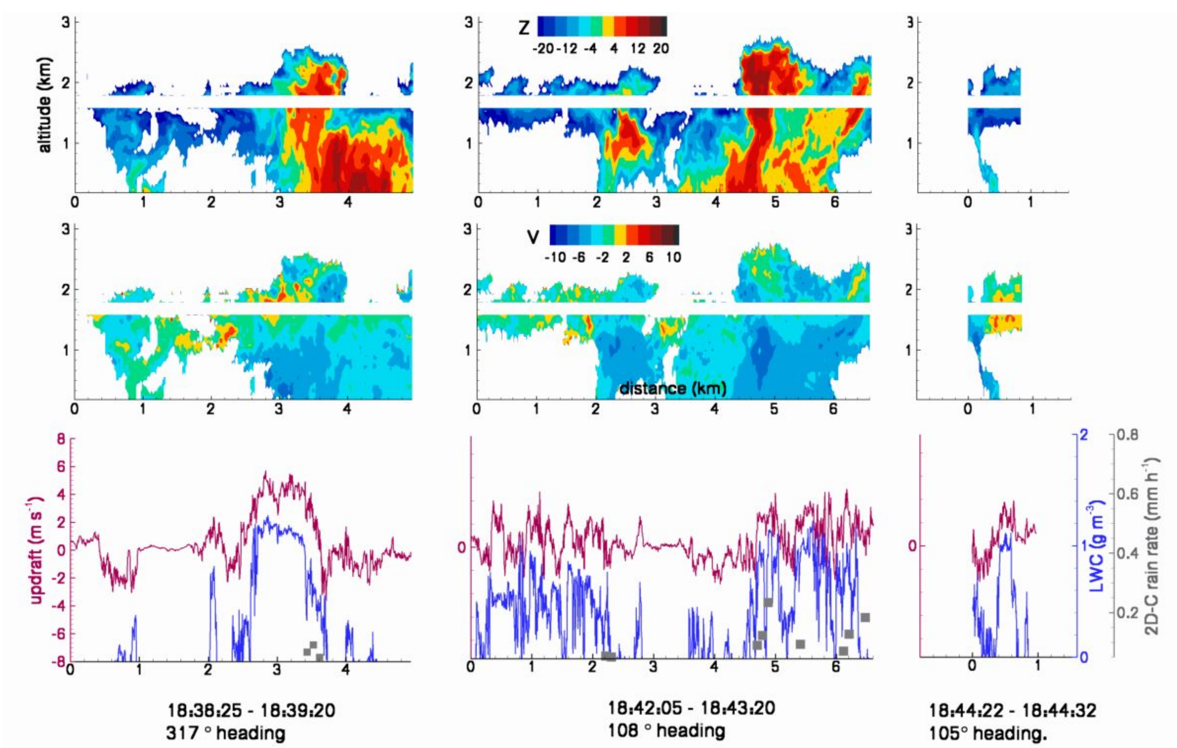
An SPol image for this region is shown below; reflectivity values ranged to about 15 dBZ and maximum echo heights were near 2.5 km. The King Air sample includes clouds which produced no detectable SPol echo.

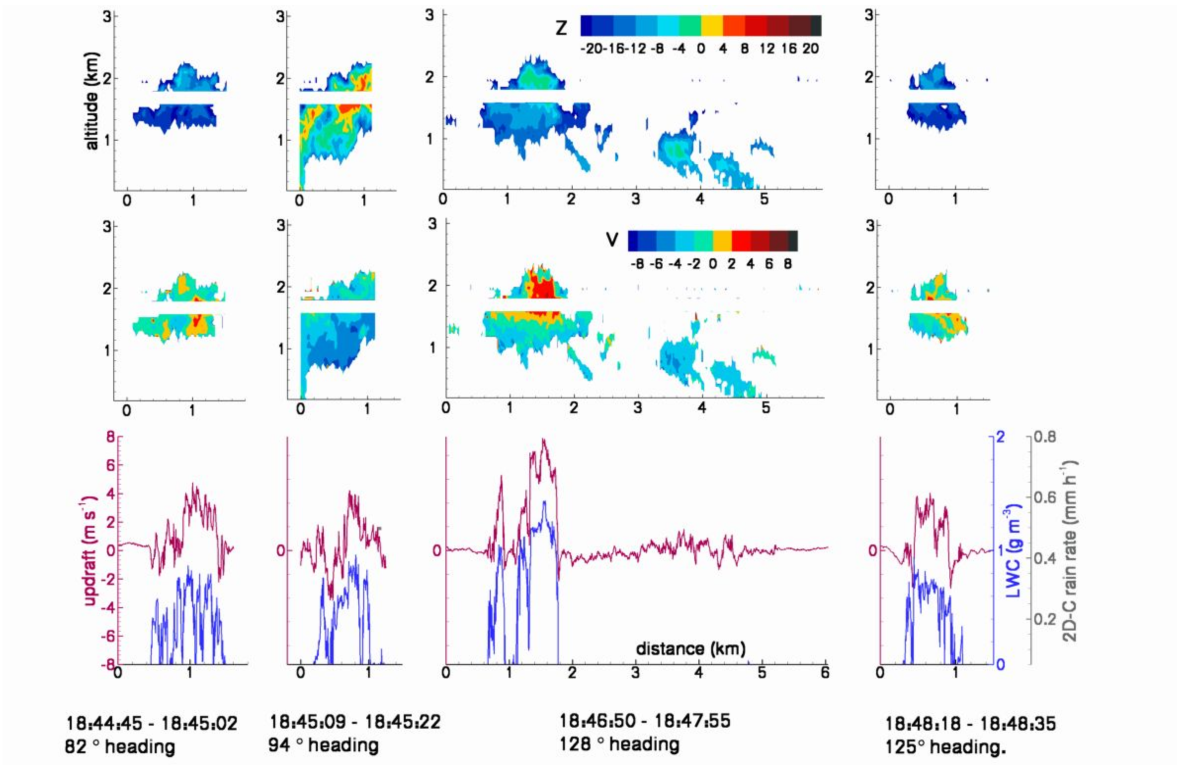


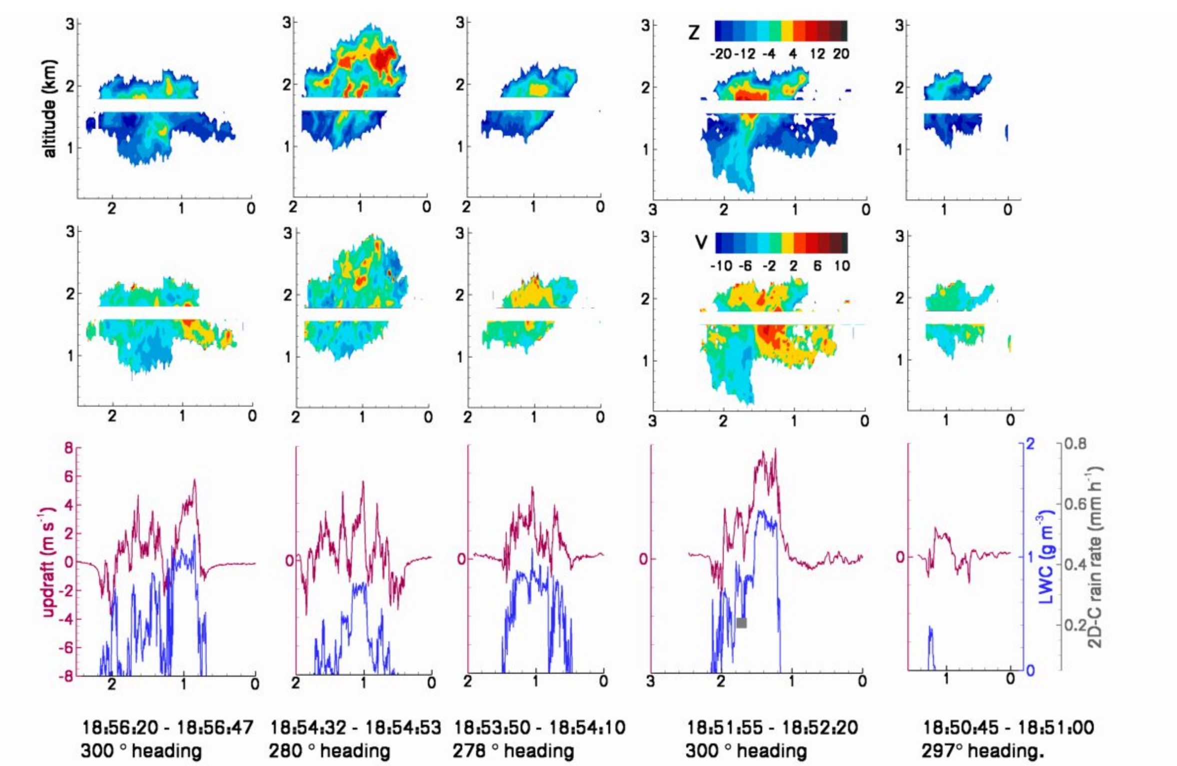
The King Air and WCR data for this sequence are summarized in 7 figures. Because the clouds cover quite a variety, all are included on the following pages. On some pages the abscissa is reversed so that all pages have the prevailing wind from left to right.

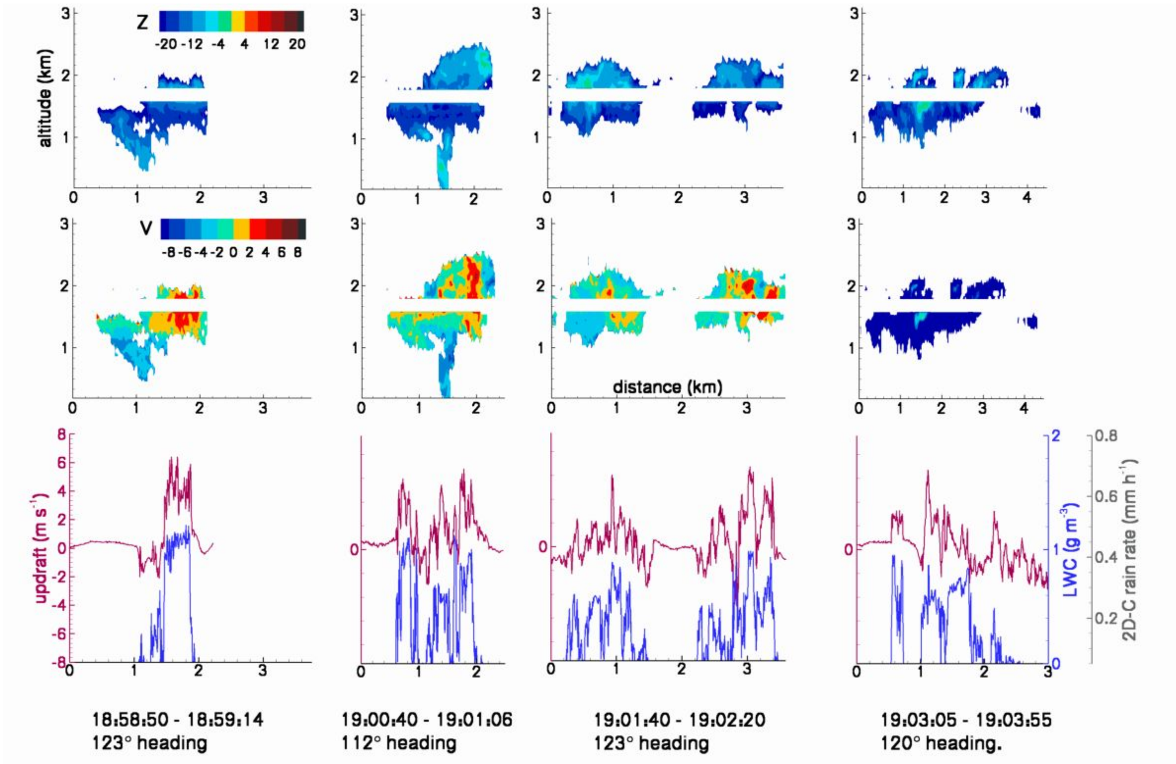
Because the LWC in these clouds is relatively low, the attenuation of the radar signal is not as serious a problem as in the clouds described earlier and this cloud and precipitation are depicted more faithfully.

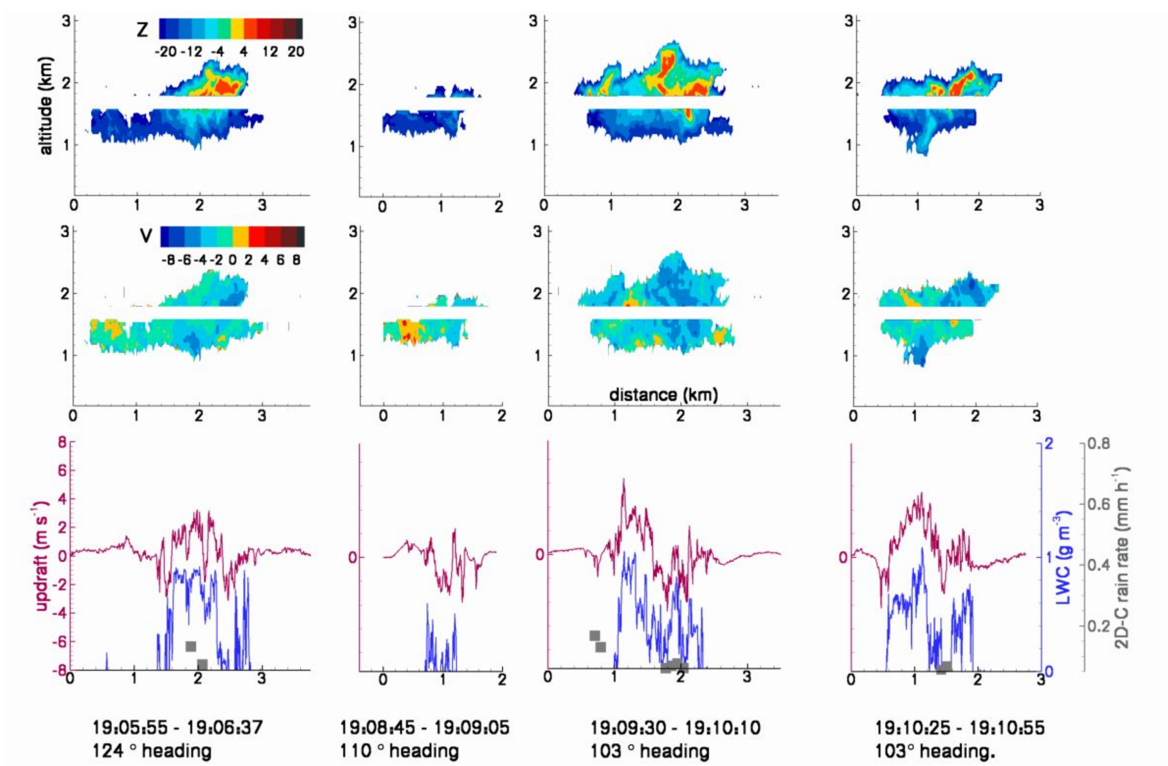

Z
-20 -12 -4 4 12 20
V
-10 -6 -2 2 6 10
altitude (km)
distance (km)
updraft (m s⁻¹)
LWC (g m⁻³)
2D-C rain rate (mm h⁻¹)
18:36:45 - 18:37:57
282 ° heading
18:35:00 - 18:36:05
280 ° heading
18:34:00 - 18:34:30
280° heading.

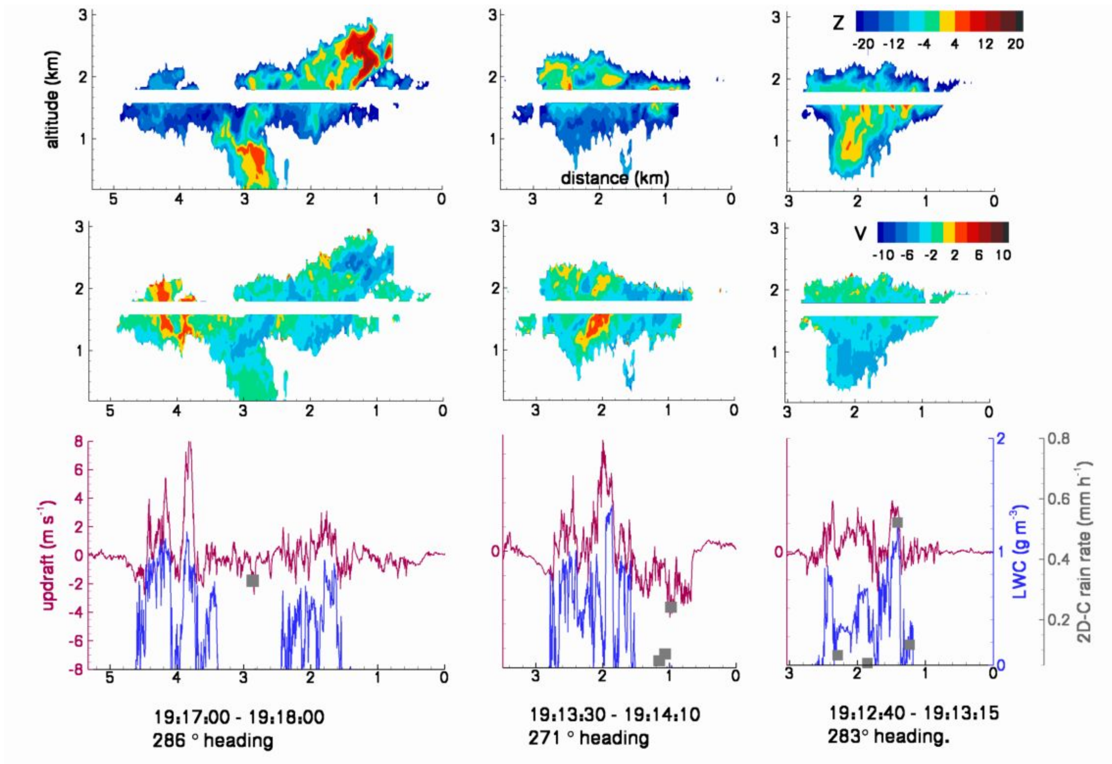

Z
-20 -12 -4 4 12 20
V
-10 -6 -2 2 6 10
altitude (km)
distance (km)
updraft (m s⁻¹)
LWC (g m⁻³)
2D-C rain rate (mm h⁻¹)
18:38:25 - 18:39:20
317 ° heading
18:42:05 - 18:43:20
108 ° heading
18:44:22 - 18:44:32
105° heading.


Z
-20-16-12 -8 -4 0 4 8 12 16 20
V
-8 -6 -4 -2 0 2 4 6 8
altitude (km)
updraft (m s-1)
LWC (g m-3)
2D-C rain rate (mm h-1)
distance (km)
18:44:45 - 18:45:02
82 ° heading
18:45:09 - 18:45:22
94 ° heading
18:46:50 - 18:47:55
128 ° heading
18:48:18 - 18:48:35
125° heading.

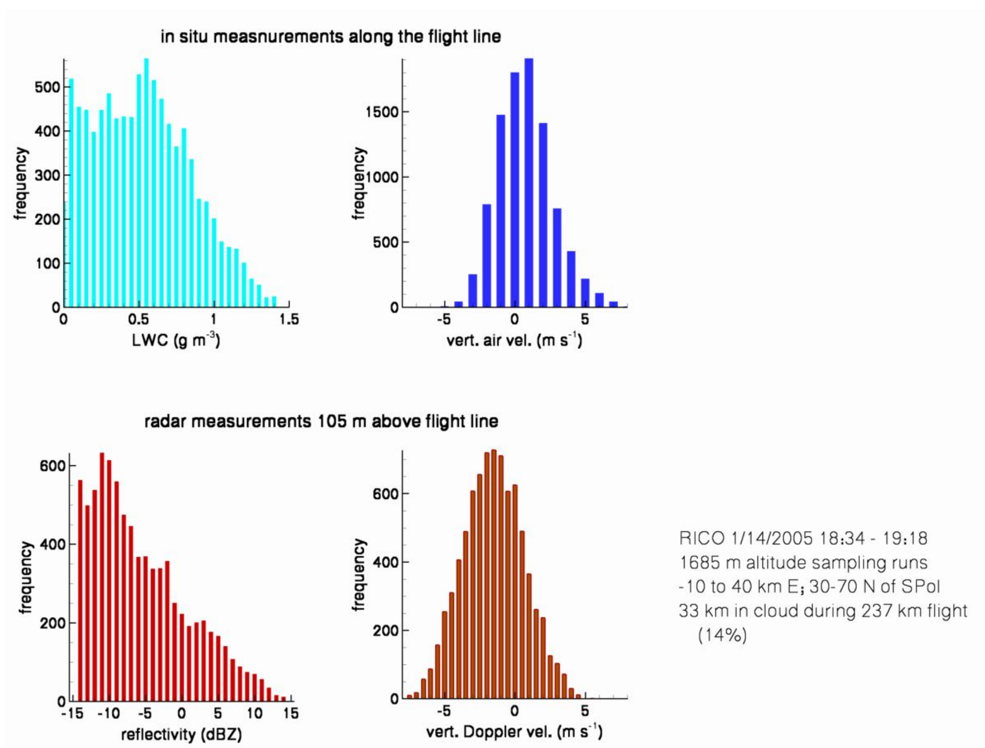

Z
-20-12 -4 4 12 20
V
-10 -6 -2 2 6 10
altitude (km)
updraft (m s-1)
LWC (g m-3)
2D-C rain rate (mm h-1)
18:56:20 - 18:56:47
300 ° heading
18:54:32 - 18:54:53
280 ° heading
18:53:50 - 18:54:10
278 ° heading
18:51:55 - 18:52:20
300 ° heading
18:50:45 - 18:51:00
297° heading.


Z
-20 -12 -4 4 12 20
V
-8 -6 -4 -2 0 2 4 6 8
altitude (km)
distance (km)
updraft (m s⁻¹)
LWC (g m⁻³)
2D-C rain rate (mm h⁻¹)
18:58:50 - 18:59:14
123° heading
19:00:40 - 19:01:06
112° heading
19:01:40 - 19:02:20
123° heading
19:03:05 - 19:03:55
120° heading.

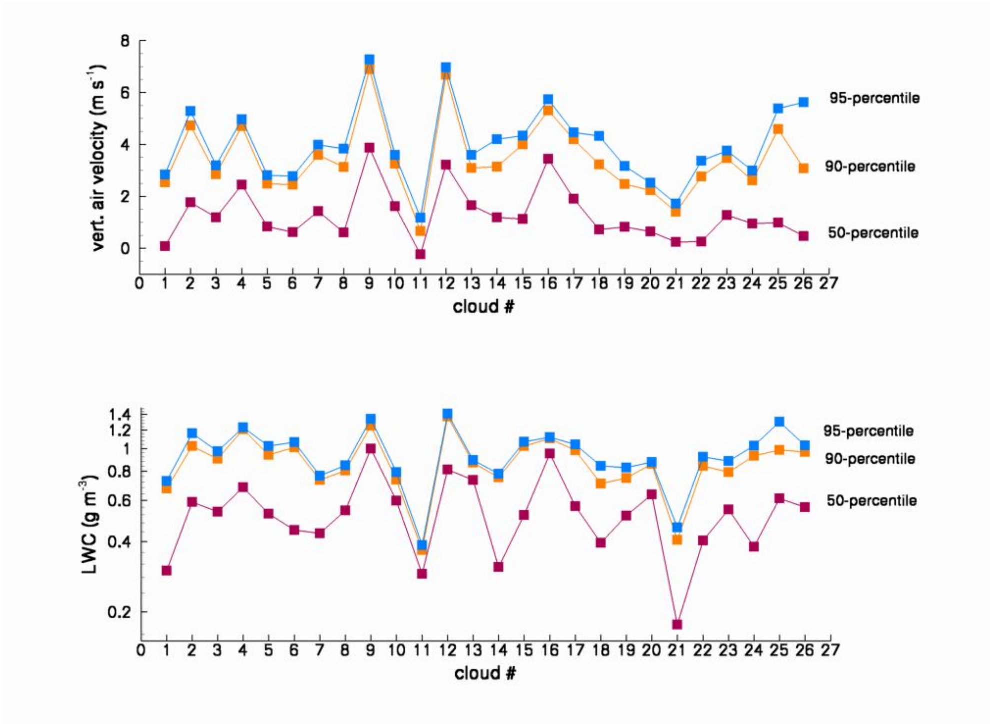

Z
-20 -12 -4 4 12 20
V
-8 -6 -4 -2 0 2 4 6 8
altitude (km)
distance (km)
updraft (m s⁻¹)
LWC (g m⁻³)
2D-C rain rate (mm h⁻¹)
19:05:55 - 19:06:37
124 ° heading
19:08:45 - 19:09:05
110 ° heading
19:09:30 - 19:10:10
103 ° heading
19:10:25 - 19:10:55
103° heading.



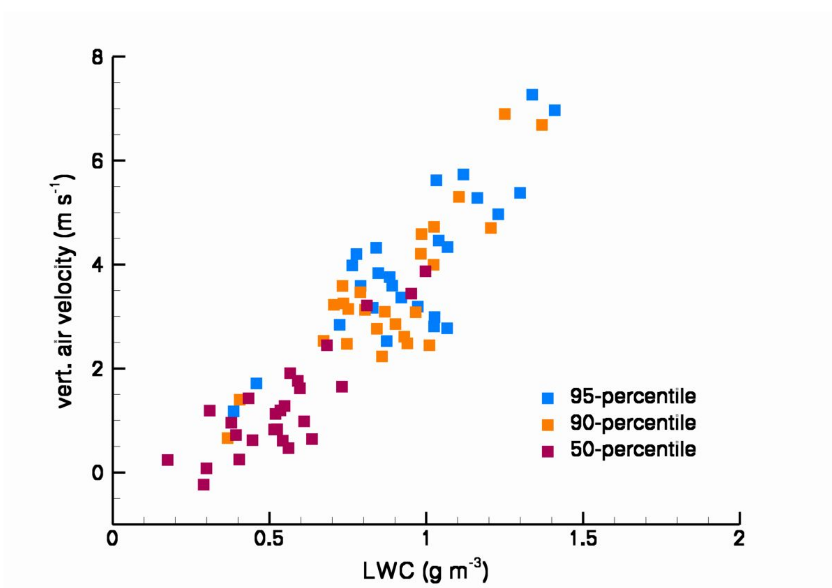
As the figures illustrate, there was considerable variation in the size and in the stage of evolution among these clouds. A statistical summary of the range of values observed for four major parameters is shown in the figure below.



The cloud-to-cloud variability is demonstrated in the figure below, showing the 50-, 90-, and 95-percentile values of the vertical air velocity and of the LWC for each cloud.



As can be readily perceived from the time series shown above, there is a parallel variation between updraft velocity and liquid water content, at least in this statistical sense: clouds which contain (along the flight path) a stronger updraft also contain higher liquid water contents. This data presentation doesn't reveal whether those higher values also coincide spatially – this aspect remains to be examined later. The degree of correlation is quite strong, as illustrated in the figure to the left, for each of the percentile values alone (the correlation coefficient for the median values is 0.85 and for the 90-percentile values it is 0.81), but even stronger for the combined set. This points to an



important entrainment impact at flight level (roughly 1-km above cloud base); even the 99-percentile LWC is only about 56% of the adiabatic value. That this occurs in spite of strong updrafts is noteworthy.

For the overall cloud sample, defined as points with LWC > 0.03 g m^{-3}, vertical velocity (***w***) and LWC statistics are:

TABLE 1.

	percentile						
	1	5	10	50	90	95	99
w (m $s^{-1)}$	-2.7	-1.7	-1.1	1.1	3.8	4.8	6.6
LWC g m^{-3}	0.037	0.070	0.12	0.53	0.99	1.1	1.3

It is also revealing to look at the fraction of cloud volumes that are updrafts. From the in situ data, 32 % of the flight path had ***w*** > 2 m s^{-1} and 8.7% had ***w*** > 4 m s^{-1}.

The Doppler velocity images complement the in situ data in revealing aspects of the updraft structure, with the caveat that particle velocities are combined with air velocities. In this instant, with relatively low reflectivities indicating only moderate rainfall, and with LWC also being limited, the fall velocities are also expected to be modest. Even so, with details not given here, stratification by reflectivity of the difference between Doppler velocity and in situ air velocity shows that at –10 dBZ the fall velocity contribution is about 1 m s^{-1}, and at 0 dBZ it is 2-3 m s^{-1}. (These are preliminary results.)

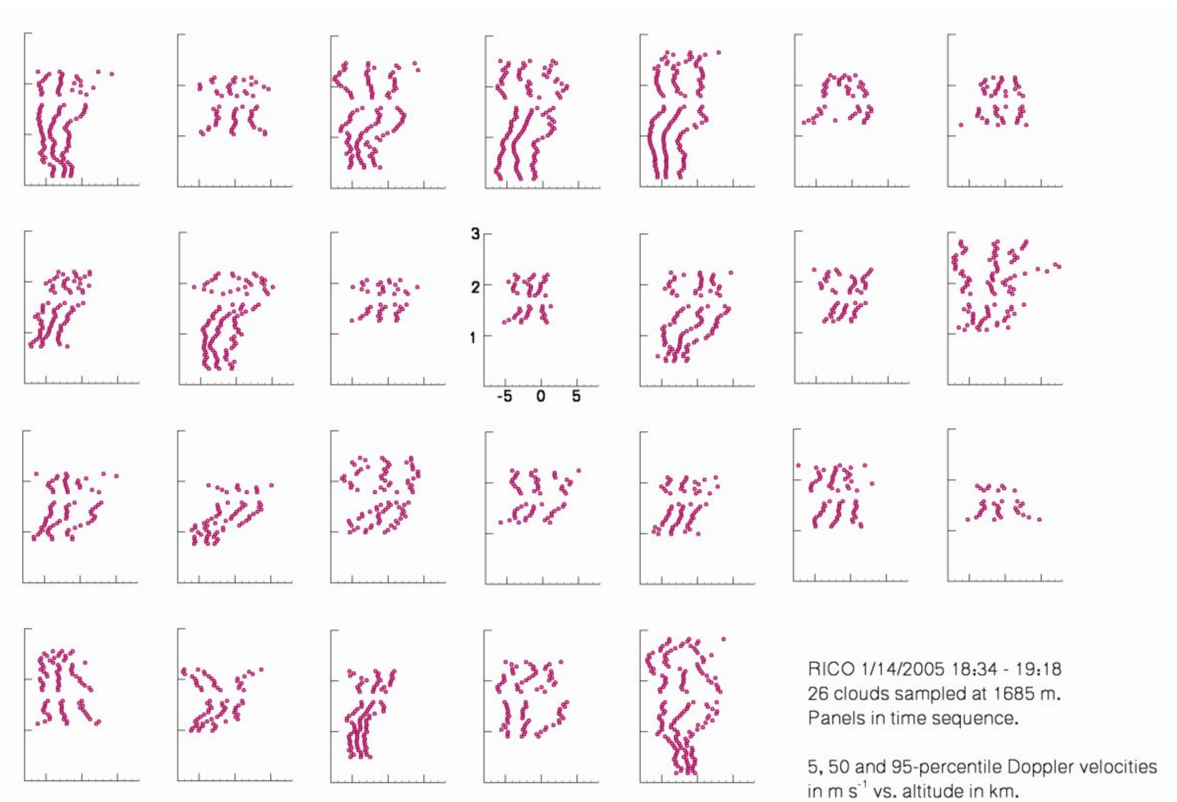
The statistics of vertical Doppler velocities are summarized in the table below in terms of the fraction of data points with velocities exceeding the given values in each of the 26 cloud segments depicted in the figures above. The means and standard deviations are:

TABLE 2.

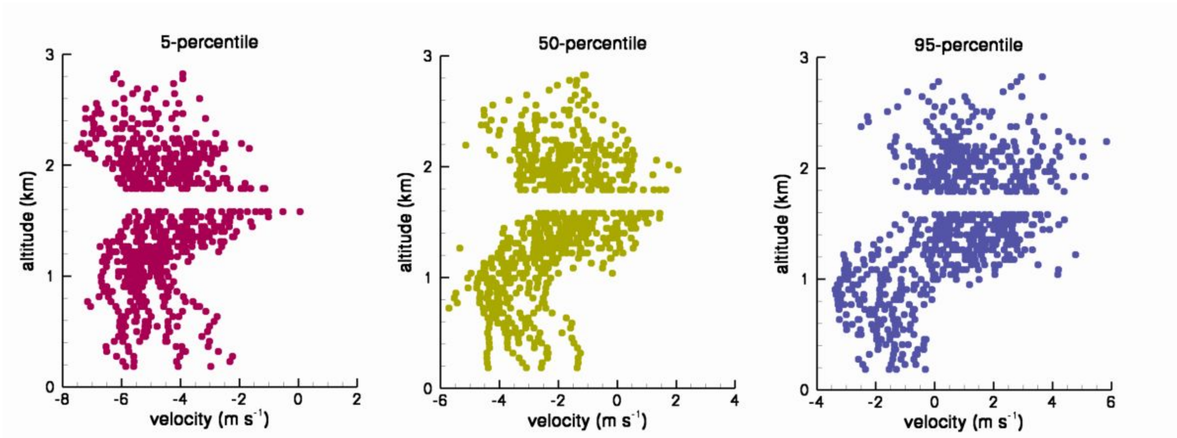
Velocity threshold (m s^{-1})	Fraction of echo (%) area (mean ± std. dev.)
-2	53 ± 20
-1	36 ± 18
0	21 ± 14
1	11 ± 8
2	4.8 ± 4.2
3	2.0 ± 1.6
4	0.93 ± 0.3

Appreciable updrafts occupy rather small fractions of the observed volume. The mean values of 1, 10, 90, 50, 90, 95, and 99-percentile Doppler velocities are: -5.8, -4.8, -4.2, -1.9, 0.62, 1.3 and 2.9 m s^{-1}. These are all roughly 3 m s^{-1} lower than the corresponding percentile values of ***w*** in the Table 1, but this is not a good indication of the contribution of fall velocities because these figures refer to all observable echo above cloud base (taken as 590 m) whereas the in situ measurements in Table 1 refer to the flight altitude only.

Profiles of Doppler velocity with altitude show a great degree of variation, as is evident in the images. Another expression of the vertical velocity profiles is given in the figure below. (Caveat: the known range-dependent bias in the Doppler velocities in these data leads to a distortion of these profiles by a few m/s at the extremes.) There are quite a few examples of increasing velocities upward, and some of the deeper clouds show changes toward positive velocities near the top, which is likely an indication of continued development.



When all samples are overlapped in a single figure, the result is a bit of a jumble, revealing only that there was precipitation below cloud base, that, in general, one can expect to find both positive and negative velocities above cloud base. This is shown in the figure on the following page.



Another aspect of the vertical velocities is evident from the radar images, namely that the shapes of the updraft regions (also considering the roughly 2 m s^{-1} bias in the Doppler velocities) are quite complex, highly fractal. In view of that it is interesting to take a quick look at the granularity of the updraft velocities.

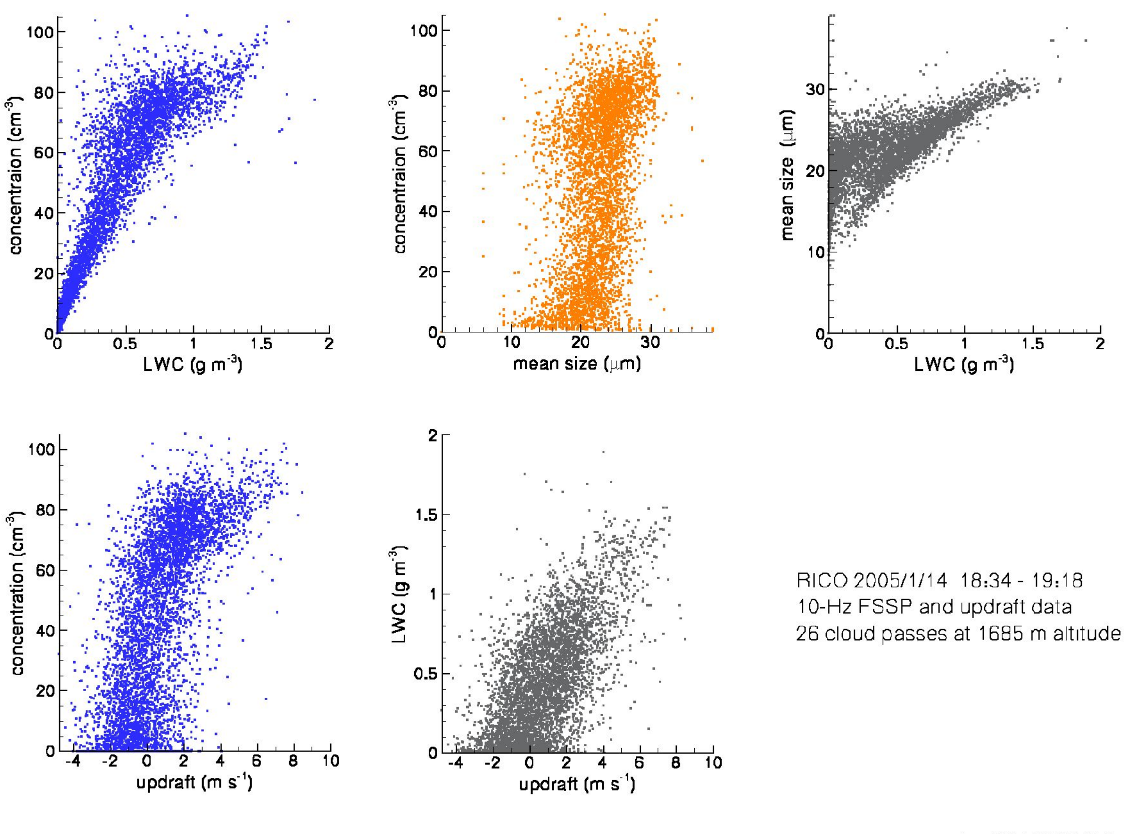
From the in situ data, of the 32% of the cloud sample (along the flight line) that had $\boldsymbol{w}$ > 2 m s^{-1}, about a third was in segments < 50 meters, and only about a third > 200 meters in length. The four longest contiguous updraft segments exceeding 2 and 4 m s^{-1} limits, in the 30 clouds sampled, were:

for $\boldsymbol{w}$>2 m s^{-1}: 432, 468, 488 and 908 meters

for $\boldsymbol{w}$>4 m s^{-1}: 136, 216, 356 and 460 meters.

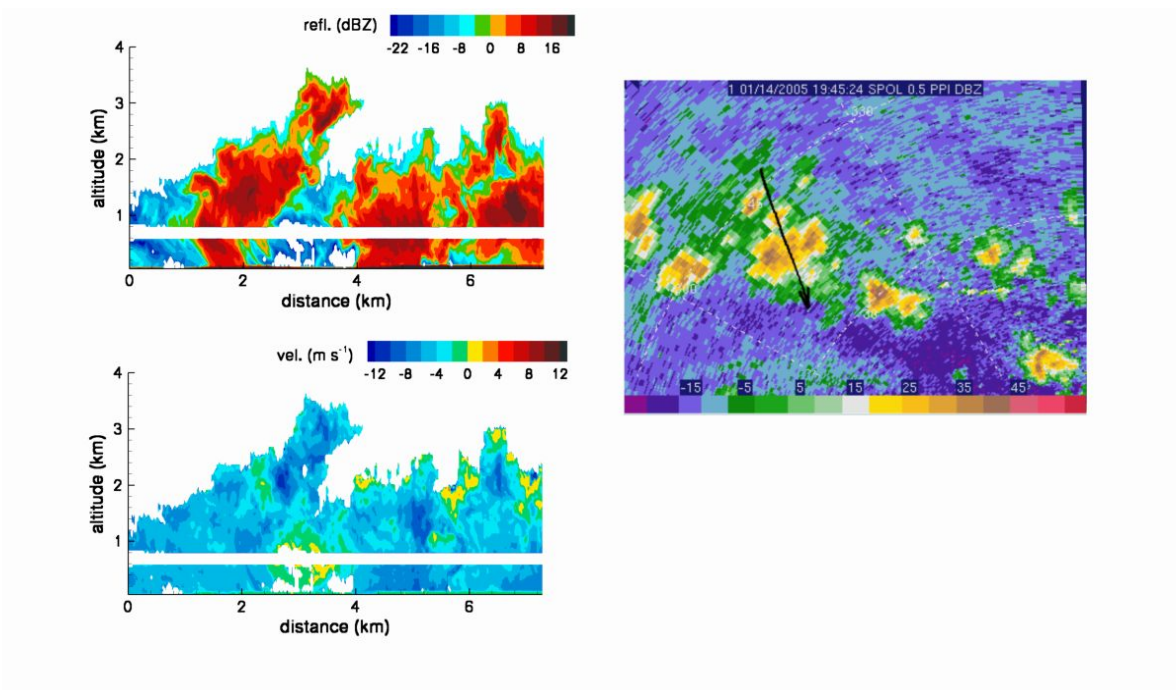
Finally, some photographs of the clouds sampled.

A quick look at some in situ data for the aggregate of all the clouds in this sequence reveals the combined roles of entrainment and scavenging by a strong correlation between droplet concentration (0 – 45 µm diameter; from the FSSP) and LWC (also from the FSSP). There is also a trend for concentration and LWC to increase with updraft velocity. As a check, the LWC from the PVM100 and from the FSSP compare with 0.94 correlation and best-fit slope of 0.915. The adiabatic LWC at this level is around 2.1 g m^{-3}.



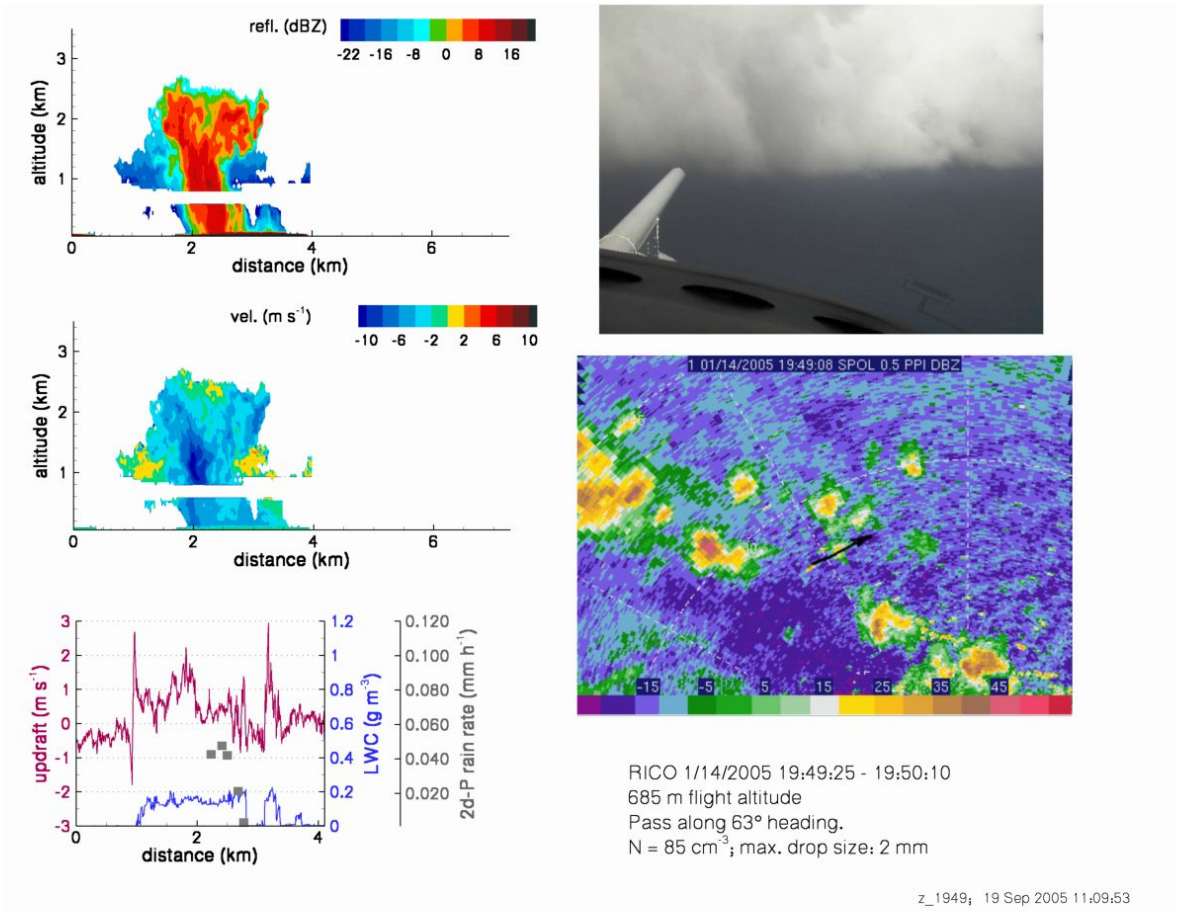
D. Roughly 19:20 to 20:20, this is the last segment of the flight plan. KA to be at 3000' and lower, i.e. cloud base and precip. sampling. Looked around briefly in the vicinity of RVSJ, but found no good targets nearby. After about 19:36 we were attempting to pick up the tracks being followed by the other two aircraft (they had good visual and TCAS contact), but there was considerable confusion due too unreliable TCAS signals and conflicting voice communications. The end result is probably little coincidence of flight tracks.

Cloud base and rain samples were obtained in a good number of passes. Two interesting examples are shown here. The first one is noteworthy for the apparent inducement of an updraft between the precipitation cores – the vertical pumping idea. This is seen in the figure below near the 3-km mark, with the updraft area tucked in between the two echoes, and this updraft has to contain some drops, evidently recirculating from the nearby rain shafts, to produce the echo near the surface.



RICO 1/14/2005 19:44:10 - 19:45:30
685 m flight altitude
Pass along 148° heading.

The second example (next page) is for a penetration <100 m above cloud base. It is interesting because it shows what appears to be a precipitating cloud still with moderate updraft throughout the base, and with sharply higher values at the cloud boundaries. The LWC profile is close to flat across most of the cloud. The 2D-C and 2D-P probes detected drops to 2 mm diameter but the calculated rainfall rate was still <0.1 mm h^{-1}. That value is a little low, but not inconsistent with reflectivity values of 10-12 dBZ from WCR.



Summary:

The plan for coordinated flights with 3 aircraft worked only to a point, in part because of the rather varied, rapidly changing and fast advecting cloud field. Definitions of sampling "lines" in terms of VOR/DMA quickly became obsolete as clouds moved away from that line and were not linearly organized to any significant extent. Only when good TCAS readings and/or visual contact allowed two aircraft to stay together was the sampling of the same cloud assured. Nonetheless, at least during the middle period (section **C**) the KA and the C130 were sampling roughly the same clouds, and there were perhaps other similar periods.

Strong winds and large instability determined the character of the clouds this day, and there was a significant impact of the mesoscale organization as well. These are complicating factors in some sense, but the large variety of clouds that developed and the opportunity to sample them at different stages of evolution, plus coincident observations by all of the RICO systems contribute to a rich data set.

Flight notes:

1625	engines started; filed 090/40 @ 11kft; will then wait for sector selection
1634	T/O
1650	11kft, passing 11 m s^{-1} updraft but then turn out before big one
1653	pass on return
1655	360 and descend to 7000'
1658	12 m s^{-1} right at cloud entry w/ high LWC; 060 hdg at 9000'
......	210 hdg to pointer, red NRE on right, SD mode
1703	updraft ahead of the pointer, right at cloud edge; jumble of soft clouds follow
1705	90/270
1708	back at pointer, red NRE; swung away from deepest part
1714	8000', pass moderate cloud
1715	no target picked yet; 030/68 is last report of position
1716	head to 030/68 at fixed 4000', as per plan, but not sure about target
1718	C130 can't get 3000' and below; negotiating space
1719	at 4000', trying to enter block of other 2 a/c
1721	can't confirm reference point with 146
1722	lots of traffic. center is very busy; 146 reports 060/66 position and E-W track from there; is that the target ???
1723	can't get clearance
1725	cleared for 030-070 segment, outside of 40; will head to 060/66
1728	checking with C130 – they're at 2500' 021/61
1729	messy cloud field
173140	at 060/66, will turn to West and pick moderate clouds along the way
1735	reverse heading
1743	near segment limit, continue to good target ahead
1745	good looking target, but no ride and little rain
174650	return pass
1748	ops center w/o radar or track – 146 lead is vague
1801	042/51
1804	042/51 target, advised C130 - they are following by TCAS
1805	turn to target, C130 following

1808 no new development under the anvil and can't see much else

1811 in rain

1812 146 will linger until new t3 is decided; they report N side of deep convection as good target

1820 arranging swap, this is t3

1822 got 5000'-7000' for KA, 4000' for C130, 2500' and below for 146; block is 360-060/ 40-70

1826 still on N flank of precip.; see no new development

1825 KA restricted to hard 5000'

1826 decide to move away from anvil shadow toward the N

1833 getting organized on new 'line'

jog to take 300 hdg; E end of 'line' to be 033/65 with 300 heading and reverse legs

183625 C130 in sight

1855 010/65 and reverse heading

191845 cld pass

1919 start altitude swap; KA to be 3000' and below

1923 swap completed,

1924 Perry has CCN in good shape again; heading to RVSJ

192827 RVSJ on our right; some doubt about having the right ship

1931 RVSJ reports position as 17:57.4 / 61:32.3 - that agrees with where we are looking

1933 more passes by RVSJ; no targets of interest – good for CCN run

1935 end of CCN run, try to pick up pattern C130 and 146 using

1936 2000' to be above cld base; aiming for 160-340 legs reported by other A/C

1939 closing in on C130 / 146 pair, according to TCAS readings

1940 unsure about where they are

1941 may be the end of line flown by them

1942 TCAS indication is that they are at other end of sampling line; we aim for good cloud bases

1948 C130 behind ???

194920 nice base ahead

194950 rain; unsure about position of other A/C

195139 rain

1954 climb to 2500'

195430 nice cloud on nose

1957 TCAS indication is that we are on track, but not convincing

1958 C130 at 053/73 and looking at cloud to E

2003 descend to sample precip at 1000'; looking for other A/C but taking best samples possible in the meantime

2028 146 coming into same cld about 20 angle to our path (KA at 4000', 146 at 5000')

2051 L/D