DETECTION OF ICE CLOUDS BY RADAR AND LIDAR AND COMPARISON WITH OPERATIONAL NWP MODELS.

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1. INTRODUCTION

Satellite missions are planned in which a lidar and a radar will be flown together for the first time. In this note we analyse observations with a ground based radar and lidar at Chilbolton in the UK to answer the following questions.

a) What is the sensitivity required by a spaceborne instrument so that all radiatively significant ice clouds will be detected? Is the lidar more sensitive to tenuous clouds than the radar?

b) Cloud base and cloud top detection.
Do spaceborne radar and lidar provide reliable detection of the top and base of ice clouds and is this a function of the instrument sensitivity? How often is radar cloud base lower because of fall streaks?

c) Embarking the radar and lidar on different platforms.
Can the radar and lidar be embarked upon different satellite platforms without prejudicing the main objectives? Is it still possible to use the backscatter ratio to derive ice particle size? What is the spatial scale of cirrus cloud inhomogeneity?

Comparisons of observations with the values of cloud parameters held in the ECMWF operational model have been made to address the following questions:

d) Cloud overlap.
All models assume maximum–random overlap in the vertical. What is the true sub–grid scale overlap?

e) Comparison of fractional cloud cover.
How do the values of fractional cloud cover inferred from the ground based observations compare with those in the model?

Finally, for a future spaceborne mission:

f) Spaceborne use of 215 and 94GHz radars.
Can the ratio of reflectivities measured at these two wavelengths provide an estimate of ice particle size?

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The data used in this study were gathered over the period October 1998 to January 1999 using a vertically pointing radar and lidar. The 94GHz radar used had a sensitivity of −52.5dBZ at a range of 1km and −32.5dBZ at a range of 10km with a range resolution of 120m for a 2 minute integration time. The calibration to 1dB is achieved by comparing the simultaneous 94GHz and 3GHz returns for Rayleigh scattering target such as drizzle; the 3GHZ radar was calibrated to 0.5dB using the redundancy of polarisation parameters in heavy rain. The lidar had a sensitivity of 2 x 10^{-7} m^{-1} sr^{-1} . The ground based instruments are more sensitive than the spaceborne instruments proposed by ESA (−35dBZ for the radar and 8 10^{-7} m^{-1} sr^{-1} for the lidar) so it is possible to check the effect of changing the spaceborne instrument sensitivity. Because the radar responds to the sixth power of the particle size and the lidar approximately to the second power, there has been much concern and debate over the following aspects:
i) Will the radar miss many thin but radiatively significant clouds which are only sensed by the lidar?
ii) Will the presence of larger particles falling below cloud base mean that the radar persistently detects a cloud base lower then that inferred from the lidar?

2. COINCIDENCE OF ECHOES FROM RADAR AND LIDAR.

A comparison of the radar and lidar returns (see figure 1) reveals that it is in fact extremely rare for a cloud detected by the lidar not to be seen by the radar. The converse is of course very common when the lidar signal is completely extinguished by optically dense clouds. Clouds were identified by returns that were more than three pixels thick to reject anomalous echoes. For the three month data set with the full 'ground–based' sensitivities, only 3.9% of the clouds detected by the radar were not seen by the radar. For the 'spaceborne' sensitivity this value drops to 2.1%; this reduction arises because, when degrading the instruments to spaceborne sensitivity, the lidar loses more signal than the radar. However, the average optical depth of the clouds seen only by the lidar is only 0.05 (assuming an extinction to backscatter ratio of 14). If we consider that only clouds with an optical depth above 0.05 are likely to be radiatively significant then the fraction of clouds seen by the lidar but not the lidar is reduced to 1.5% for the ground–based sensitivities, and to only 1% for the spaceborne sensitivities. It would be interesting to extend such studies to the tropics where high altitude cirrus composed of very small crystals may be more extensive.

Figure 1: Detection of cloud by radar and lidar. The cloud detected only by the lidar is shown in red.

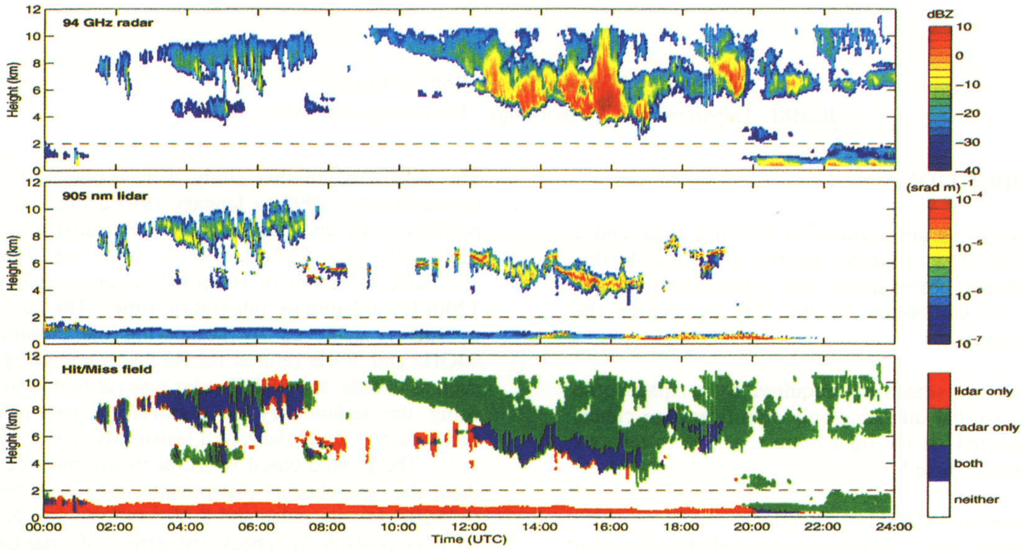


Figure 2: Base of ice cloud derived from radar and lidar.

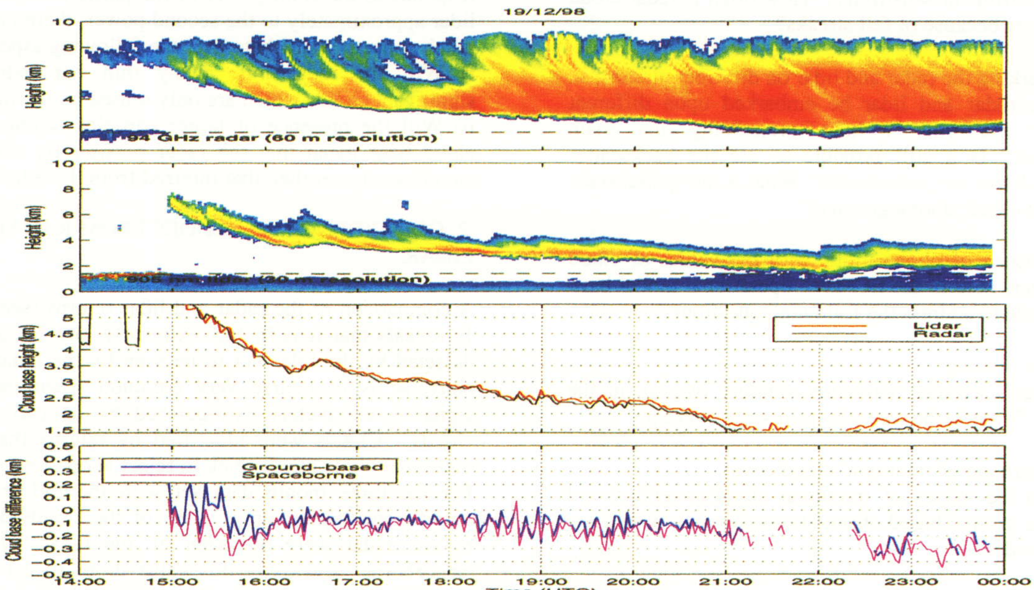
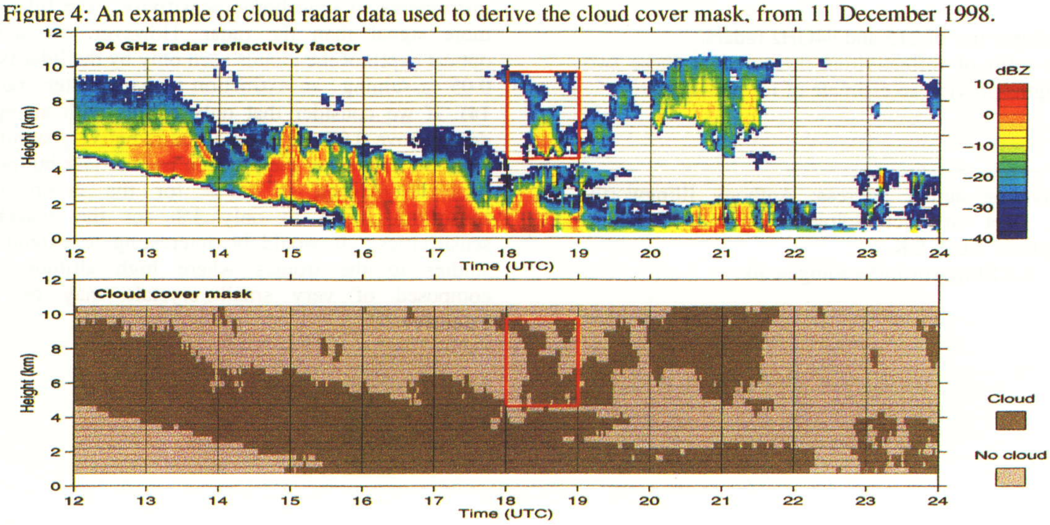


Figure 4: An example of cloud radar data used to derive the cloud cover mask, from 11 December 1998.



3. CLOUD BASE AND CLOUD TOP DETECTION OF ICE CLOUDS.

Forty five hours of data from 6 different days were identified when the lidar had an unobstructed view of the base of an ice cloud. Figure 2 shows the radar and lidar returns and the derived values of cloud base for the 19 December and indicates that cloud bases from the two instruments agree to within 100m. The lower panel compares cloud base differences using the full ground–based sensitivity with the spaceborne sensitivity and shows that derived cloud base depends upon sensitivity. The lower sensitivity of the spaceborne lidar is responsible for the difference of the two traces.

For the full 'ground based' instrument sensitivity it is found that 80% of the time the cloud base agrees to within 200m and 96% of the time to within 400m. For spaceborne sensitivities these values become 73% and 95%. We conclude that there is a difference in the cloud base measured by radar and lidar but it is usually less than 200m and is not really of great concern, when we consider that for typical lapse rates in the troposphere, a change in cloud base of 500m corresponds to a change in long–wave emission of only about 10 W m^{-2}.

4.EMBARKING A RADAR AND LIDAR ON DIFFERENT PLATFORMS

A powerful synergy of the radar and lidar instruments could be to use the ratio of the basckscattered signals to provide an estimate of the ice particle size. If this is to be possible it is important that the footprints of the radar and lidar are sampling ice cloud with similar characteristics.

An analysis of the spatial variability of ice clouds has been carried out in order to investigate the effect of separating the footprints of the two instruments. The time series of reflectivity from the vertically pointing radar was converted into spatial variability using the mean wind speed, and then a power law of the form:

$$E = E_0 k^{\mu}$$

was fitted to the Fourier spectra of these data, where E is the power spectral density and k is the wave number. A typical best fit was of the form $E = 2 \times 10^{-5} k^{-2.16}$ dBZ^2 m (where k is in m^{-1}). Synthetic cloud fields were generated by calculating the inverse two–dimensional Fourier transform of synthetic matrices containing wave amplitudes consistent with the energy at the various scales indicated by this one dimension spectrum. The phase of each wave component of the matrix was random so that each cloudfield was different. The domains were square and measured 25.6km on a side with a resolution of 100m. We shall consider a 1–second averaging time for the spaceborne radar and lidar to achieve sufficient sensitivity, which results in a pixel length of 7km. The effect of footprint separation has been simulated using 64 synthetic cloud fields. The footprint of the lidar was taken as 100m and that of the radar to be 700m with both instruments

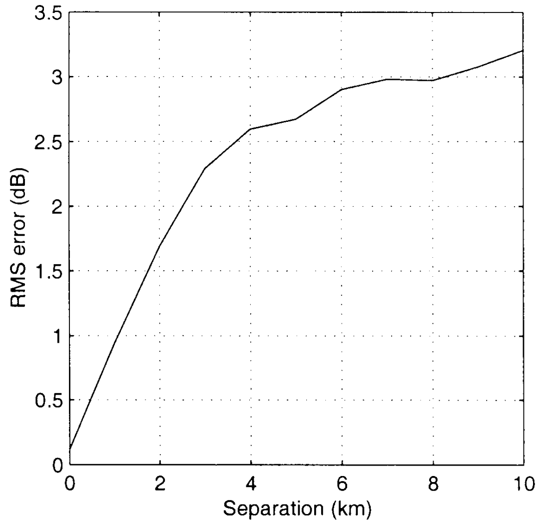


Figure 3: The effect of separating the radar and lidar footprints on the radar/lidar backscatter ratio for ice clouds.

having a Gaussian beam pattern. Calculation of the radar backscatter is relatively straightforward, but to calculate the lidar backscatter the radar reflectivity field was transformed to an optical extinction using an empirical relationship from Hogan and Illingworth (1999). The swaths of the spaceborne radar and lidar were offset by up to 10km in the direction parallel to the satellite motion. The result of the mean fraction error in the backscatter ratio as a function of the separation distance is displayed in figure 3. Note that even when the centres of the footprints are both co–located there is an error in the backscatter ratio because the radar footprint is larger than that of the lidar, but the RMS vale of this error is only 0.2dB or less than 5% and so can be neglected. When the footprint separation reaches 3km the RMS error is 2.3dB or 70% which could give an appreciable error in the derived sizes. In practice the errors will be worse than this, because of the difficulty of correcting the lidar attenuation and also because of temporal evolution and advection of the cloud if there is a time delay between the passage of the two instruments on separate platforms.

5. CLOUD OVERLAP.

The assumed overlap of cloud fraction in a vertical stack of grid boxes has a considerable influence on the model performance. Two extreme assumptions are that the cloud at each level is maximally overlapped or that at each level the overlap is random. It is now common practice to assume that vertically continuously cloud is maximally overlapped but that clouds separated by cloud free grid boxes are randomly overlapped.

Figure 4 shows an example of cloud radar data together with the cloud mask derived from the radar data. The boxes superposed over the cloud mask are for one hour and 360m in the vertical and the derived cloud fraction is the fraction of such a box which is judged to contain cloud. The rectangular box highlighted in the upper part of figure 2 demonstrates that although adjacent levels may well be maximally overlapped, there is a tendency for the overlap to be come more random as the separation of the levels increases.

The complete data set has been analysed and the overlap parameter, α, calculated as a function of the separation of the levels and plotted in figure 5, where $\alpha=1$ implies maximal overlap and $\alpha=0$ is for random overlap. For vertically non-continuous cloud the random assumption is confirmed, but for vertically continuous cloud as the level separation increases there is a change from maximum to random overlap which occurs with an e-folding distance of about 1.68km. These results suggest that the overlap assumption in models should be adjusted. A future spaceborne radar and lidar would provide global statistics on this degree of overlap.

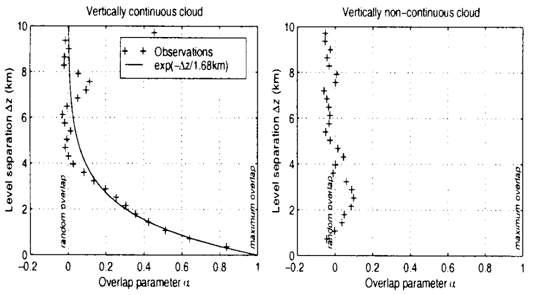


Figure 5: The overlap parameter versus level separation for vertically continuous and non-continuous cloud, using boxes 360m in height and 1 hour in duration. A value of unity indicates maximum overlap and a value of zero indicates random overlap.

6. COMPARISON OF THE FRACTIONAL CLOUD COVER WITH THE ECMWF MODEL.

The method of deriving fractional cloud cover described in the previous section has been adapted slightly to derive the vertical profile of fractional cloud cover over Chilbolton and compare it with the ECMWF model representation for the enite three month period data set. The lidar was used to derive cloud base when light drizzle was falling from the cloud to avoid difficulties when the radar echo extended to the ground. The comparisons of fractional cloud cover were made for hourly periods at the heights of the grid boxes in the ECMWF model. Rainfall can cause attenuation of the 94GHz radar, so periods when the rainfall rate exceeded 0.5mm/hr were excluded from the analysis. A typical ten day period of observations of fractional cloud cover and model representations is shown in figure 6. The overall agreement is very encouraging. However the mean profiles in figure 7 do show some disagreements. Although the frequency of occurrence of any cloud is

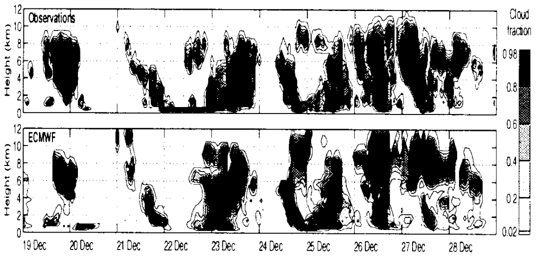


Figure 6: Comparison of observed and ECMWF model cloud fraction at Chilbolton for a ten-day period in 1998.

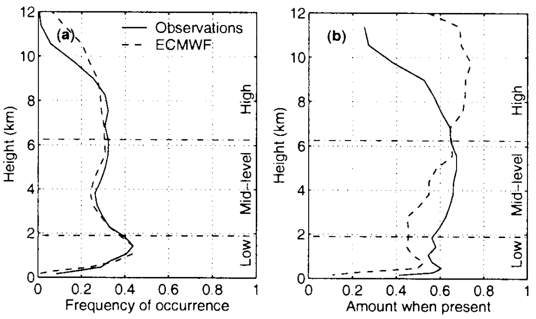


Figure 7: Cloud fraction climatology split into (a) the frequency that the grid-box mean cloud fraction was greater than 0.05, and (b) the mean cloud amount when greater than 0.05.

generally well predicted, the amount when present is too low in the model below 6km and too high above 6km. The disagreement below 6km arises because, in contrast to the model, the observations cannot meaningfully distinguish precipitating snowflakes from non-precipitating ice crystals. If model snow fluxes below 0.05mm/hr were reclassified as clouds, then there was very good agreement of the amount when present below 6km. Examination of the lidar observations suggests that such low fluxes of snowfall really are associated with optically thick clouds. The radiation scheme in the model is interpreting such regions as cloud-free and this could be a source of error.

The difference in cloud amount when present above 6km seems to be associated with very tenuous ice clouds which may be below the sensitivity of the radar. However, removal of such low ice water content clouds from the model still leaves an apparent model overestimate of cloud fraction by up to a factor of two for these high altitude ice clouds.

7. SPACEBORNE USE OF 215 AND 94GHZ RADARS.

Hogan and Illingworth (2000) have shown that simultaneous observations of reflectivity with 35 and 94GHz ground based radars can be used to provide an estimate of ice particle size. The large particles Mie scatter at the higher frequency and so there is a measurable reduction of reflectivity at 94GHz. At ground level the use of frequencies higher than 94GHz is not possible because of the attenuation by the high levels of absolute humidity. Hogan and Illingworth (1999) show that from space this restriction is much less severe because the satellite is looking down at ice clouds through cold dry atmosphere and, for example, the total two–way attenuation looking vertically down through a standard tropical atmosphere to the freezing level at 215GHz is only 1dB. Figure 8 displays the predicted values of dual wavelength ratio as a function of the median volume diameter for an exponential distribution of ice particles. They recommend the frequency pair 215GHz and 79 or 94GHz. If the dual wavelength ratio can be measured to 1dB then it should be possible to estimate median diameters down to about 150μm. The sensitivity of a spaceborne radar at 215GHz should not be a major restriction. Although the transmitted power from available tubes may be 12dB lower at 215GHz than 94GHz, this is offset by the 14dB increase in sensitivity due to increased scattering efficiency.

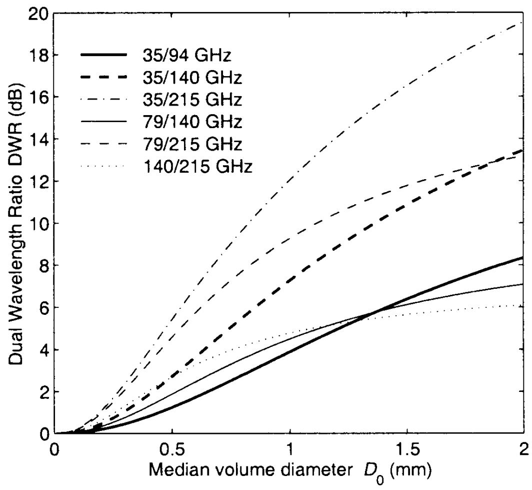


Figure 8: Dual wavelength ratio of reflectivity as a function of median volume diameter for ice particles with an exponential distribution.

8. CONCLUSIONS.

Based on an analysis of three months of simultaneous ground based radar and lidar observations we draw the following conclusions:

a) Radar and lidar Sensitivity.

For the proposed spaceborne sensitivities of −35dBZ for the radar and 8 10^{-7} m^{-1} sr^{-1} for the lidar then the radar fails to detect only 1% of the radiatively significant ice clouds sensed by the lidar.

b) Cloud base and cloud top detection for ice clouds.

For the proposed spaceborne sensitivities we conclude that the cloud base sensed with radar and lidar agree to within 200m for 73% of the time, and to within 400m for 95% of the time. These differences are not significant when estimating the radiative properties of clouds. The agreement can be improved if the lidar sensitivity is increased.

c) Embarking the radar and lidar on different platforms.

Because of the inhomogeneity of ice clouds if the lidar and radar footprints are separated by 3km, then the root mean square error in the radar/lidar backscatter ratio will be at least 70%; this could compromise the use of such a parameter to estimate ice particle size.

d) Cloud overlap.

Although the use of maximum–random overlap is used by nearly all models, the radar data shows that vertically continuous clouds are only maximally overlapped for small vertical separations. When the separation reaches 4km the cloud overlap is essentially random.

e) Comparison of fractional cloud cover.

The vertical profiles of fractional cloud cover predicted by the ECMWF operational model are in very good agreement with those measured. The model distinguishes between ice clouds and snow, but if occasions when the snow flux in the model is less than 0.05mm/hr are classified as clouds then the improvement is even better. The lidar indicates that such low snow fluxes are associated with optically thick clouds and so the model really should consider them as clouds from a radiation point of view. There is still a tendency for the model to overestimate ice cloud fraction above 6km by about a factor of two.

f) Dual wavelength radar.

The use of a dual frequency radar operating at 215 and 94GHz appears to have great potential for providing an estimate of the size of ice particles. We suggest the that technological challenge of developing such a system warrants further research.

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References:

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