Analysis of radar and lidar returns from clouds: Implications for the proposed Earth Radiation Mission

Robin J. Hogan* **Anthony J. Illingworth**

Department of Meteorology, University of Reading, UK
***Email: R.J.Hogan@reading.ac.uk**

INTRODUCTION

In the three months between 24 October 1998 and 23 January 1999, a near-continuous dataset of observations by cloud radar, lidar ceilometer and drop-counting raingauge was obtained at Chilbolton, England. There are many uses for it that are relevant to the proposed ESA Earth Radiation Mission, and in this study we examine the frequency distribution of radar reflectivity, the difference in radar and lidar measured cloud base, and the frequency of occurrence of radiatively significant clouds that are seen by the lidar but not the radar.

DISTRIBUTION OF RADAR REFLECTIVITY

The first simple way to characterise the clouds in the dataset is to calculate the probability distribution of radar reflectivity (Z) of all clouds at all heights. This is shown in Fig. 1, and includes data from both the 35 GHz 'Rabelais' radar and the 94 GHz 'Galileo' radars, although not for the same days. It was calculated from data averaged over 2 minutes and 2 range gates, so for the 35 GHz radar the range resolution after averaging is 150 m and for the 94 GHz radar is 120 m. We see that in the lowest 4 km of the atmosphere the most probable value of Z is around 2 dBZ. Above this height the most probable value of Z drops steadily, from around -5 dBZ at 5 km to around -27 dBZ at 9 km. The lack of observations below -35 dBZ at high levels reflects the sensitivity limit of the radars; the dashed line shows the approximate minimum-detectable reflectivity for the 94 GHz radar with 2 minute/120 m averaging. At a range of 1 km this radar can see down to around -52.5 dBZ. It should be noted that the radiative significance of the clouds that are missed because of the sensitivity limit is likely to be very small (Brown et al. 1995).

The next step is to perform the analysis on stratocumulus only; globally stratocumulus is the most common cloud type and also the most important for the earth's radiation budget. It has been suggested that radar reflectivity is related to liquid water content (LWC) in stratocumulus and therefore that a spaceborne radar could retrieve LWC using a simple empirical relationship. However it was shown by Fox and Illingworth (1997) using aircraft-measured size spectra from the Atlantic Stratocumulus Transition Experiment (ASTEX) that these clouds nearly always contain drizzle drops several hundred microns in diameter, which contribute negligibly to LWC while dominating Z. This is shown clearly in the scatterplot of Fig. 2. Drizzle-free stratocumulus typically has a reflectivity less than -30 dBZ, so

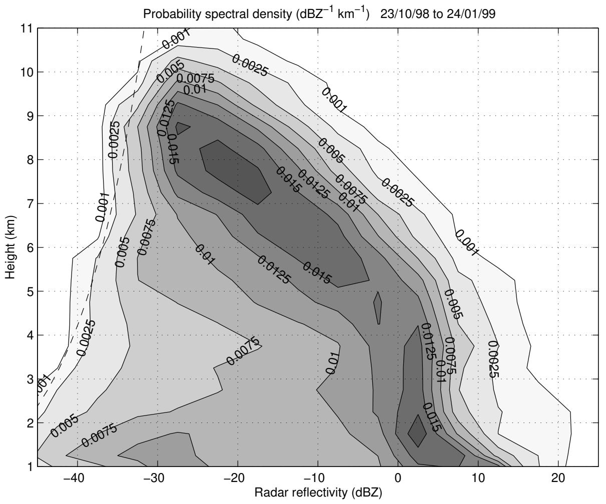

Fig. 1: The probability spectral density of Z for all the cloud radar data taken at Chilbolton in the three months between 23 October 1998 and 24 January 1999. The dashed line indicates the approximate sensitivity limit of the 94 GHz radar.

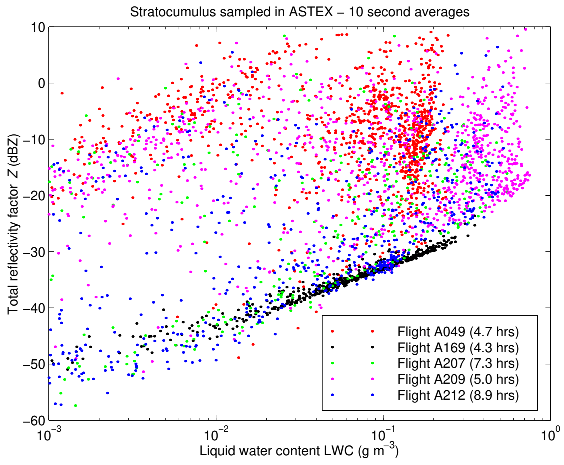

Fig. 2: Scatterplot of radar reflectivity versus liquid water content in stratocumulus, calculated from the FSSP and 2DC size spectra measured by the UK Meteorological Office C-130 aircraft during 5 flights of ASTEX. Only flight A169 is entirely free from drizzle.

the beneficial effect of these drops is to raise the reflectivity so that the cloud is well above the sensitivity limit of a spaceborne radar, but conversely this has the effect that LWC is essentially unrelated to Z.

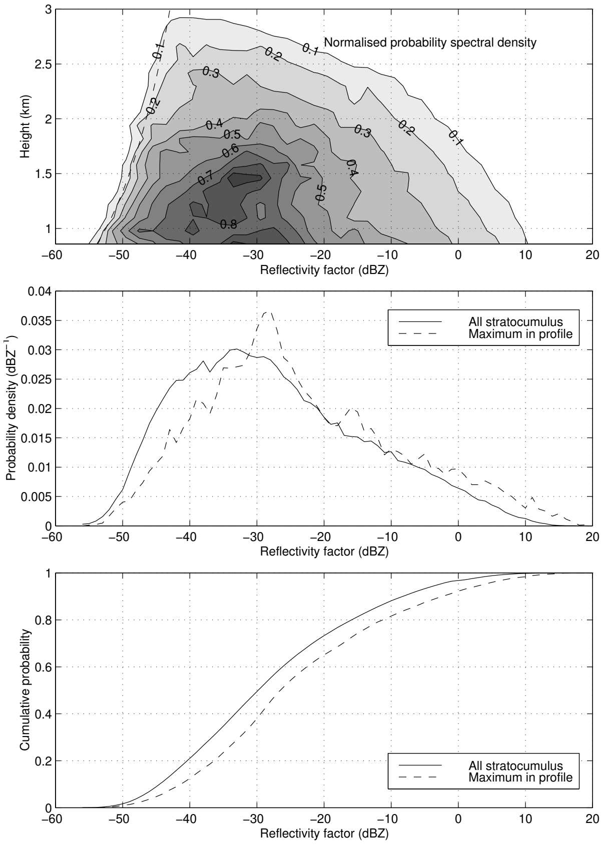

Fig. 3: Statistics of the distribution of Z within stratocumulus only, taken from all the 94 GHz radar observations in the dataset. The top panel depicts the probability density in arbitrary units as a function of height and Z. Again the dashed line indicates the approximate minimum-detectable reflectivity of the radar. The second panel shows the probability distribution of both the Z of all stratocumulus, and of the maximum Z in each profile. The last panel shows the cumulative probability.

Naturally conclusions drawn from aircraft measurements need to be confirmed using real radar observations. To isolate stratocumulus from the other cloud types in the dataset we impose the following conditions on each ray in turn:

- Only clouds lower than 3 km are considered.
- Any cloud extending below 3 km that has a cloud top higher than 3 km is rejected. However, if there is a lower layer with cloud top lower than 3 km then it is not rejected.
- The rain rate at the ground should be less than 0.1 mm hr^{-1} (although it is found that the results are virtually unchanged if the more-stringent requirement that there should be absolutely no rain at the ground is imposed).

Only the 94 GHz radar is used for this analysis because it is more sensitive than the 35 GHz radar at short range. The results for the 76 days of 94 GHz data are shown in Fig. 3. The first panel shows the probability density as a function of height and reflectivity. Around 61% of all cloud between 0.9 and 3 km have been rejected by the imposition of the conditions listed above, most because their cloud top was above 3 km. For this reason the probability density is in arbitrary units (unlike Fig. 1). Again the effect of the sensitivity limit of the radars is very apparent in the sharp cut-off in probability density at low reflectivities.

The probability distribution of Z is indicated by the solid line in the second panel. Below 900 m the sensitivity of the radar was much less because of the leakage of the transmit pulse into the receiver, so to avoid biasing the distribution, data below 900 m has not been included in this analysis. The distribution peaks at around -33 dBZ, corresponding to the secondary peak apparent at 1 km in Fig. 1. The primary peak in Fig. 1 at around 2 dBZ and 1 km has been entirely removed by the rejection of non-stratocumulus clouds.

The last panel shows the cumulative distribution of Z, from which we see that 50% of the data has Z greater than -30 dBZ. Aircraft observations suggest that value this can be approximately regarded as the threshold above which stratocumulus contains drizzle drops, and hence we conclude that around half of the stratocumulus observed over Chilbolton during the period contained drizzle.

The dashed line in the last two panels of Fig. 3 corresponds to the probability distribution of the *maximum* reflectivity in each profile (or ray). Using the same -30 dBZ criterion for cloud containing drizzle, it can be seen that approximately 60% of profiles through stratocumulus contain drizzle somewhere through their depth.

The geographical location of Chilbolton is such that most of the time the stratocumulus can be considered to be continental, that is, containing relatively large numbers of cloud condensation nuclei. The results of Fox and Illingworth (1997) were derived from stratocumulus with much more maritime characteristics, which explains why drizzle was somewhat more prevalent in their dataset. However drizzle is still clearly significant in more than half the stratocumulus sampled at Chilbolton, and hence this analysis supports their claim that in most stratocumulus, radar reflectivity alone cannot be used to infer liquid water content.

COMPARISON OF RADAR AND LIDAR CLOUD BASE

The apparently very different scattering behaviour of radar and lidar implies that the sizes of cloud particles they are sensitive to are very different, and hence that there will be some clouds that one can see that the other cannot, or at the very least cloud base height will be different. This is certainly true for non-meteorological targets in the boundary layer; here the lidar can detect aerosols invisible to the radar, but conversely the radar can see insects that the lidar cannot. The question is whether it is a problem in the case of fall streaks beneath ice clouds and drizzle beneath liquid-water clouds.

The location of a cloud is obviously of primary importance in determining its radiative properties in the infra red so there is a need to investigate whether radar and lidar see the same cloud boundaries. Short periods of simultaneous ground-based radar/lidar observations have been presented previously by Uttal et al. (1995), who found good agreement in cloud base height, and by Weitkamp et al. (1997) who found apparent disagreement. It should be noted that the data presented in the latter study were not accompanied by absolute units, so it was impossible to judge what part the sensitivity of the instruments could have played. Some comparisons in the past have also been biased by inappropriate definitions of cloud base, such the height at which the signal falls to 10% of its peak value (Russchenberg et al. 1998). Clearly the rejection of a good cloud signal near cloud base merely because the peak value several kilometres higher up has increased can severely distort the results of such comparisons. With the long dataset obtained at Chilbolton it is now possible to investigate the issue more systematically.

In this study, 45 hours of data from 6 different days have been identified in which the lidar had an unobstructed view of the base of an ice cloud. Only the 94 GHz radar was used since this is the proposed frequency of the spaceborne radar. The data in the lowest 900 m are unreliable because of leakage of the transmit pulse into the receiver, so such a comparison is much more difficult to perform on low-level liquid water clouds. Aerosols are also apparent in the lidar data below 2 km, so the cloud bases in the study have been selected to range between 2 km and 9 km. We consider two different instrument sensitivity scenarios. In the ‘ground-based’ scenario the maximum achievable sensitivity of each instrument is used; for the lidar this is $2 \times 10^{-7}(\mathrm{srad\ m})^{-1}$ and for the radar it varies with altitude, although at the base of ice clouds is typically between -40 dBZ and -35 dBZ. In the ‘spaceborne’ scenario we calculate cloud base after first reducing the sensitivity of the instruments to approximately match that of the instruments on the proposed Earth Radiation Mission; $8 \times 10^{-7}(\mathrm{srad\ m})^{-1}$ for the lidar (in the daytime) and -35 dBZ for the radar. Note that sometimes the minimum-detectable reflectivity of the ground-based radar is greater than -35 dBZ, in which case its sensitivity is left unchanged. Cloud base is defined simply as the height corresponding to the boundary between the first cloudy pixel and the empty pixel immediately beneath it. The cloud must however be at least three pixels deep to reject the occasional anomalous echo. The maximum vertical resolution of each instrument is used; this is 30 m for the lidar and 60 m for the 94 GHz radar. The temporal resolution of both instruments is 2 minutes and where there is a time offset between the two we interpolate the cloud base height on to a common time axis before computing the difference.

Two examples of the comparison, from 19 and 28 December 1998, are shown in Fig. 4. The difference in cloud base is shown in the bottom panels for the two different instrument sensitivities, and the features appear to match up very well. On 19 December cloud base is relatively low, and radar cloud base is mostly between 0 and 200 m below that of the lidar for both sensitivity scenarios, because of the presence of large snowflakes at the base of the cloud. In the second case cloud base is higher and there is a tendency for the lidar cloud base to be lower than that of the radar, because the particles are smaller and therefore give a relatively larger return at lidar wavelengths. In addition, the decrease in radar sensitivity with height probably contributes to the radar base rising above that measured by the lidar when above 6 km. In both cases the lidar signal is strongly attenuated, and is completely extinguished after penetrating 2 km through the cloud.

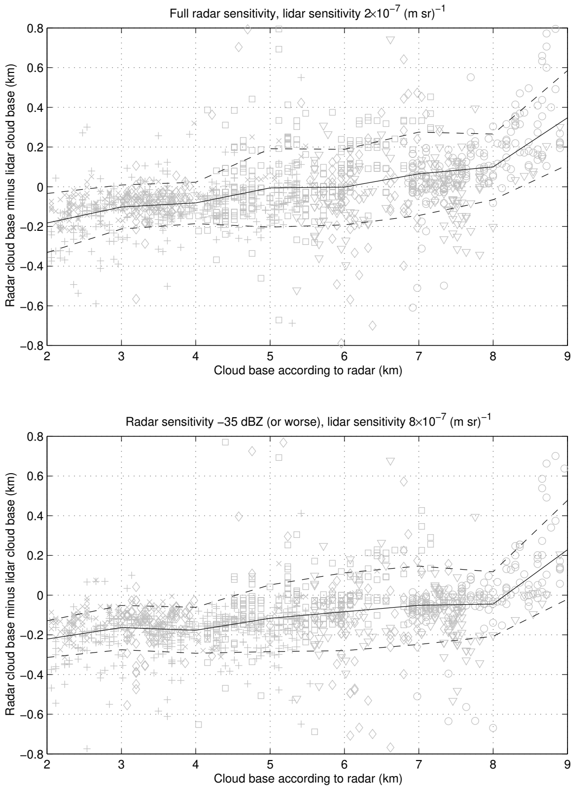

Fig. 5: The distribution of the difference in cloud base height between the radar and the lidar, versus the radar base height, for ground-based (upper panel) and spaceborne (lower panel) sensitivities. Negative values correspond to a lower radar cloud base (indicating that the radar is more sensitive). The 1362 grey symbols correspond to individual cloud-base comparisons from 2-minute averaged data from 11 November (○), 19 December (×), 27 December (+), 28 December (□), 7 January (◇) and 16 January (▽). Overlayed on each is the mean cloud-base difference (solid line) and one standard deviation to either side (dashed lines).

Figure 5 shows the difference in cloud base as a function of cloud base height, from these and four other days in which the lidar had an unobstructed view of the base of an ice cloud. As one might expect, the radar is more sensitive for the lower clouds and the lidar more sensitive for high clouds, because of the intrinsic sensitivity of the radar to large particles and the lidar to small particles. Using the full (‘ground-based’) instrument sensitivity it is found that 80% of the time cloud base agrees to within 200 m and 96% of the time it agrees to within 400 m. Using the spaceborne instrument sensitivities, we find that these values become 73% and 95% respectively. The reason that these values are lower is that the sensitivity of the spaceborne radar is not very different to that of the ground-based radars at Chilbolton, whereas the spaceborne lidar is around four times less sensitive than the Chilbolton lidar ceilometer. Hence when the Chilbolton data are degraded to simulate spaceborne instrument sensitivities, the effect on the lidar is much greater. This illustrates the need to always consider instrument sensitivity when comparing cloud base.

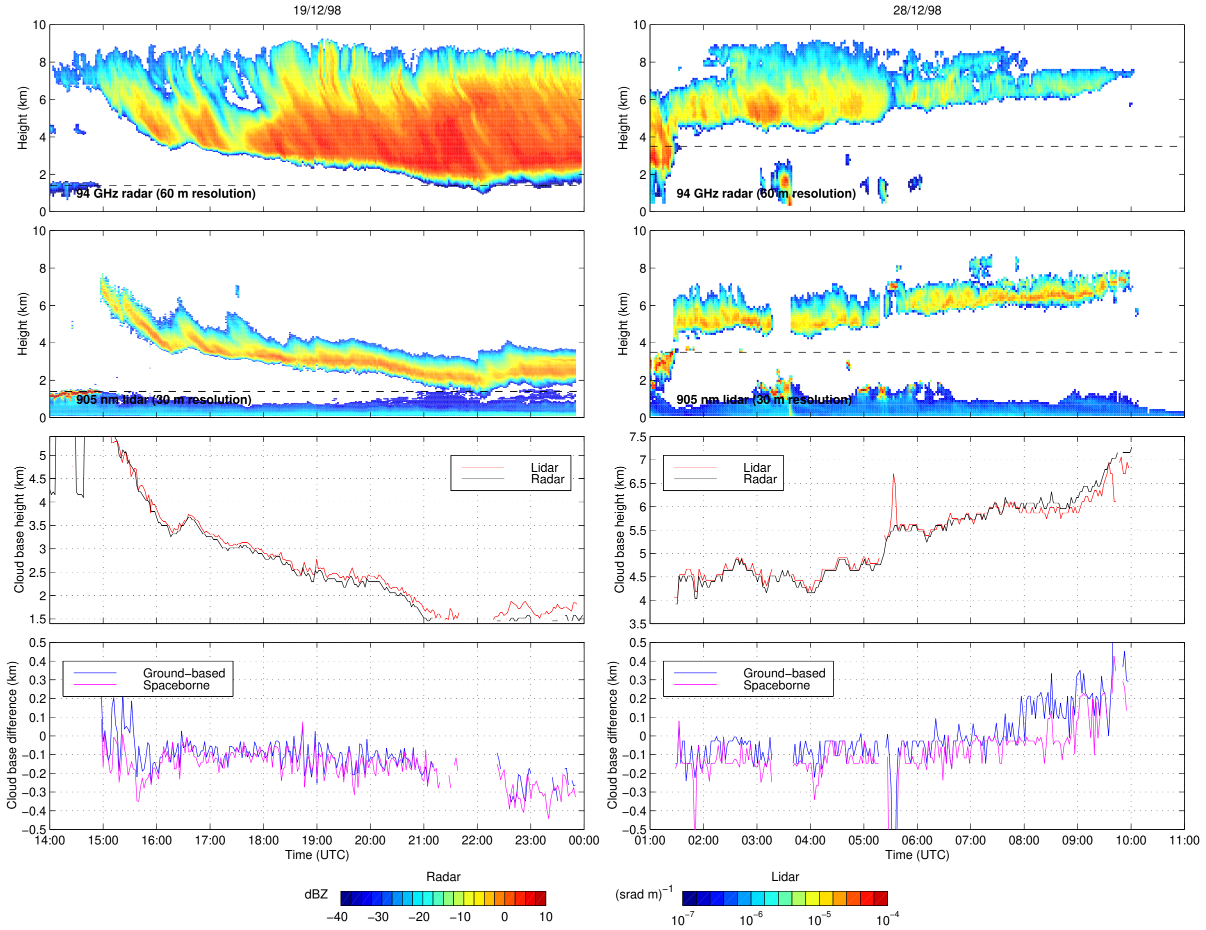

Fig. 4: Two examples of the comparison of radar and lidar cloud base, from 19 and 28 December 1998. The top panels show 94 GHz radar reflectivity (resolution 2 minutes/60 metres) and the second show 905 nm backscatter coefficient (resolution 2 minutes/30 metres). The dashed horizontal lines in each show the minimum cloud base height permitted for this particular day (to ensure that the two instruments are observing the same cloud, and that the lidar is not detecting aerosol layers). The third panel in each example shows cloud base height from the two instruments using the full 'ground-based' sensitivities, and the last depicts the difference in cloud base height calculated assuming both ground-based and spaceborne instrument sensitivities (see text for details).

In conclusion, there is a difference in the cloud base measured by radar and lidar but it is usually less than 200 m, which is not really of great importance. This is particularly true for the Earth Radiation Mission since the vertical resolution of the radar will be 500 m. It should be noted that given typical lapse rates in the troposphere, a change in cloud base of 500 m corresponds to a change in long-wave emission of approximately 10 W m^{-2}. This is commonly considered to be the accuracy required for both observations and model radiation schemes, so the differences in cloud base found in this study are not large enough to be a serious concern.

COINCIDENCE OF ECHOS FROM RADAR AND LIDAR

It is very common for the lidar signal to be extinguished completely, even in ice clouds as seen in Fig. 4, but it is of interest to determine how often there are clouds detected by the lidar that are not seen at all by the radar, and to characterise them by height and optical depth.

We use all the 94 GHz radar data taken in the three-month period. The lidar and radar data are both averaged by 2 minutes and 120 m, and are interpolated on to a common grid. Because the lidar sees aerosols in the boundary layer, only data above 2 km are considered. For each day a 'hit/miss' field is calculated, which for each point on the grid contains a value that states whether

1. One (or both) of the instruments was not operational at the time.
2. No cloud was seen by either instrument.
3. Cloud was seen by both instruments.
4. The radar saw cloud and the lidar did not.
5. The lidar saw cloud and the radar did not.

Each ray is examined in turn, and clouds are identified that are more than three pixels thick (to reject anomalous echos), consist entirely of cloud seen by the lidar and not the radar, and

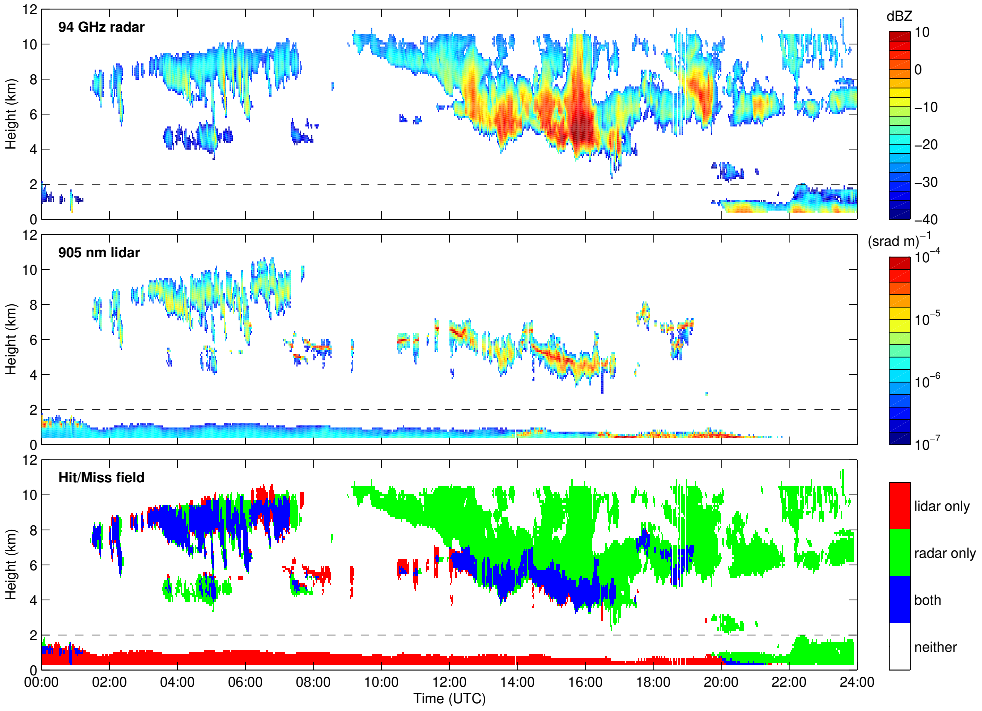

Fig. 6: Comparison of radar and lidar observations of cloud occurrence on 13 December 1998. The top panel shows 94 GHz radar reflectivity, the seconds shows lidar backscatter coefficient, and the third show the 'Hit/Miss' field, described in the text, for the full 'ground-based' sensitivity scenario. The dashed line at 2 km indicates the minimum height at which one can be sure the lidar is observing cloud and not aerosol.

are bounded at the top and the bottom by pixels for which no cloud was seen by either instrument. The same two sensitivity scenarios that were used in the previous section are again considered here. An example is shown in Fig. 6 for a whole day of data. In this case there are some supercooled water clouds at around 6 km that are seen by the lidar but only intermittently by the radar. It was found from the CLARE'98 campaign that supercooled water tends to occur in the form of thin layers that, because of the small droplet size, give a much larger echo for the lidar than the radar.

For the full or 'ground-based' instrument sensitivities, 3.9% of clouds detected by the lidar in the entire three-month period were not seen by the radar. For the 'spaceborne' sensitivity scenario (−35 dBZ for the radar, 8×10^{-7}(srad m)$^{-1}$ for the lidar), this value drops to 2.1%. Again, the difference is because in degrading the data to spaceborne sensitivities the lidar loses relatively more signal than the radar.

These are very small fractions, but it is important to know how radiatively significant the clouds missed by the radar are. Figure 7 shows the distribution of the base height and optical depth of the clouds seen by the lidar and not the radar. Optical depth is estimated by simply converting the observed backscatter coefficient to an extinction coefficient using an assumed extinction-to-backscatter ratio of 14 srad (the value used by the ARMAR ESTEC cirrus model), and integrating up through the cloud. We find that the mean optical depth of these clouds is around 0.05 which is fairly low, although the maximum is 0.27. These low values justify the fact that no attempt was made to

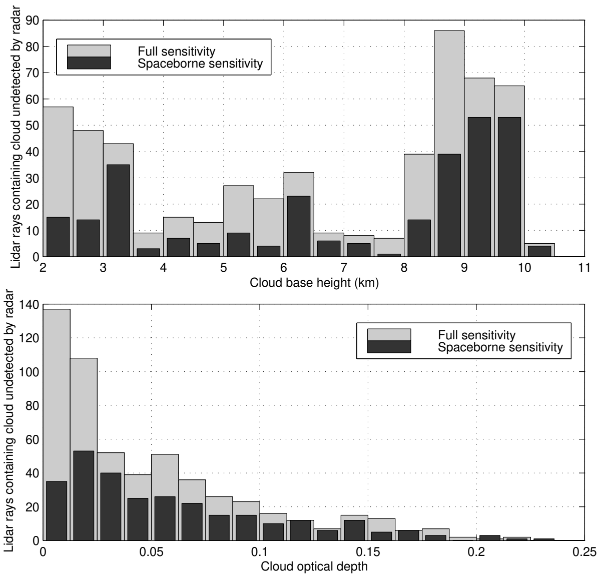

Fig. 7: Distribution of cloud base height and optical depth for all clouds in the dataset that were detected by the lidar but not the radar. The same two sensitivity scenarios have been considered.

correct for attenuation. For a cloud to be undetected by the radar means that the particles must be very small; it is likely that they are either tenuous supercooled water clouds before the onset of glaciation, or aircraft contrails consisting of very small ice crystals. It was estimated by Brown et al. (1995) that the radiative significance threshold for mid-latitude cirrus is an optical depth of around 0.05. Hence we can calculate the fraction of *radiatively significant* clouds seen by the lidar but not the radar; it is found that for ground-based instrument sensitivities the value is 1.5%, and for spaceborne sensitivities it is only 1.0%.

In summary, it seems that there will not be large expanses of radiatively significant cloud not seen by the proposed spaceborne radar. The same conclusion was reached by Brown et al. (1995) using aircraft data. It is clear that much more radiative significant clouds will be missed by the lidar because of the problem of attenuation.

CONCLUSIONS

The proposed ESA Earth Radiation Mission is likely to involve both a radar and lidar on a spaceborne platform. A number of misconceptions about the ability of these instruments to measure clouds are frequently stated, and analysis of this dataset has enabled them to be examined more closely:

"Radar reflectivity can be used in stratocumulus clouds to retrieve liquid water content"

We have found that even over Chilbolton where the air is predominantly continental, 60% of the stratocumulus clouds have a radar reflectivity of in excess of -30 dBZ at least somewhere in the profile; this can be regarded as a crude indication that there is drizzle present, and therefore that reflectivity is essentially unrelated to liquid water content. For a spaceborne radar that is to observe clouds on a global scale, it should be noted that 90% of the earth's stratocumulus occurs over the oceans, and drizzle is ubiquitous in maritime stratocumulus (Fox and Illingworth 1997).

"Cloud boundaries measured by radar and lidar are very different"

Differences in cloud boundaries are very much a function of the sensitivity of the two instruments. Because the data in this study were taken from the ground during winter, it has only been possible to examine the differences in the height of the base of ice clouds. We have found that with the proposed sensitivity of the spaceborne radar and lidar, 73% of the time cloud base should agree to within 200 m and 95% of the time to within 400 m. Given that the range-gate spacing of the spaceborne radar will be 500 m, this is acceptable. The next step is to perform the analysis on the bases of liquid water clouds (using data taken in summer when the 0°C isotherm is much higher). Because of the strong attenuation of the lidar signal, the coincidence of radar and lidar cloud top cannot be meaningfully compared from the ground.

"There are many radiatively significant clouds that the radar will not detect"

We have found that using the full sensitivity of the instruments, 3.9% of the clouds detected by the lidar above 2 km were not seen by the radar. When the data are degraded to the sensitivity of the spaceborne instruments this figure drops to 2.1%. If we further only consider 'radiatively significant' clouds, defined as those with an optical depth greater than 0.05, this value becomes only 1%. Hence it would appear that there are *not* large expanses of radiatively significant cloud that will not be detected by the radar. This is certainly true for ice clouds, but the restriction that only observations above 2 km could be used (because of boundary-layer aerosols) meant that the amount of low-level liquid water cloud considered in the analysis was relatively low.

ACKNOWLEDGEMENTS

We wish to thank the Radiocommunications Research Unit at the Rutherford Appleton Laboratory for the use of the Chilbolton radars and lidar ceilometer. The Galileo radar was developed for the European Space Agency by Officine Galileo, the Rutherford Appleton Laboratory and the University of Reading under ESTEC Contract No. 10568/NL/NB. The ASTEX data were supplied by Philip Brown. This research received funding from NERC grant GR3/8765.

REFERENCES

Brown, P. R. A., A. J. Illingworth, A. J. Heymsfield, G. M. McFarquhar, K. A. Browning and M. Gosset, 1995: The role of spaceborne millimeter-wave radar in the global monitoring of ice-cloud. *J. Appl. Met.,* **34**(11), 2346–2366.

Fox, N. I., and A. J. Illingworth, 1997: The potential of a spaceborne radar for the detection of stratocumulus clouds. *J. Appl. Met.,* **36**(6), 676–687.

Russchenberg, H. W. J., V. K. C. Venema, A. C. A. P. van Lammeren, A. Feijt and A. Apituley, 1998: *Cloud measurements with lidar and a 3 GHz radar.* Final report, ESTEC Contract 151912.

Uttal, T., E. E. Clothiaux, T. P. Ackerman, J. M. Intrieri and W. L. Eberhard, 1995: Cloud boundary statistics during Fire II. *J. Atmos. Sci.,* **52**(23), 4276–4284.

Weitkamp, C., O. Danne, H. Flint, W. Lahmann, M. Quante, E. Raschke and F. E. Theopold, 1997: Lidars for cloud measurements at GKSS and first radar-lidar comparisons. *Workshop on 'Synergy of active instruments in the Earth Radiation Mission', 12-14 November 1997,* GKSS, Geestacht, Germany.