Stratocumulus Liquid Water Content from Dual Wavelength Radar

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INTRODUCTION

Of all clouds, low-level stratus and stratocumulus have the most profound impact on the earth's radiation budget because of their high optical depth and large global coverage. Microwave radiometry has the capability of measuring the path-integrated liquid water content (LWC) of such clouds, but active measurements are required in order to obtain information on the vertical distribution of liquid water in the cloud. One of the main problems in developing radar algorithms for measuring LWC is the ubiquitous presence of occasional drizzle drops, which contribute negligibly to LWC but dominate radar reflectivity such that the absolute value of reflectivity is essentially unrelated to LWC (Fox and Illingworth 1997).

In this paper we use the difference in attenuation between vertically-pointing 35 and 94 GHz radars to measure this parameter. In the Rayleigh regime the attenuation is proportional to LWC and increases with frequency, so there is no need to resort to any empirical relationships and, furthermore, the absolute calibration of the radars is unimportant. The differential-attenuation principle was first proposed for use in rain, although the problems of large drops attenuating in the Mie regime and Mie scattering by hail were difficult to overcome. More recently the concept was applied to clouds when Martner et al. (1993) measured LWC from horizontal scans of a dual-wavelength radar at 10 and 35 GHz, although the two-way differential attenuation per g m^{-3} of liquid water at 10°C is only 1.5 dB km^{-1} at these frequencies, and was only measurable at a resolution of 4 km or worse. At the higher frequencies we are using this figure becomes 7.1 dB km^{-1}, which is clearly measurable even for vertically-pointing radars. The differential attenuation due to atmospheric gases needs to be subtracted before the retrieval can be performed; this is calculated using the temperature and pressure diagnosed by the UK Met. Office (UKMO) Unified Model. For example, at 10°C and mean-sea-level pressure it has a (two-way) value of 1.0 dB km^{-1} if the air is saturated.

Measurements of liquid water path (LWP) and LWC taken during the 1998 Cloud Radar and Lidar Experiment (CLARE'98) at Chilbolton, England are presented. Good agreement is found with the LWP measured by microwave radiometers, giving us some confidence in the derived profiles of LWC.

THEORY

In conventional logarithmic units the reflectivity at frequency f and height z can be written as

$$Z_f = Z + 10\log_{10}\left(\frac{|K_f|^2}{0.93}\right) - 2\int_0^z \alpha_f + \kappa_f \mathrm{LWC}\,dz \ \ \mathrm{dBZ},$$

where Z is the unattenuated reflectivity factor at centimeter wavelengths (for which $|K|^2 = 0.93$), α_f is the one-way specific attenuation coefficient due to atmospheric gases (predominantly molecular oxygen and water vapor) in dB km^{-1}, and κ_f is the specific attenuation coefficient of liquid water and has the units dB km^{-1}(g m^{-3})$^{-1}$. We calculate K and κ_f as functions of temperature using the formulation for dielectric constant of Liebe et al. (1989). The line-by-line model of Liebe (1985) is used to compute α_f as a function of temperature, pressure and humidity. Defining the dual-wavelength ratio as $\mathrm{DWR} = Z_{35} - Z_{94}$, we can then determine the mean LWC in a layer using the DWR measured at the top and bottom (indicated by the subscripts 2 and 1 respectively):

$$\overline{\mathrm{LWC}} = \frac{\mathrm{DWR}_2 - \mathrm{DWR}_1 - \beta - 2\int_{z_1}^{z_2} \alpha_{94} - \alpha_{35}\,dz}{2\int_{z_1}^{z_2} \kappa_{94} - \kappa_{35}\,dz} \ \ \mathrm{g\,m^{-3}},$$

where

$$\beta = 10\log_{10}\left(\frac{|K_{35}(T_2)|^2}{|K_{35}(T_1)|^2}\frac{|K_{94}(T_1)|^2}{|K_{94}(T_2)|^2}\right) \ \ \mathrm{dB}.$$

The temperature and pressure are taken from the UKMO model, and the air is assumed to have a relative humidity of 100% wherever the radar sees cloud. The sensitivity of the retrievals to errors in temperature and reflectivity factor was examined theoretically by Hogan (1998), who found that a dwell time of at least one minute is required to measure Z accurately enough that LWC can be retrieved with a vertical resolution of 150 metres.

INSTRUMENTATION

During the CLARE'98 campaign three ground-based cloud radars were in operation: the 35 GHz 'Rabelais' on loan from the University of Toulouse, the 94 GHz 'Galileo' funded by ESTEC, and the 95 GHz 'Miracle' owned by the GKSS institute near Hamburg. For logistical reasons the radars could not be installed right next to each other; the Rabelais and the Miracle were around 30 m apart and the Rabelais and the Galileo were 100 m apart. Stratocumulus can often be very inhomogeneous for radar, especially when drizzle is present (which is nearly always the case when the cloud is sufficiently deep to allow measurement of differential attenuation). This meant that rather more temporal averaging was needed to overcome the differences in sampled cloud than would have been the case if the radars were next to each other. This was particularly true for the Rabelais and Galileo.

Another important consideration is the near-field effect; the antenna diameters of the Rabelais, Miracle and Galileo radars are respectively 1.4, 1.2 and 0.6 m. Conventionally the far-field approximation is taken to be valid beyond a range of $2D^2/\lambda$, where D is the antenna diameter and λ is the wavelength. The corresponding ranges for these radars are therefore 450, 900 and 225 m. Because the technique relies on measuring small differences in reflectivity, it cannot be used for clouds which lie in the near field of either radar of the dual-wavelength pair, and may even fail beyond this range if the errors associated with the far-field approximation are of the same order as the accuracy required. At a range of $2D^2/\lambda$, reflectivity is underestimated by approximately 10% (0.4 dB), although this figure varies from antenna to antenna.

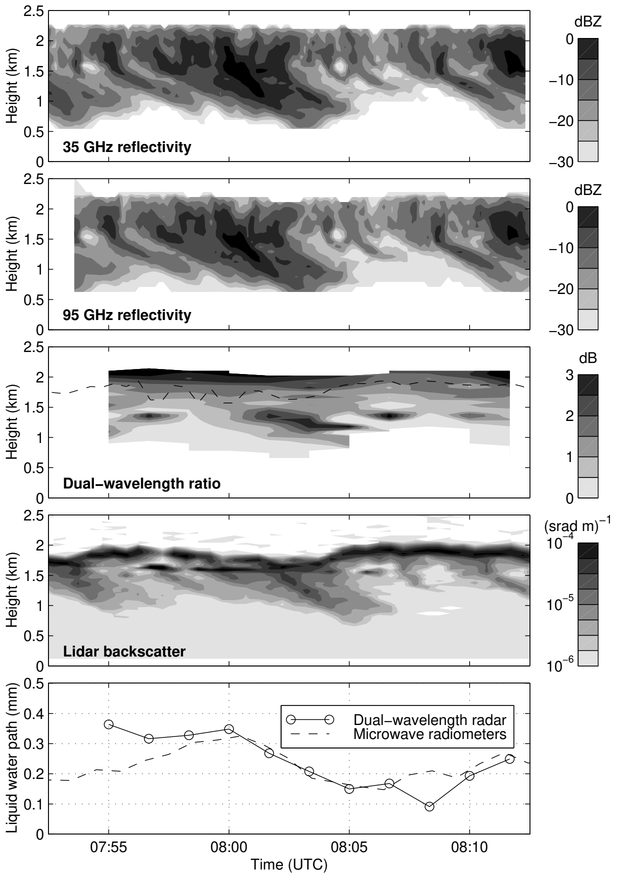

Fig. 1: Dual-wavelength radar measurements taken on 20 October 1998. The first two panels depict reflectivity at 35 and 95 GHz. The third shows the dual-wavelength ratio (DWR) calculated after averaging the two reflectivity fields over 100 seconds and interpolating onto a common height grid. The dashed line shows cloud base derived from lidar backscatter coefficient, which is shown in the fourth panel. The fifth panel shows LWP derived from DWR above cloud base, together with that measured by the microwave radiometers.

The other instruments used were a Vaisala CT75K lidar ceilometer, which was found to be useful for locating cloud base when the cloud was precipitating, and three microwave radiometers at 21.3, 23.8 and 31.7 GHz belonging to the Technical University of Eindhoven in The Netherlands, which provided an estimate of LWP.

RESULTS

There is an obvious trade-off between the accuracy of the retrieved $\overline{\mathrm{LWC}}$ and the vertical resolution, and the most accurate measurement that can be made is of LWP through the whole depth of the cloud. We first present a comparison between LWP measured by dual-wavelength radar and by the three microwave radiometers during the CLARE'98 campaign. The radars used were the 35 GHz Rabelais and the 95 GHz Miracle. The first two panels of Fig. 1 show the reflectivity fields measured by the two radars, each with temporal resolution of 10 seconds. The vertical resolution of the 35 GHz radar was 75 m and that of the 95 GHz radar was 82.5 m. The two reflectivity fields were averaged in time into 100 s bins, and interpolated on to a common 40 m height grid. DWR was then calculated and is shown in the third panel of Fig. 1. It can be seen that through most its depth it fluctuates and so taking the vertical derivative to determine LWC would seem impossible. However, when the backscattered signal from the lidar ceilometer at Chilbolton is examined we see that most of the depth of the radar echo is in fact drizzle falling out of the base of the cloud (which is indicated by the dashed line overlayed on DWR), and the cloud itself only occupies the top 200 to 500 m of the signal. The fluctuating DWR in the drizzle is probably due to Mie scattering at 94 GHz by drops up to 1 mm in diameter, whereas in the cloud above, DWR appears to increase monotonically with height due to attenuation. The LWP of the cloud derived using the method described previously is shown in the last panel, together with that from the three microwave radiometers. The agreement is very good for most of the period although there are two points which show differences of a factor of two between the two measurements. There were no other liquid water clouds above 2.5 km during this period that could have contributed to the radiometer LWP.

The agreement between vertically-integrated LWC is encouraging, so the next step is to measure the vertical profile of LWC through a thicker cloud. Figure 2 shows profiles of Z, DWR and LWC measured by the Rabelais and Galileo radars on 22 October. Because these radars were 100 m apart, 6-minute averaging was required to overcome differences due to the inhomogeneous nature of stratocumulus. It was also necessary to fit a 5th-order polynomial through the measured DWR profile to reduce the noise caused by this separation. The ceilometer measured the base of the cloud to be at 500 m, so the Miracle radar could not be used reliably because its near-field zone extends up to 900 m. The derived profile of LWC looks reasonable, and is comparable to what one would expect for an adiabatic profile, although simultaneous aircraft measurements are

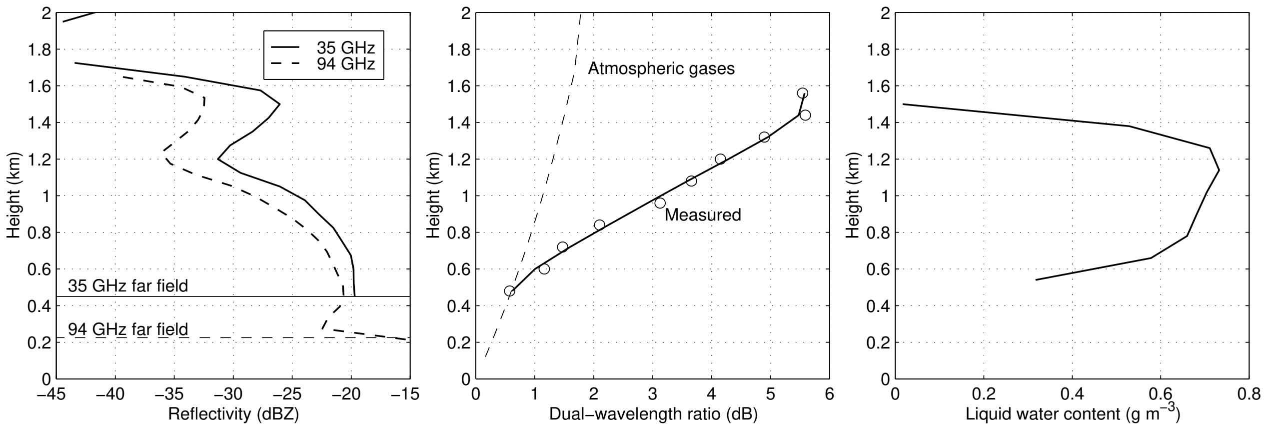

Fig. 2: Dual-wavelength radar measurements taken on 22 October 1998. The first panel depicts a 6-minute average of reflectivity at 35 and 94 GHz, starting at 15:00 UTC. The circles in the second panel show the corresponding dual-wavelength ratio (DWR), and the solid line is a 5th-order polynomial through these points. Also shown by the dashed line is the contribution to DWR from atmospheric gases, calculated from UKMO-analysed thermodynamic fields. The third panel shows the retrieved profile of LWC.

required for validation.

The importance of a good range calibration has become apparent in the course of this study, and it has been found that small changes in the relative range calibration of the two radars can have a surprisingly large effect on DWR, particularly in the vicinity of sharp gradients in reflectivity, such as at cloud top.

CONCLUSIONS AND FUTURE WORK

There is clearly promise in the use of dual-wavelength radars to make vertically-resolved measurements of LWC in stratocumulus, although a limitation of the current study was that the radars were not mounted next to each other and so rather a lot of temporal averaging was required to obtain believable profiles. Since this work was carried out, the Rabelais and Galileo radars have been mounted next to each other, so the next step is to try the technique with much less spatial averaging on recent data. We also intend to make simultaneous measurements of the Doppler spectrum in order to

- Estimate the number of independent pulses from the spectral width, and from this the magnitude of the error in derived LWC;
- Identify when drizzle drops larger than 600 μm are present as these Mie scatter and therefore can bias the retrievals;
- Compare derived LWC with the reflectivity of the cloud-droplet component of the spectrum (as opposed to the drizzle component), as analysis of aircraft-measured size spectra suggest they should be well correlated (Hogan 1998).

Comparison of retrieved liquid water contents with aircraft measurements is seen as essential to validate the technique.

ACKNOWLEDGEMENTS

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. Thanks to Olaf Danne for providing the data from the GKSS 95 GHz radar and to Peter Panagi and Ed Dicks for the UKMO model fields. Thanks also to Jon Eastment for some useful discussions. The CLARE'98 campaign was funded by ESTEC grant 12957/98, and this research also benefited from NERC grant GR3/8765.

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