Polarimetric radar observations of the growth of highly-aligned ice crystals in the presence of supercooled water

Robin J. Hogan*, **Anthony J. Illingworth and Paul R. Field**†

Department of Meteorology, University of Reading, UK
†**Meteorological Research Flight, DERA, Farnborough, UK**
***Email: R.J.Hogan@reading.ac.uk**

ABSTRACT

In this paper, observations by a Rayleigh-scattering S-Band radar are presented of high values of differential reflectivity (up to 6 dB) in stratiform ice clouds, and are shown to coincide with the presence of supercooled liquid water. By contrast differential reflectivity tends to be much lower (less than 0.5 dB) when no liquid water is present. Because liquid droplets are too small to contribute significantly to the radar signal themselves, the indication is that ice crystals in a highly supersaturated environment tend to grow very aspherical (aspect ratios in excess of 10:1), whereas under the more usual low-supersaturation growth conditions they tend to remain more spherical (aspect ratios generally less than 2:1). Aircraft 2D-probe observations indicate that under usual conditions ice crystals tend to be irregular although not highly aligned, which suggests that the normal growth mechanism (for the larger crystals at least) is aggregation and it is only when liquid water is present that vapour deposition can dominate.

THEORY

Differential reflectivity (Z_{DR}) is defined as the ratio of radar reflectivity factor measured at horizontal and vertical polarisations, and is usually expressed in logarithmic units:

$$Z_{DR} = 10\log_{10}\left(\frac{Z_H}{Z_V}\right) \text{ dB}.$$

It is a measure of hydrometeor alignment in the pulse volume, and in rain can be directly related to mean size because of the unique relationship between raindrop size and shape. In ice its interpretation is much more ambiguous because ice crystals occur in a multitude of different shapes and sizes. It also varies with density, and at sizes greater than around 100 µm inclusions of air mean that ice crystals can no longer be regarded as being composed of solid ice. Furthermore, it is known that the longest axes of free-falling crystals usually tend to be aligned in the horizontal (e.g. Liou 1986), but any deviation from this behaviour will result in a lower Z_{DR} for a given aspect ratio and density.

Figure 1 shows Z_{DR} as a function of ice-air ratio for homogeneous oblate spheroids with a variety of different aspect ratios, calculated using an extension to Rayleigh theory developed by Gans (1912). Note that Z_{DR} is not directly related to size, but size can have an indirect effect because larger crystals tend to be less spherical (Auer and Veal 1970) and have a lower density (Brown and Francis 1995).

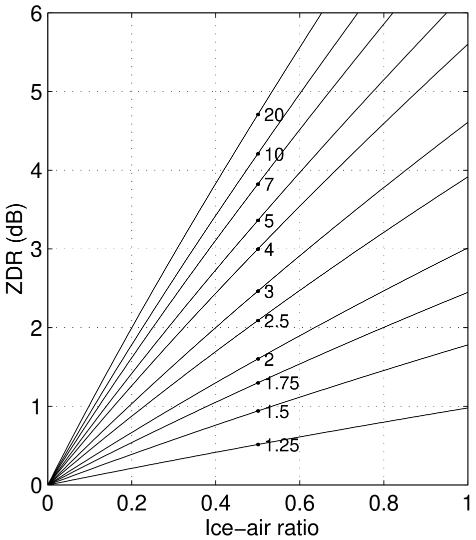

Fig. 1: Z_{DR} as a function of ice-air ratio for single horizontally-aligned oblate spheroidal crystals with various aspect ratios.

Mostly the Z_{DR} of cirrus and mid-level cloud at Rayleigh-scattering frequencies ranges between 0 and 0.5 dB, indicating that the crystals are not highly aligned. Simultaneous aircraft 2D probe and radar observations by Hogan (1998) in cirrus confirmed that in such situations the particles are irregular polycrystals that fall with their longest axes in the horizontal, resulting in positive but small Z_{DR}.

Observations of high values of Z_{DR} at temperatures down to -10°C have been presented in the literature, although all are in strongly convective systems (associated with values of Z often well in excess of 30 dBZ) and have been shown to be caused by small numbers of very large supercooled raindrops carried up in strong updraughts (Illingworth et al. 1987). However, high values of Z_{DR} are also observed in relatively quiescent stratiform clouds at temperatures lower than -10°C, for which another explanation is required.

To understand the observations presented in the following section, use will be made of Fig. 2, which shows the crystal habits that tend to grow as a function of temperature and supersaturation.

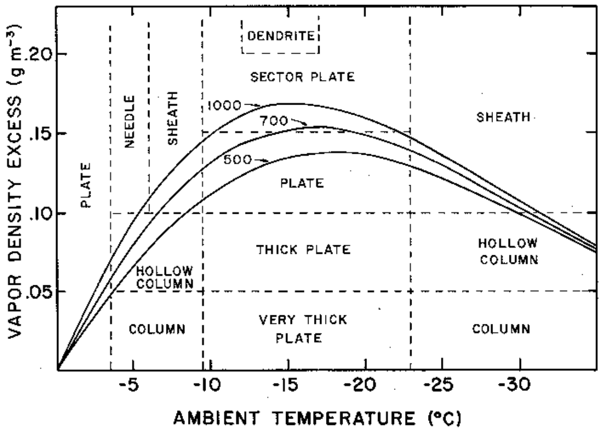

Fig. 2: The habits attained by large ice crystals growing by vapour deposition as a function of temperature and the vapour density excess between the environment and the crystal surface. The vapour density excesses corresponding to water at 100 mb, 700 mb and 500 mb are shown to indicate the types of crystal that will grow if there is supercooled water present. From Young (1993).

OBSERVATIONS

Results are presented from two case studies in which high Z_{DR} was observed by the Chilbolton radar while simultaneous aircraft measurements indicated the presence of supercooled liquid water in the same location.

CLARE'98 case study on 20 October 1998

The first event took place on 20 October 1998 during the Cloud Lidar And Radar Experiment (CLARE'98), and is summarised in Fig. 3. The first panel depicts backscatter coefficient (β) as measured by the nadir-pointing ALEX lidar on board the DLR Falcon aircraft. Thin layers of high β can be seen embedded in the mid-level cloud, and the low depolarisation of these layers as shown in the second panel indicates that they are supercooled water. The temperature of the highest layer is around $-15°$C. The third panel shows Z as measured by the scanning 3 GHz radar at Chilbolton, and the fourth shows the corresponding Z_{DR}. The cirrus above 9 km is largely below the sensitivity limit of the radar. There is no sign of the supercooled layers in the reflectivity field because the radar signal is dominated by the contribution from the much-larger ice crystals. However Z_{DR} is observed to rise to 6 dB in the vicinity of the layers, indicating a distinct change in ice growth behaviour. The UK Meteorological Office C-130 aircraft was making in situ microphysical measurements at an altitude of 4 km, where the temperature was $-7°$C, and the last panel shows liquid water content (LWC) measured by the Johnson-Williams probe and ice water content (IWC) measured by the 2D cloud and precipitation probes.

LWC is seen to rise to 0.2 g m^{-3} directly beneath the region of highest Z_{DR}. There is a suggestion of layers in the lidar echo at the altitude of the C-130 that coincide with the measurements of liquid water, although strong attenuation by the layers above mean that the signal is very weak. After this run the C-130 performed two further inbound and outbound runs, at 4.6 km ($-10°$C) and 5.5 km ($-15°$C), but by the time it had as-

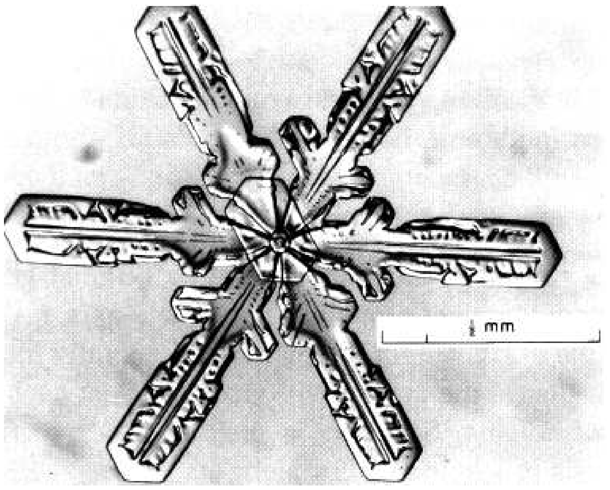

Fig. 4: Photograph of a sector plate. From Young (1993).

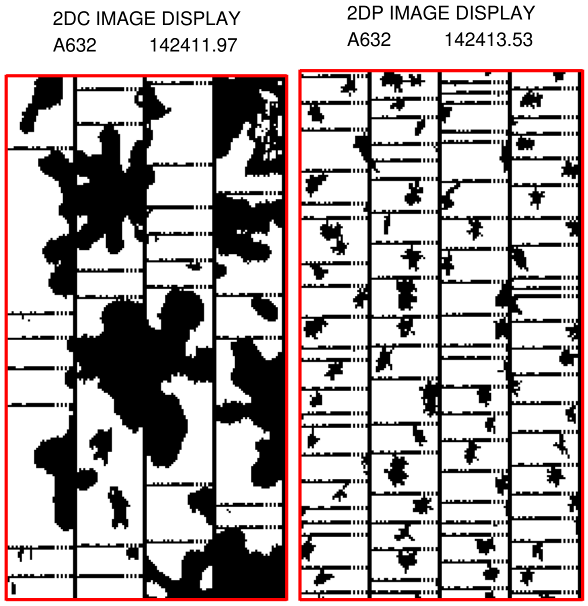

Fig. 5: Crystal images from the 2D cloud and 2D precipitation probes beneath the high Z_{DR} region shown in Fig. 3, but from the outbound leg a few minutes later. The array width of the 2D cloud probe is 0.8 mm and that of the 2D precipitation probe is 6.4 mm.

cended to these altitudes layers were no longer visible by the lidar, Z_{DR} had fallen back to its more usual range of 0 to 0.5 dB, and no significant liquid water was detected. This strongly suggests that high Z_{DR} is intimately associated with the presence of liquid water.

The C-130 did not fly directly through the very high Z_{DR} region on this occasion, but the crystals sampled beneath it will have fallen through the liquid water layers and be strongly affected by them. At $-15°$C, the temperature of the highest layer, growth is mainly in the prism faces of the crystals and thus plates tend to be the predominant crystal type. From Fig. 2 we see that at high water vapour excesses (caused by evaporating liquid water droplets), sector plates in particular should form. Sector plates are characterised by distinctive broad branches, as

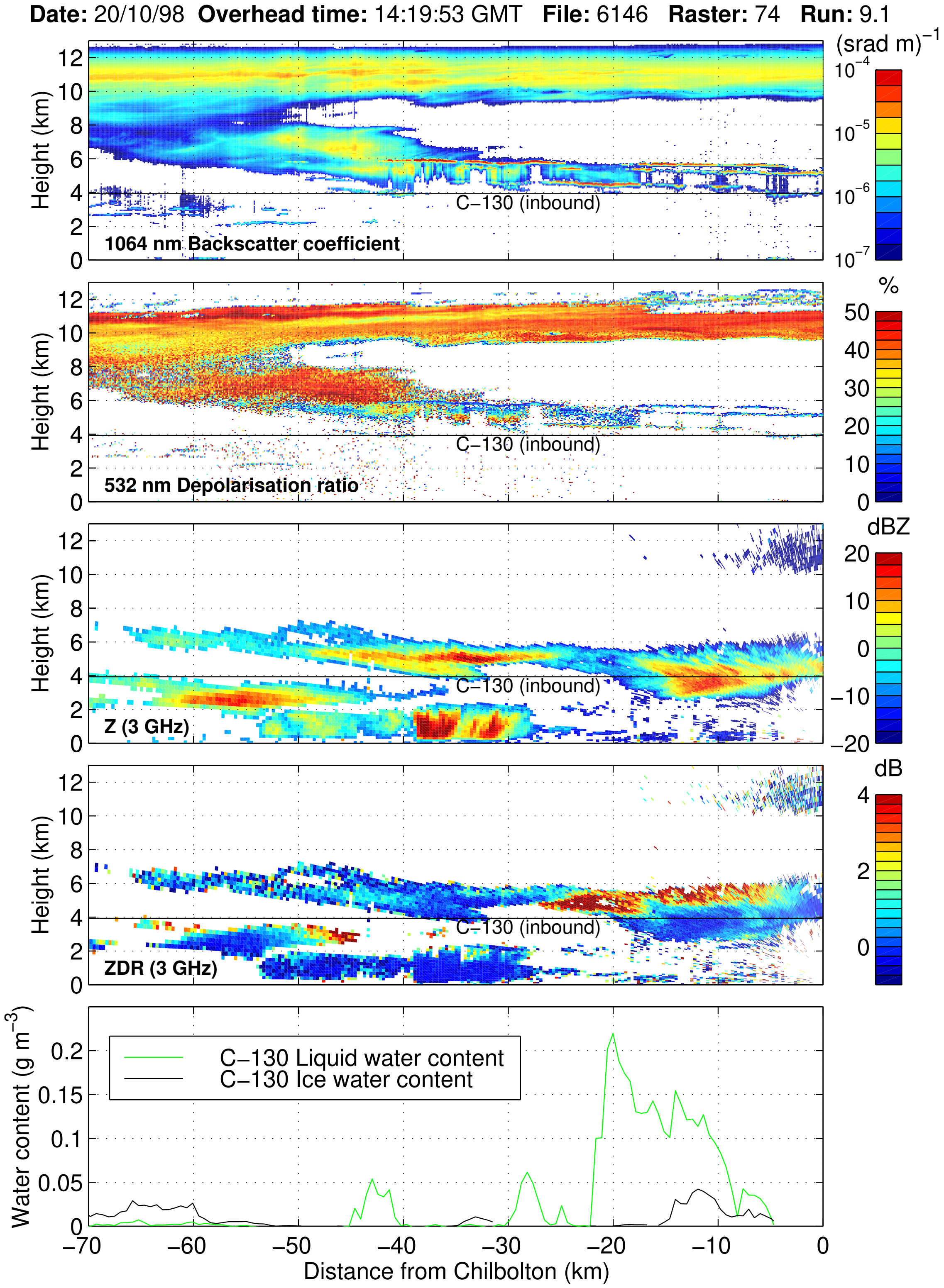

Fig. 3: Composite of observations from 20 October 1998 during CLARE'98. The first two panels show measurements by the nadir-pointing lidar on board the Falcon aircraft flying at an altitude of 13 km. Simultaneous measurements of Z and Z_{DR} by the ground based 3 GHz radar at Chilbolton are shown in the next two panels, and the last shows liquid and ice water content measured by the C-130 aircraft at an altitude of 4 km.

shown by the photograph in Fig. 4, and indeed the crystal images from the 2D probes on the C-130 as it flew beneath the high Z_{DR} regions exhibited precisely the same broad branches (Fig. 5).

It is easy to see why sector plates should have such a high Z_{DR}. It is known that free-falling ice crystals tend to be aligned with their longest axis in the horizontal (e.g. Liou 1986), although this is not apparent from 2D probe images because turbulence generated as crystals are drawn into the sample volume of the instrument sets them tumbling. Hence we cannot measure extreme aspect ratios from the 2D probes. However, the crystals measured by the C-130 were around 1 mm across, corresponding to an aspect ratio in excess of 10:1 according to the typical diameter-width relationships of Ono (1970). Young (1993) estimates the bulk density of sector plates to be 0.5 g m^{-3}, so from Fig. 1 we see that this corresponds to a Z_{DR} of around 4.5 dB, in agreement with what was observed.

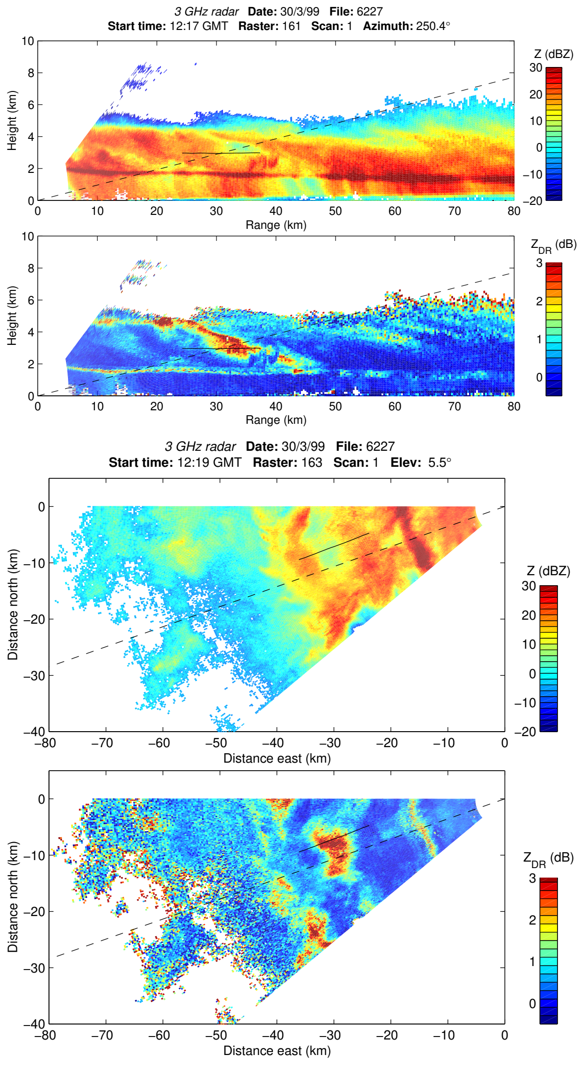

Fig. 6: Horizontal and vertical scans through a region of high Z_{DR} during the CWVC flight on 30 March 1999. The solid lines show the path of the C-130 aircraft during run 19.

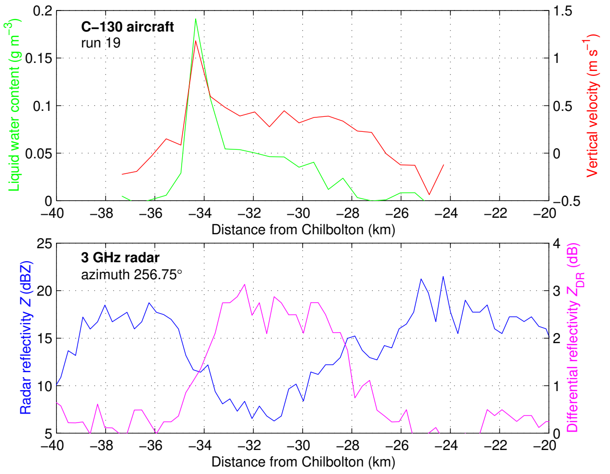

Fig. 7: Comparison of simultaneous aircraft and radar parameters for aircraft run 19. The top panel shows LWC and vertical velocity measured by the aircraft, and the bottom panel shows the corresponding Z and Z_{DR} measured by the radar during the horizontal scan shown in Fig. 6.

CWVC case study on 30 March 1999

The second case study was a C-130 flight over Chilbolton on 30 March 1999, part of the NERC-funded Clouds, Water Vapour and Climate (CWVC) program. The main interest was in supercooled water associated with weak ‘embedded convection’ within stratiform precipitation, and it was only afterwards that it was realised that the high liquid water contents coincided with high Z_{DR}. The flight strategy was for the aircraft to fly towards and away from Chilbolton at around -5°C until a localised region of supercooled water was encountered in coincidence with an updraught, and then to switch to a Lagrangian flight pattern, consisting of a sequence of short 2-minute runs while slowly drifting and ascending with the air.

Figure 6 shows two scans through a region of supercooled water that was sampled by the C-130 during one of these ascents. The first two panels show Z and Z_{DR} from a vertical scan, and the convective plume is indicated clearly by a region of high Z_{DR}. The solid line shows the path of the C-130 during a short run, and the dashed line indicates the elevation of a horizontal scan taken 2 minutes later and shown in the following two panels.

The top panel of Fig. 7 shows LWC measured by the Johnson-Williams probe and vertical velocity as the aircraft flew through the plume, and the bottom panel shows Z and Z_{DR} measured simultaneously by the radar. LWC peaks at 0.19 g m^{-3} at the same time that the maximum updraught of 1.2 m s^{-1}. As well as Z_{DR} rising to 3 dB in the plume, we see that Z falls by 10 dB. Crystal images taken by the 2D cloud probe (not shown) indicate the presence of columns in the regions of liquid water and larger aggregates (with the suggestion of sector-plate-like broad branches) to each side. Hence it appears that the updraught prevents the large aggregates from falling into this region, leaving only aligned columns, which grow in situ. The temperature at the altitude of the aircraft was -5.9°C, corresponding to around the middle of the column growth region (Fig. 2).

There appears to be an extensive region of Z_{DR} greater than 1 dB at the top of the cloud. This can be explained by the fact that when crystals first grow it is by vapour deposition, and it is only when they have an appreciable fall speed that aggregation becomes important and Z_{DR} falls to around 0 dB.

DISCUSSION

The picture that emerges from the aircraft observations in the CWVC case is of localised patches of supercooled water being carried up in updraughts, and this is backed up to some extent by the radar scans showing a plume of high Z_{DR} around 5 km across. The lidar observations from CLARE'98 showed a number of very distinct layers rather than a plume, so the question is whether the two cases, which are in the same temperature range, can be reconciled. It is not easy to speculate on what an airborne lidar would have seen in the CWVC case. Certainly in the absence of the lidar observations in CLARE'98 the two cases do not look dissimilar, with both seeing a localised region of high Z_{DR} around 5 km across, which coincides with supercooled water with an LWC peaking at 0.2 g m^{-3}. The layers observed in CLARE'98 were far from horizontally homogeneous, and it is possible that the aircraft observations of liquid water in CWVC were from passes through a number of layers at different levels.

Long-term observations by lidar ceilometer suggest that supercooled layers at the top of altocumulus can be very long lived (12 hours in some cases), but as one would expect, when ice is falling through them they tend to be eroded more rapidly and usually last no longer than one hour.

We have seen how the types of crystals that are produced in highly supersaturated environments such as sector plates can give very high values of Z_{DR}. From Fig. 2 it is clear that between $-9.5°$C and $-23°$C, Z_{DR} should depend strongly on whether liquid water is present, since at lower supersaturations much thicker plates (aspect ratios of around 2:1) will tend to grow. Outside this temperature range, columns and needles are the dominant crystal types and from this one might expect to see high Z_{DR} in all clouds regardless of supersaturation, rather than the usual range of 0 to 0.5 dB. However, 2D probe images at temperatures colder than $-23°$C show needles relatively rarely; by far the most common are irregular 'polycrystals', although bullet rosettes occur fairly frequently also. One should remember that radar parameters such as Z_{DR} are weighted by the square of the mass of the particles, and it is therefore the larger particles that are most important. From this it would seem likely that aggregation is the dominant growth mechanism at the larger sizes in most ice clouds, resulting in the observed irregular, low-density crystals, and it is only when liquid water is present that vapour deposition becomes important at all sizes producing the highly-aligned high-density crystals that were observed in these two cases.

CONCLUSIONS AND FUTURE WORK

For the first time high Z_{DR} in ice cloud has been shown to coincide with the presence of liquid water, explained by the rapid growth of either columns or thin sector plates. Given the importance of supercooled water for radiation and the development of precipitation, there is a clear need for more aircraft flights over Chilbolton to further investigate the spatial and microphysical properties of liquid water within ice clouds. The finding that Z_{DR} is linked to the presence of liquid water means that the radar could be much more useful in directing the aircraft towards the most promising areas. It also means that Z_{DR} could be used near airports for to warn about the possibility of aircraft icing.

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