# Cloud boundaries and structure in mixed phase, mid-level clouds as deduced from ground-based 95-GHz radar and airborne lidar measurements during CLARE'98.

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## INTRODUCTION

For the assessment of the influence of clouds on global climate and related feedback mechanisms an accurate knowledge of macroscopic parameters of clouds like altitudes of their boundaries, number of layers, their internal structure and dominant phase is essential. Present observational methods only deliver crude estimates of these quantities. The combined use of cloud radar and lidar measurements is in the focus of current research in order to improve the retrieval of cloud parameters.
The combination of cloud radar and lidar has previously been used to obtain information on cloud boundaries, e.g. [1, 2, 3, 4], or cloud microphysical structure [5]. The studies concentrated mainly on the derivation of location and boundaries of either ice or water clouds. No systematic investigations on mixed phase clouds are available, essentially because the lidar beam often is attenuated by liquid water in the clouds. However, the examples of this study show that the complimentary information in radar and lidar data is potentially useful for research on mixed phase clouds.
The CLARE'98 campaign between 5 and 23 October 1998 at Chilbolton, UK, concentrated on the combined use of cloud radar and lidar for the detection of cloud properties of mid-level clouds. During conduced flight missions, additionally *in situ* microphysical data was obtained by instrumented aircraft for validation purposes. Here, results from the ground-based GKSS cloud radar 'Miracle' and the airborne DLR lidar 'Alex' for two case studies targeting on mixed phase clouds are presented.

## INSTRUMENTATION

In this section we briefly describe the measurement systems used for the study. A more detailed description of the instruments along with a discussion of their performance during Clare'98 is provided in respective chapters at the beginning of this report.

### *Cloud radar MIRACLE*

For the Clare'98 campaign the transportable 95-GHz cloud radar operated by GKSS, Institute for Atmospheric Physics, was set up at Chilbolton, UK.
The pulsed-Doppler radar is fully polarimetric and has a peak power of 1.7 kW. The system has been taken into operation in summer 1996. Since its capabilities cover those of a planned spaceborne system, the radar is well suited for preparatory studies for such a mission. Pulse repetition frequency (up to 80 kHz), number and location of range gates, pulse width and pulse polarisation are software selectable and allow for a range resolution between 7.5 m and 82.5 m up to a range of 15 km. The beamwidth of the center-fed Cassegrain antenna of 0.17° leads to a range cell diameter of 30 m at a distance of 10 km. Tab. 1 provides the main specifications of the radar.

*Tab. 1 Main characteristics of the MIRACLE cloud radar.*

| | |
|---|---|
| Transmitter | EIA (klystron) |
| Frequency | 95 GHz (3.2 mm) |
| Peak power (EIA) | 1.7 kW |
| Pulse repetition frequency | 50 Hz – 80 kHz |
| Pulse width | 50 – 550 ns |
| Antenna diameter | 1.2 m |
| Beamwidth (3dB) | 0.17° |
| Antenna gain | 60 dB |
| Transmit polarization | lin. horizontal and vertical |
| Dynamic range | 70 dB |

The real-time data products include, beside reflectivities, polarimetric quantities (ZDR, LDR, ρ) and the first three moments of the Doppler spectrum (total power, mean velocity, velocity variance) derived by the pulse pair algorithm or an up to 1024 point FFT full spectrum analysis. The minimum sensitivity at an altitude of 1 km and 1 s integration is about -40 dBZ. The GKSS radar is currently used for a variety of studies related to the structure and properties of layer clouds, e.g. [6, 7, 8].

The system has been internally calibrated and operated simultaneously with the externally calibrated Cloud Profiling Radar Sytem (CPRS) [9]. The absolute error of the derived reflectivities was found to be less than 3 dB. This value was confirmed by recent comparisons with in situ forward scattering spectrometer data obtained over Geesthacht from simultaneous measurements in pure water clouds. Cross-calibration with the calibrated CAMRa (3 GHz), 'Rabelais' (35 GHz), and 'Galileo' (94 GHz) radars at Chilbolton suggested a difference of 2 dB to 'Miracle' [10], which has been corrected for in this study.
For the determination of cloud boundaries a cloud mask scheme based on probability decisions for running 5x5 pixel matrices was used in order to separate cloud signals from those produced most probable by noise. A comprehensive description of the radar is provided in [11], the system performance and data products with respect to Clare'98 measurements are summarised in [12].

*Backscatter lidar ALEX*

During Clare'98 the lidar system ALEX was installed onboard the FALCON 20 of the DLR, Oberpfaffenhofen. It was operating in a downward looking mode.
The 3 wavelengths lidar makes use of a Nd:YAG laser emitting at 1064nm. Frequency doubling and tripling provides 532nm and 354nm channels. The received 532nm signal is split into the two perpendicularly polarised portions which allows to calculate the depolarisation of the light. With a repetition rate of 10Hz for typical aircraft speed of 150m/s the raw data resolution is about 15m horizontally and 12m vertically. However, to improve the S/N ratio the compromise between signal noise and resolution leads to a respective processed data resolution of some 100m/some 10m horizontally/vertically. The receiver is a Cassegrain telescope (r = 17.5cm) with 1mrad field of view. Technical aspects concerning ALEX are given in [13], the performance of the lidar system and the other FALCON instruments during the Clare'98 campaign is described in more detail in [14]. Main characteristics of ALEX are provided by Tab. 2.

*Tab. 2: Main characteristics of the ALEX lidar.*

| | |
|---|---|
| Transmitter | Nd:Yag-laser |
| Wavelengths | 1064, 532, and 354 nm |
| Pulse energy | 150 mJ at 1064 and 354 nm<br>120 mJ at 532 nm |
| Pulse repetition rate | 10 HZ |
| Pulse length | 6 ns |
| Beam divergence | 0.7 mrad |
| Telescope diameter | 35 cm |
| Field of view | 1 mrad |
| Receive polarisation | horizontal and vertical |

The lidar directly measures atmospheric backscatter which is either given absolutely as backscatter coefficient [$m^{-1}sr^{-1}$] or relative to Rayleigh scattering (calculated from air density) as backscatter ratio ($\beta_{particle}$ + $\beta_{molecule}$)/$\beta_{molecule}$, the relative contribution of particle scattering to the total signal. The attenuation of the laser beam in the atmosphere is considered employing a numerical inversion whereby an extinction/backscatter ratio (lidar ratio) and a starting value at some distance from the receiver has to be assumed to iteratively derive the profiles. With the inferred lidar ratio the extinction coefficient and its integral, the optical depth, can be estimated from the backscatter signal [15]. The ratio of the orthogonal and parallel (to the incident beam) polarised 532nm signals $\beta_\perp / \beta_\|$ i.e. the depolarisation of the light by the scattering particles can be used directly to obtain information about their sphericity. A volume depolarisation of 1.4% occurs if only the unsymmetrical air-molecules contribute to the depolarisation. If depolarising (non-spherical, solid) particles are within the measured volume the volume-depolarisation is between 0.014 and 1 depending on the concentration and shape of the scattering particles. Clouds with *only* spherical (liquid) particles may cause volume-depolarisation ratios below 1.4% since they increase only the intensity in the parallel channel.

## MEASUREMENTS AND RESULTS

The measurements presented here were obtained on two days, 20 October and 21 October, 1998, during the Clare'98 campaign. These days were chosen because simultaneous radar, lidar and in situ observations are available for mixed phase mid-level clouds. The four overpasses of the Falcon over the radar site (co-ordinates: –1.4367E, 51.1444N) selected for analysis are listed in table 3, which in addition provides the lidar ratio used for the data inversion.

*Table 3: Date, time, position, and applied lidar ratio for selected passings of the Falcon over the radar site. The position difference is given in meters as indicated by the navigation system of the Falcon relative the ground site co-ordinates.*

| Date | Time UTC hh:mm:ss | relative position of Falcon | applied lidar ratio |
|---|---|---|---|
| 20 Oct.1998 | 14:20:29 | 170 m south | 15 |
| 20 Oct.1998 | 14:32:53 | 40 m south | 11 |
| 21 Oct. 1998 | 10:19:03 | 220 m south | (170)* |
| 21 Oct. 1998 | 10:49:54 | 50 m south | 25 |

* qualitative lidar-inversion due to strong attenuation

Lidar backscatter coefficients (ß) presented here are corrected for extinction. Shown radar reflectivities are not corrected for atmospheric attenuation, but estimates of the respective values are provided.

*Case 20 October 1998:*

On October 20 fronts were approaching from south west with strengthening south westerly winds. Fig. 1 shows a NOAA-AVHRR composite image for 14:55 UTC. At this time the experimental area (Chilbolton is marked by a cross) is fully

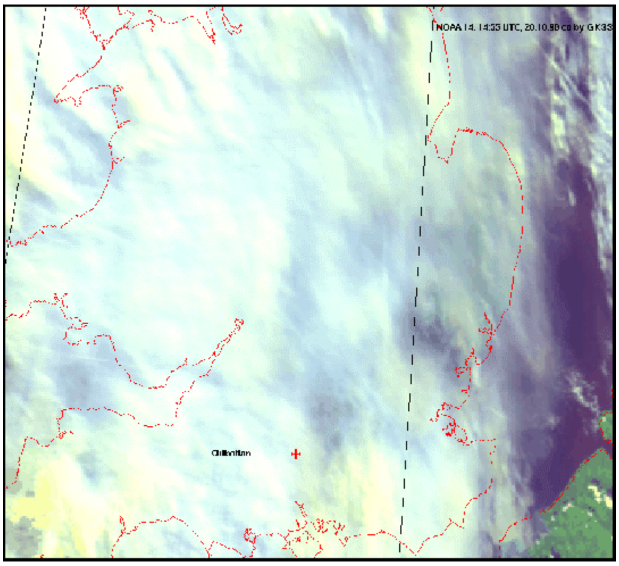


*Fig. 1: 14:55 UTC 20 October 1998 satellite image from NOAA-14. Composite of channels 1,2, and 4, red cross marks Chilbolton.*

covered by clouds. The passive instrument onboard the satellite indicates the presence of thin high level cirrus above lower level clouds.

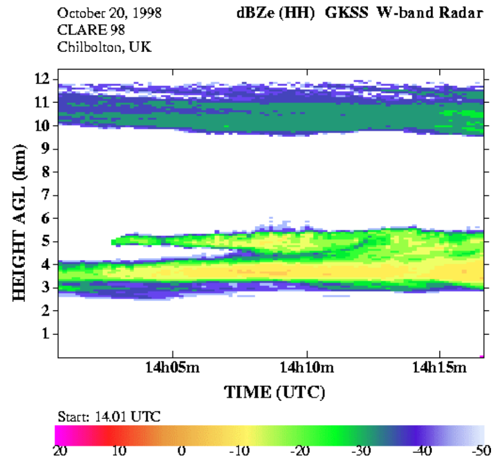
MIRACLE radar measurements on this day started at 7:53 UTC and ended at 17:16 UTC. Backscatter coefficients from ALEX are available for 9:25 to 10:50 UTC and 12:43 to 14:55 UTC (2 flights).

The inspection of the radar data revealed the changing appearance of the clouds during the day. In the morning low-level clouds dominated with occasionally thin cirrus above. At about 13:00 UTC the upper level clouds thickened followed by a layer of mid-level cloud which developed into an extended altostratus during the course of the day (from about 4 to 11 km in the later afternoon). The mid-day change in cloudiness can also be seen in Fig. 1, it is marked by a band of lower clouds east of Chilbolton.

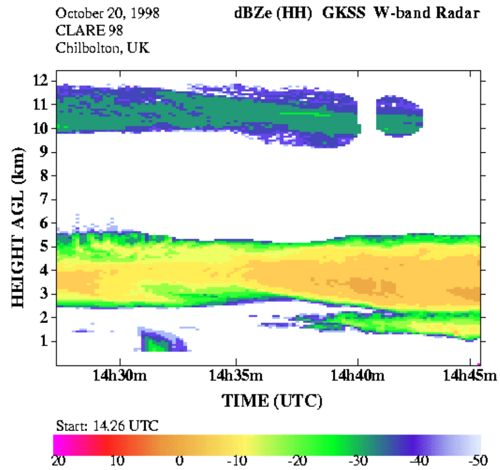
Fig. 2 a) and b) shows radar reflectivities from 14:01 to 14:45 UTC covering the time period of the selected overpasses of the lidar. The mid-level clouds appear in the radar data at altitudes between about 2.5 and 5.5 km and have typical reflectivies ranging from 0 $dBZ_e$ to –20 $dBZ_e$. The two-way attenuation by gases at 95 GHz calculated (by R. Hogan) from data diagnosed by the UK Met. Office Unified Model added up to about 2 dB at an altitude of 5 km. The given reflectivities are not corrected for this effect.

As can be seen in figure 2 a), the mid-level clouds first appeared in two well separated layers which later merged into more or less one layer by keeping the layer signature up to about 14:35 UTC. Doppler data for the time period (not shown here) reveals downward velocities of about -0.5 $ms^{-1}$ in the upper layer and values around –1 $ms^{-1}$ and slightly higher for the lower layer.

An upper level ice cloud with maximum reflectivies below -20 $dBZ_e$ is also visible in the radar data between altitudes of 10 and 12 km.




a)




b)

*Fig.2: Height-time cross-section of equivalent radar reflectivities in $dBZ_e$ for time segments a) 14:01 to 14:17 UTC and b) 14:26 to 14:45 UTC on 20 October 1998.*

The corresponding lidar data is shown in Fig. 3, which displays the backscatter ratio at 532nm and 1064 nm as well as the depolarisation at 532 nm along flight leg 11 of the Falcon (second flight). Around the time when the Falcon overflew the radar site (at 14:20:29 UTC) the lidar detected a cirrus layer between about 9.5 km and 12.5 km. Below the cirrus 3 thin layers appear in the lidar data between 4 and 5.5 km, where the radar measurements suggest a continuous, (although structured) cloud layer. Radar reflectivity and lidar backscatter coefficient profiles for the overpass are directly intercompared in Fig. 4. The altitudes are given with respect to sea level, their accuracy is estimated to be about ±30 m. The lidar profile is averaged for 1 s which can be converted to a horizontal cloud scale of 218 m using the true airspeed of the aircraft. The radar data has been averaged over 9 s in order to match the spatial scale of the lidar data at an altitude of 4 km. Here, the time-space conversion used the horizontal wind measurements obtained by the UK Met. Office Hercules aircraft. For the displayed time segment the radar was operated in FFT-mode, with a resulting limited range window [12] which was set between 2.8 and 5.2 km (resolution: 37.5m). Comparison of the profiles in the overlapping height

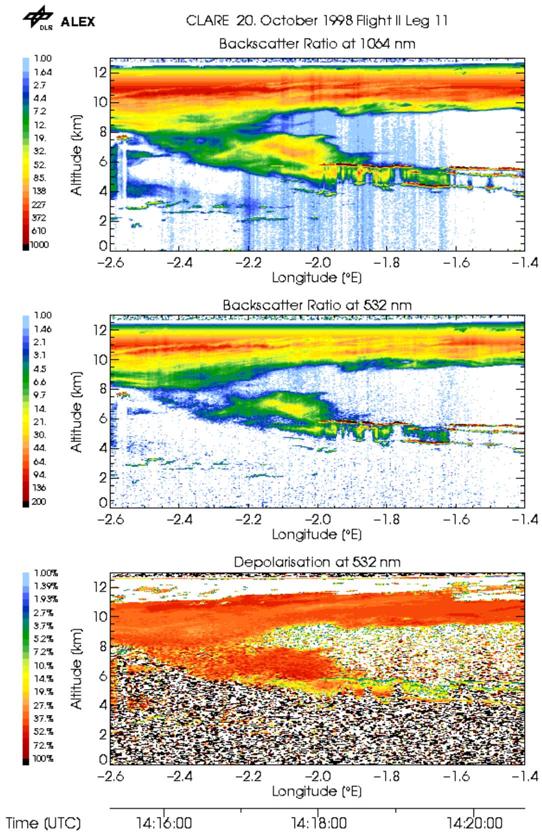



*Fig. 3: Lidar backscatter ratio at 1064 nm, 532 nm and the depolarisation ratio at 532 nm as measured by ALEX along flight leg 11 of the Falcon.*

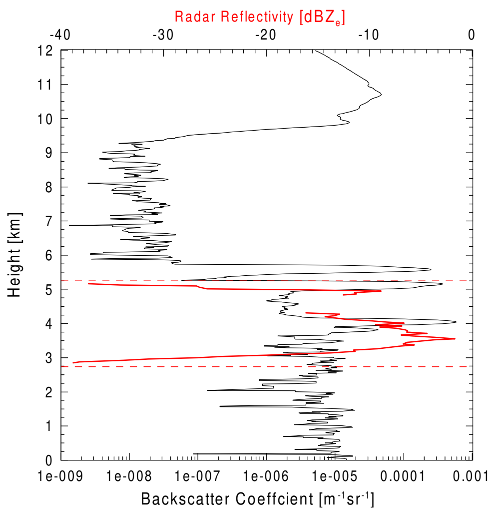



*Fig. 4: Vertical profiles of radar reflectivity (red) and lidar backscatter coefficient for 1064 nm (black) at 14:20:29 on 20 October 1998. The lidar data has been averaged over 1 s (about 218 m), the radar data was averaged over 9 s to represent the same spatial scale.*

band reveals the different cloud signature for the sensors. The lidar detected two narrow, well separated peaks. The radar profile shows also two peaks, of which the lower peak is much broader and maximum values occur well below the corresponding lidar peak. The gap in the radar data between 4.3 and 4.8 km is due to noise effects [12]. The lidar signal probably experienced strong attenuation along the path through the thin layers, as an inspection of neighbouring time segments in Fig. 3 suggests, and therefore could not detect the weaker signals from in between and below them. The thin layers did not appear as a clearly distinguishable feature in the radar data.

The differences between the profiles are due to the different microphysical characteristics of individual parts in the cloud region affecting the scattering properties and attenuation. In Rayleigh approximation the radar signal is proportional to $D^6$, while the lidar signal is proportional to about $D^2$, with D denoting the diameter of the scattering particles. The phase of the particles plays a role for signal attenuation. It is assumed that the extended thin layers detected by the lidar consisted of liquid water droplets while the rest of the cloud consisted of larger ice crystals dominating the radar backscatter. As can be seen in Fig. 3, the depolarisation of the lidar signal around 14:20 UTC was very low in the 3 layers suggesting that the relevant scatterers for the lidar tended to be mainly spherical particles. Depolarisartion ratios of less than 10 % were found. Due to sensitivity limitations, linear depolarisation ratios measured by the radar only indicate the presence of crystals in the lower part of the cloudy region (cross-pol. isolation is 26 dB). There is no evidence for a decreased LDR around the height of the lowest lidar peak at 4 km. This might be an indication for the coexistence of liquid water and ice at this

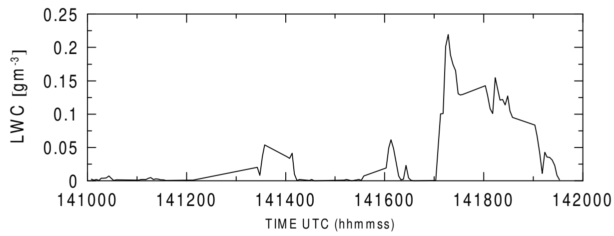



*Fig. 5: Liquid water content (LWC) as measured with the Johnson-Williams Liquid Water probe of the Hercules along flight leg 9.1. on 20 October 1998.*

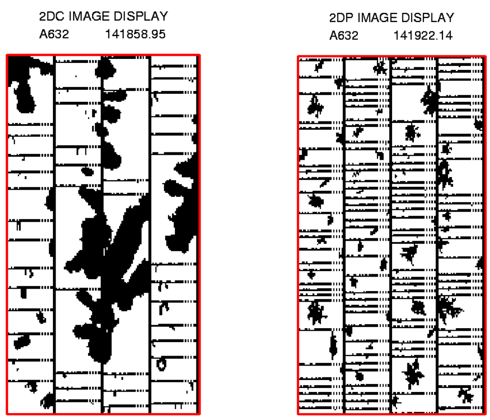



*Fig. 6: Examples of particle images from the OAP-2-DC (left) and OAP 2-DP probe (right) onboard the Hercules during the overpass at about 14:20 UTC on 20 October 1998.*

height level. This aspect is confirmed by *in situ* mircophysical measurements made with probes installed on the Hercules C-130, which passed Chilbolton at 14:19:53 UTC at an altitude of 4 km and detected ice as well as liquid water. The liquid water content measured with the Johnson-Williams liquid water probe along flight leg 9.1 of the Hercules is given in Fig. 5. In parts of the cloud the liquid water content exceeded 0.1 $gm^{-3}$.

The super-cooled liquid layers do not appear as discernible peaks in the radar signals because the droplets were probably very small (an indication for small droplets is the large difference between Johnson-Williams derived LWC and PMS 2D-probe habit derived LWC, not shown here). The radar signal is mainly produced by the ice component of the cloud, which contained fairly large particles. The radar beam might have been slightly attenuated by the liquid water droplets. Typical two-way attenuation is 10 dB/km per $gm^{-3}$.

Fig. 6 shows examples of particle images from the PMS OAP-2-DC (nominal size range: 25 to 800 µm) and OAP 2-DP (nominal size range: 0.2 to 6.4 mm) probes onboard the Hercules. It can be seen that quite large particles were present in the lower cloud layer, some of the ice crystal had sizes up to a few millimetres. The effective radius derived from these measurements varies between about 60 and 80 µm around this overpass.

The direct comparison of radar reflectivity and lidar backscatter coefficient profiles for the overpass at 14:32:59 UTC is shown in Fig. 7. At this instance the radar was profiling the entire troposphere and a signal from the upper level cirrus layer with reflectivities around –30 $dBZ_e$ was also received. At mid-level again the two dominant narrow peaks in the lidar data between 4 and 4.5 km are not an obvious feature in the radar profile, which received signals from a much thicker layer. The lidar obtained also signals from the probably ice dominated part of the cloud between 4.5 and 5.3 km. For the mid-level layer the cloud top detected by the lidar

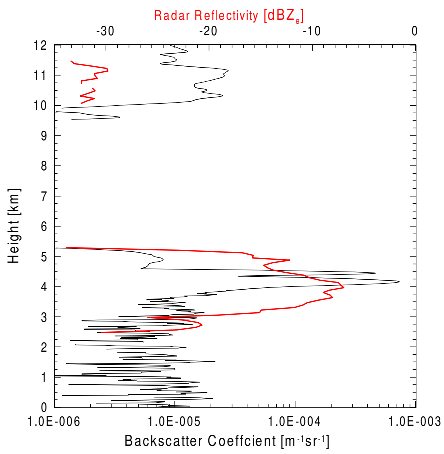



*Fig. 7: Vertical profiles of radar reflectivity and lidar backscatter coefficient (1064 nm) at 14:32:53 on 20 October 1998. The lidar data was averaged over 1 s (about 212 m), the radar data was averaged over 8 s in order to match the spatial scale.*

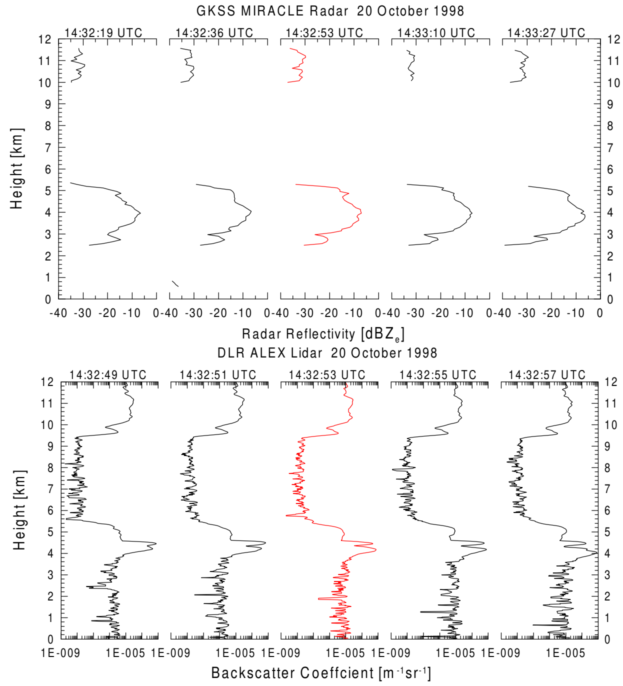



*Fig. 8: Five consecutive profiles of equivalent radar reflectivity and lidar backscatter coefficient (1064 nm) for the overpass at 14:32:53 UTC on 20 October 1998. Different times are selected for corresponding radar and lidar profiles to partly account for the relative movement of aircraft and clouds.*

is placed about 100 to 200m above that of the radar when lidar signals down to $10^{-8}$ $m^{-1}sr^{-1}$ are considered. Exact matching is not expected due to sampling of slightly different locations. Due to attenuation the base region, which extended down to about 2.5 km, and its structure is not resolved by the lidar. Fig. 8 compares 5 consecutive profiles (averaged horizontally over 212 m) of radar reflectivities and lidar backscatter coefficients around the overpass time. It can be seen that the lowest lidar peaks, which are again associated with a thin, presumably liquid layer, decrease in altitude, while the radar peaks stay almost at a constant height. This

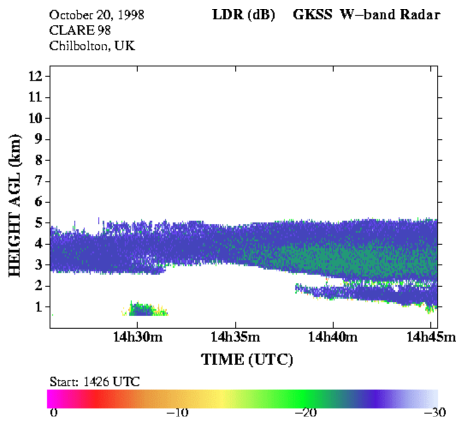



*Fig. 9: Linear depolarisation ratio (LDR) as measured by MIRACLE from 14:26 to 14:45 UTC on 20 October 1998.*

could be an indication that the liquid layers might have been detached from the rest of the cloud.

Inspection of the lidar derived depolarisation again provides the tendency of low values for the thin layers pointing toward a dominance of the liquid phase. LDR values measured by the radar around the overpass at 14:32:53 UTC shown in Fig. 9 are quite small but indicate the presence of non-spherical particles up to an altitude of about 5 km. Above this height the sensitivity limit of the cross-pol channel was reached. There is no structure in LDR data which would support the dominance of spherical particles, where the lidar detected the thin layers.

Doppler velocities from the radar for this time segment show an increase by about 0.5 $ms^{-1}$ for the layer between about 3.5 and 4 km (just below the lowest lidar peak) pointing to the presence of larger particles. Whether the lowest radar signals mark the cloud base or are caused by some falling larger particles stays open.

In conclusion it can be stated that without the lidar there would have been almost no indication for the liquid layers. On the other hand in case of strong attenuation the lidar could not penetrate to the cloud base area, on which information can be obtained from radar data.

*Case 21 October 1998*

Behind a cold front passing by on 21 October at about 9:00 UTC low clouds broke up, they were followed by midlevel clouds approaching in a strong south westerly flow. According to the radar measurements these midlevel clouds disappeared after 11:15 UTC. The NOAA-15 image from 8:19 UTC (Fig. 10) shows the less cloudy air mass approaching behind the cloud band associated with the passing cold front.

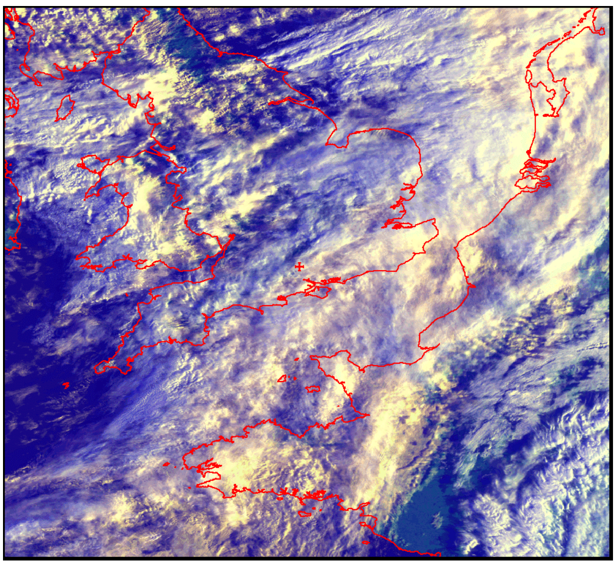
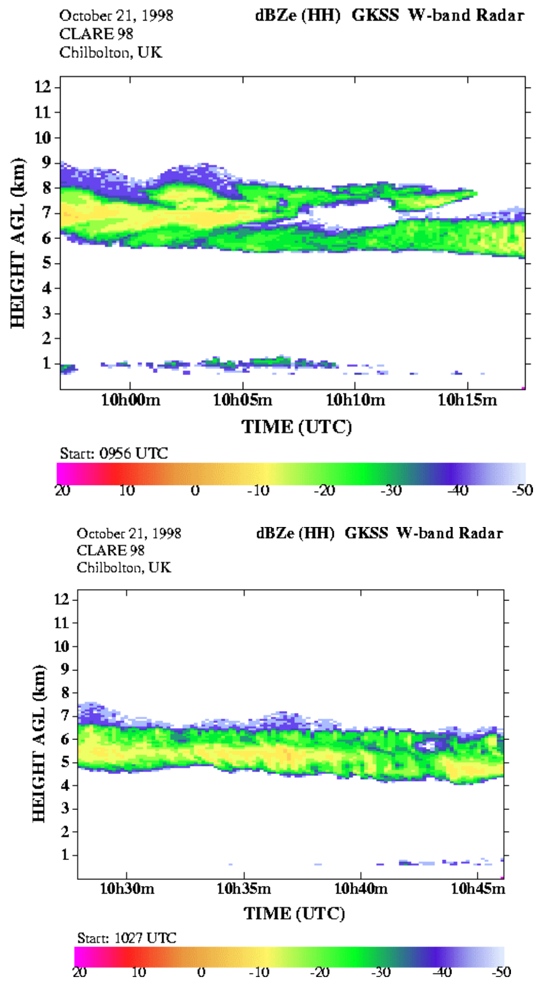


*Fig. 10: 8:19 UTC 21 October 1998 satellite imagery from NOAA-15. Composite of channels 1,2, and 4, red cross marks Chilbolton.*

a)




b)

*Fig.11: Height-time cross-section of equivalent radar reflectivities in $dBZ_e$ for time segments a) 9:56 to 10:17 UTC and b) 10:27 to 10:46 UTC on 21 October 1998.*

The radar was operating from 9:34 UTC to 11:37 UTC, the lidar gathered data between 9:57 and 10:50 UTC.

As can be seen in figure 11 a) and b), in which the radar reflectivities for the time periods around and respectively just before the discussed overpasses are displayed, the cloud altitude as well as the thickness of the upper cloud layer decreased with increasing time. Cloud top sank from 9 km to about 6 km. Typical radar reflectivities ranged between –10 $dBZ_e$ and –25 $dBZ_e$. Also some thin low level clouds are visible in Fig. 11.

Fig. 12 provides lidar profiles along leg 4 of the Falcon on this day. The backscatter returns show the elevated mid-level cloud layer as well as the lower level clouds. Again thin band-like structures can be seen in the midlevel clouds.

The direct comparisons between the radar and lidar profiles for the overpasses at 10:19:03 UTC and 10:49:54 UTC are plotted in figures 13 and 14 respectively. At 10:19 UTC the 500 m thick cloud layer around 6.7 km seen by the lidar, which attenuates its beam totally, is only barely detected by the radar. The maximum radar reflectivities occur about 1 km lower at 5.5 km. Either the lidar data or the radar data alone would lead to totally different statements on the cloud layer

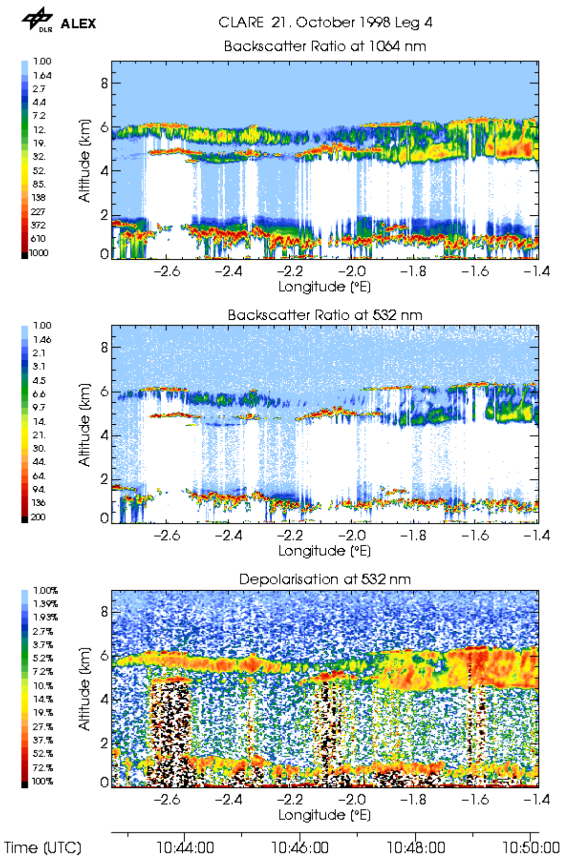



*Fig. 12: Lidar backscatter ratio at 1064 nm, 532 nm and the depolarisation ratio at 532 nm as measured by ALEX along flight leg 4 of the Falcon on 21 October 1998.*

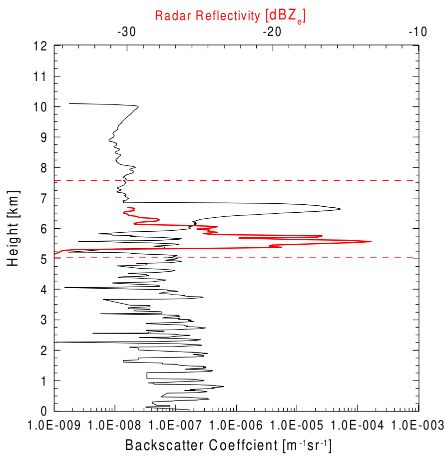



*Fig. 13: Vertical profiles of radar reflectivity and lidar backscatter coefficient (1064 nm) at 10:19:04 on 21 October 1998. The lidar data has been averaged over 1 s (about 175 m), the radar data has been averaged over 6 s in order to match the same spatial scale. Red dashed lines mark the range window for the radar.*

and its boundaries. The situation altered at 10:49:54 UTC (Fig. 14), here the radar and lidar detected almost the same macroscopic structure and estimates of cloud boundaries would agree better. An indication for layer separation is shown in both data sets at an altitude of 5.6 km. Small scale

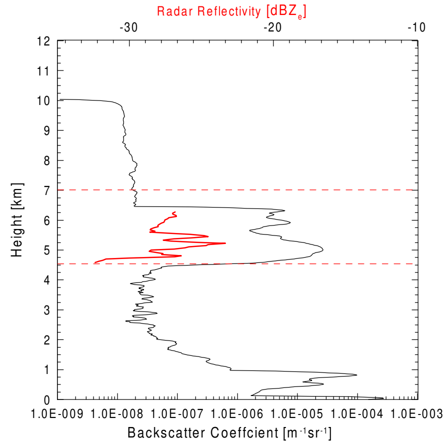



*Fig. 14: Vertical profiles of radar reflectivity and lidar backscatter coefficient (1064 nm) at 10:49:54 on 21 October 1998. The lidar data has been averaged over 1 s (about 185 m), the radar data was averages over 6 s in order to match the spatial scale. Red dashed lines mark the range window for the radar.*

features (about 100 m) in the profiles show a different behaviour. Again, a close matching is not expected, because of spatial differences as well as the distinct scattering properties for the different wavelengths used. By this time the cloud has become weaker, maximum radar reflectivities were less than –23 $dBZ_e$, (no correction applied for attenuation by liquid water in the low level cloud and by water vapour; two-way about 2.6 dB at 5 km). And the signature of a thin super-cooled liquid layer in the lidar data was not that evident any more (less pronounced and broken; see Fig. 12). The Hercules sampled microphysical data at an altitude of about 5.7 km and detected little liquid water at that height level (LWCs below 0.005 $gm^{-3}$), where it obviously did not penetrate a liquid layer. Ice crystal sizes were smaller at this level, compared to those found around the 14:20 UTC overpass in the 20 October case. Largest particles had sizes of about 1 millimetre, the effective radius varied between 40 and

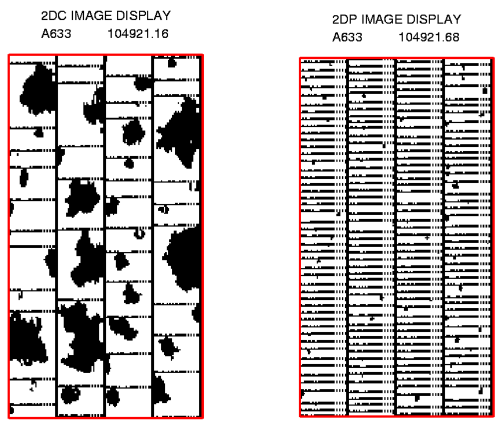



*Fig. 15: Examples of particle images from the OAP-2-DC and OAP 2-DP probe onboard the Hercules during the overpass at about 10:49 UTC on 21 October 1998.*

60 µm. Typical examples of optical array probe images for the Hercules overpass at about 10:49 UTC are provided in Fig. 15. The fewer big particles along with a lower IWC (not shown here) at this overpass time explain the lower radar reflectivities. Here, due to the absence of a strong attenuating liquid layer the lidar could penetrate to the cloud base. Since radar and lidar derived almost the same base heights, it can be assumed that the base region was not dominated by a few big falling particles.

## SUMMARY AND CONCLUSIVE REMARKS

Ground based cloud radar measurements and co-located airborne lidar measurements of mid-level, mixed phase clouds sampled during Clare'98 were analyzed and compared. In general, the two instruments highlighted different features of the clouds, which can be explained by their different sensitivities to particle size distributions and signal attenuation.

The complimentary information on cloud boundaries and cloud structure, revealed the usefulness of co-located cloud radar and lidar measurements. Only the combined use of the instruments could uncover the complete appearance of the mixed phase clouds with embedded thin layers of super-cooled liquid water and fall streak areas below cloud base. In the absence of the mentioned features the radar and lidar profiles led to almost the same conclusions concerning cloud boundaries.

The detected phenomena are of great interest for the parameterization of mixed phase clouds in numerical models. A major question is, how often this kind of super-cooled layers occur, since they will strongly influence the radiative transfer through the clouds. Systematic information on the extension of fall streak areas and their frequency of occurrence in conjunction with mid-level clouds would support research on the life-cycle of this cloud type.

A cloud radar and a backscatter lidar on a spaceborne platform would allow to derive such information for larger areas and different geographical regions.

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