The retrieval of cloud radiative and microphysical properties using combined near-infrared and microwave radiometry

By J. P. TAYLOR* and S. J. ENGLISH
Meteorological Office, UK

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SUMMARY

The optical depth of a cloud is an important parameter in describing its radiative properties. Many schemes have been developed to retrieve optical depth from measurements of reflectance in the visible or near-infrared. In this paper the impact of cloud inhomogeneity and vertical structure on the retrieval of optical depth is discussed. Retrievals of cloud optical depth and effective radius using the multi-channel radiometer flown on the UK Meteorological Research Flight C130 are presented for clouds studied during the Atlantic Stratocumulus Transition Experiment.

A new technique for retrieving cloud optical depth, which is less susceptible to cloud inhomogeneity, using combined microwave and near-infrared radiometry, is presented. This technique is tested for three flights both in the Azores and the South Atlantic and shows good agreement with in situ measurements. Finally the use of these retrieved parameters in radiation codes is considered.

KEYWORDS: Cloud microphysics Effective radius Optical depth Remote sensing

1. INTRODUCTION

It is widely accepted that stratocumulus plays an important role in the determination of the earth’s climate (e.g. Randall et al. 1984; Ramanathan et al. 1989; Slingo 1990). Marine stratocumulus clouds have a high albedo relative to the underlying sea surface and so are likely to have a major influence on both the local and, by virtue of their extensive coverage, the global radiation balance. Of great interest to those studying greenhouse-gas induced climate change is how these large cloud systems will change in a warmer world. Will their microphysical characteristics and hence radiative properties change so as to enhance or reduce the greenhouse warming? Or will their physical characteristics, such as cover, persistence or depth, change so giving some form of feedback, the sign of which is unknown? In order to answer some of these questions it is first necessary to be able to describe with some confidence the current state of large-scale stratocumulus sheets and broken cloud fields in terms of their radiative and microphysical properties.

Randall et al. (1984) suggested that an increase of the global coverage of stratocumulus of around 4% would be sufficient to offset the 2–3 K rise in global temperature predicted as a result of doubling the levels of atmospheric carbon dioxide (CO₂). It should be noted, however, that this is not a statement that cloud cover will increase in a warmer climate; cloud cover could possibly decrease in a warmer climate, with an increase in convective cloud at the expense of stratiform cloud (Taylor and Ghan 1992). The climate-sensitivity studies carried out by Randall were obtained using much simpler models than those currently available; also the spatial distribution of stratocumulus is non-uniform and hence the combined effects of increased CO₂ and stratocumulus cover are likely to vary locally. The radiative properties of clouds are governed by their microphysical properties, and changes in these properties due to variations in cloud condensation nuclei may provide a mechanism for the biological or anthropogenic modulation of global climate (Charlson et al. 1987).

The radiative properties of stratiform water clouds can be represented in radiation codes by parametrizing the extinction coefficient, single-scattering albedo and asymmetry factor in terms of the liquid-water content and cloud-droplet effective radius (Slingo and

* Corresponding author: Meteorological Research Flight, Meteorological Office, DRA Farnborough, Hampshire GU14 6TD, UK.
Schrecker 1982), the effective radius of a cloud-droplet distribution being given by the following relation:

\[ r_e = \frac{\int n(r)r^3 \, dr}{\int n(r)r^2 \, dr} \]  \hspace{1cm} (1)

where \( r \) is the droplet radius and \( n(r) \) the concentration of droplets of radius between \( r \) and \( r + dr \).

Slingo (1990) carried out a sensitivity study of the earth’s radiation budget to changes in low clouds. He used a three-dimensional general circulation model and his results showed that the top-of-atmosphere radiative forcing by doubled CO\(_2\) concentrations can be balanced by modest relative increases of \( \sim 15-20\% \) in the amount of low clouds and 20–35% in liquid-water path, and by decreases of 15–20% in mean droplet radius. The sign of the cloud feedback in a warmer climate is not known, and although many authors present the changes in cloud property required to offset the effects of increased greenhouse-gas concentrations it should be remembered that there is the possibility that clouds may react to enhance the warming.

None of the current general circulation models includes the ability to modify microphysical properties of clouds, such as droplet radius, such parameters usually being assigned some fixed value. The future inclusion of such variables in climate models is crucial, as their presence could greatly change our conclusions about the effects of greenhouse warming. Work by Jones et al. (1994) with the UK Meteorological Office’s Unified Model, using a parametrization of effective radius by Martin et al. (1994), has shown that the inclusion of a variable droplet size in a climate model has a significant impact on the radiation budget.

In order to understand the current state of the atmosphere with respect to the role of clouds, and to improve our predictions of cloud radiative feedback, it is first necessary to be able to characterize the current state of clouds on a global basis and this could be done potentially by spaceborne remote sensing of cloud microphysical parameters.

The International Satellite Cloud Climatology Project* (ISCCP) (Rossow and Schiffer 1991) maintains a detailed record of global cloud properties which includes cloud optical depth, \( \delta \), and may in the future include cloud-droplet effective radius, \( r_e \). It is important that satellite retrieved parameters are verified against \textit{in situ} data where possible and that retrieval schemes are tested using aircraft data.

A technique for retrieving cloud optical thickness using asymptotic expressions for the reflection function of an optically thick conservative scattering atmosphere has been discussed by King (1987). He noted that uncertainties in the prescribed asymmetry factor can contribute to uncertainties in the optical thickness of 20% even under conditions of plane parallel and homogeneous clouds with perfect measurements. A principal assumption in the retrieval scheme of King (1987) is that the cloud has sufficient horizontal extent and horizontal homogeneity to be considered locally plane parallel. Rawlins and Foot (1990) also developed a scheme for the retrieval of \( \delta \) and \( r_e \). Their retrievals of \( \delta \) during the First ISCCP Regional Experiment (FIRE) were in reasonable agreement with the \textit{in situ} observations, although it is noted that the measurement of \textit{in situ} optical depth is difficult and not necessarily representative of that measured remotely. Nakajima et al. (1991) also present retrievals of \( \delta \) and \( r_e \) from the FIRE campaign. Their results showed a slight tendency for a retrieval scheme using remotely sensed data to overestimate \( \delta \) when the optical depths were low, and a slight tendency to underestimate it in optically thick clouds. Nakajima et al. also noted that the measurement of \textit{in situ} optical depth for verification processes was somewhat problematical. The aim of this paper is to examine the unrealistic

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assumptions inherent in several retrieval techniques and their consequences. A possible improvement in the retrieval of cloud optical depth incorporating the use of near-infrared and microwave radiometry is presented.

In this paper a retrieval scheme for obtaining $\delta$ and $r_c$ from measurements of cloud reflectance in the near-infrared is presented for two stratocumulus cloud cases; one in maritime air the other in a continental airmass. This scheme has been previously described by Rawlins and Foot (1990), and a development of it presented by Taylor (1992) has shown good agreement with in situ data. Further tests of the scheme are presented by Taylor (1993) and Taylor (1994) where it is tested in a wide variety of cloud types. The retrieval of cloud-droplet effective radius has been shown to be in good agreement with in situ data, as will be discussed in section 7 of this paper. However, many comparisons have shown that the retrieved optical depth is typically larger than the in situ measurements, particularly for low optical depths. These overestimates will be discussed in section 4 with some modelling studies using the Discrete Ordinates Radiative Transfer (DISORT) code used to analyse the causes. In section 6 a technique using combined data from a microwave radiometer and a visible/near-infrared radiometer to retrieve cloud optical depth is presented as an alternative, more accurate technique. This new scheme is tested for three cases presented in section 7. One major point about these various retrieval techniques is how the results are to be treated. The retrieval results can be used to build up some global climatology of a particular microphysical or radiative parameter, which in itself is a useful exercise. Alternatively the retrievals could be used to infer the radiative balance of the cloud. If the latter is to be done then the question remains as to how the retrieved parameters should be treated in radiation models? These points are discussed in section 8 of this paper, where the use of these data in modelling studies is discussed and some results using the Slingo and Schrecker (1982) short-wave radiation model are presented.

2. Aircraft instrumentation and techniques

The UK Meteorological Office (UKMO) Meteorological Research Flight (MRF) operates a Royal Air Force C130 Hercules aircraft which has been extensively modified to make it suited to a wide range of atmospheric research work. The instrumentation on the C130 can be grouped into several basic categories: standard meteorological and navigational equipment, aerosol and cloud-physics instrumentation, chemistry instrumentation and radiometric instrumentation.

It is beyond the scope of this paper to describe fully all the instrumentation on the C130. Emphasis will, therefore, be given to the main instruments used in this work. A full description of the standard meteorological instrumentation is given by Nicholls (1978), of the cloud-physics instrumentation by Brown (1992) and of the radiation instrumentation by Kilsby et al. (1992) and Saunders et al. (1992).

(a) Aerosol and cloud-physics instrumentation

Liquid-water content (LWC) is measured using a Johnson–Williams hot-wire probe. The meter is insensitive to droplets larger than about 30 $\mu$m radius, and its accuracy is $\pm 10\%$.

The cloud-particle size distribution is measured by a Knollenberg FSSP (Forward Scattering Spectrometer Probe). Particles are assumed to be perfectly spherical and composed of pure water. Measurements of the rate of sizing events and the true air speed allow inference of droplet-number densities. The instrument records the number of droplets detected in 15 size categories in one of four ranges of droplet diameters selected by the operator: 2 to 47 $\mu$m, 2 to 32 $\mu$m, 1 to 16 $\mu$m or 0.5 to 8 $\mu$m, where all the sizes are
droplet diameters. The FSSP does, however, have some major limitations. Specifically, the sample volume particle-rejection criteria are not defined with sufficient accuracy to enable integrated quantities such as LWC to be obtained with any great accuracy directly from the spectra. For this reason, in this work, LWCs are taken from measurements by the Johnson–Williams probe. The effective radius is taken from FSSP measurements and we therefore assume that the FSSP measures the spectral shape accurately although the absolute concentration may be in error.

The FSSP is calibrated by sampling glass beads of known sizes, allowances having to be made for the difference in refractive index of glass from that of water. The accuracy of the FSSP sizing is at best ±1 μm.

Aerosol concentration is measured by a Knollenberg PCASP (Passive Cavity Aerosol Spectrometer Probe) fitted to the aircraft. This instrument counts and sizes aerosol in 15 size intervals covering the size range from 0.1 to 3.0 μm diameter. Heaters in the tip of the inlet pipe to the PCASP, and the sheath of dry air used to ‘focus’ the sample into the path of the laser beam, will both act to dry the aerosol. However, if the aerosol is particularly moist, or indeed saturated within cloud, then spurious results can be obtained. For these reasons measurements made by the PCASP are used only out of cloud.

(b) Radiometric instrumentation

Microwave radiometer. The Microwave Airborne Radiometer Scanning System (MARSS) is flown on the C130. The MARSS is fully described by Jones (1991) and English et al. (1994a). In brief it is a two-channel radiometer operating at 89 and 157 GHz. Due to its location on an adapted window of the C130, the MARSS scans along-track in a plane tilted 12° from the vertical. The angle defining the measured polarization rotates with the scan angle, and for the 89 GHz channel an almost equal mix of horizontal and vertical polarizations at the extreme views is detected. In order to increase the polarization information a polarizer has been added to the 157 GHz channel which rotates the polarization vector through about 45°. Consequently the 157 GHz channel now measures vertical polarization in the extreme rear view, and horizontal polarization in the extreme forward view. In this study only the nominal nadir view for both channels is used, such that the polarization is very small but is nevertheless incorporated into the retrieval.

Nine upward views, nine downward views and two calibration targets are observed during each scanning cycle which takes just under 3 seconds. The nine views are nominally at intervals of 10° from −40° to +40° viewing along the track. The calibration uses a hot target (at 334 K) and a cold target which is allowed to remain at ambient temperature (230–290 K).

The C130’s instrumentation is able to measure all parameters required by the microwave radiative-transfer model for comparison with the observed MARSS microwave brightness temperatures. An aircraft profile of temperature and humidity is used combined with a radiosonde or model atmosphere for levels above the maximum aircraft altitude. Wind speed at flight altitude is calculated using an inertial navigation system. The surface wind speed is calculated using a boundary-layer model (Ezraty et al. 1985) from that measured at the bottom of an aircraft profile (usually about 17 m).

A full description of the scheme for retrieving cloud liquid-water path (LWP) using microwave radiometry is given by English et al. (1994b). For completeness, the key components of the scheme will be presented here. The frequencies of the MARSS radiometer show sensitivity to both water vapour and liquid water absorption. A gaseous absorption model based on that of Liebe (1989) is used and has been compared with observations by English et al. (1994a). As views in the nadir are being used in this work the microwave
emissivity of the surface needs to be taken into account. A geometric sea-surface emissivity model using a Gaussian distribution of facets’ slopes (Cox and Munk 1954) is used to represent emission from the wind-roughened ocean.

For liquid clouds the scattering coefficient is negligible so the total extinction coefficient $K_{ex} \sim K_a$ (the Rayleigh absorption coefficient). The extinction can be calculated using the Rayleigh approximation which is sufficiently accurate for the size of droplets commonly observed within stratocumulus clouds. The largest departure of the Rayleigh approximation from the Mie-theory result is around 2%, which is small compared with the other uncertainties in the retrieval scheme. The microwave radiative-transfer model is nonlinear, so a damped Newtonian iterative method is adopted for the retrieval. This is the maximum probability solution in the linear limit assuming Gaussian statistics (Rodgers 1976).

For nadir views the cloud liquid water in the path from the aircraft to the surface along with the surface wind speed are the free parameters. The dependence on wind direction is neglected as the wave-slope distribution is assumed to be Gaussian. The sea surface temperature measured by the C130’s Barnes PRT-4 infrared radiometer, whilst flying at a height of 30 m, is used and is a constant in the retrieval scheme. An aircraft profile of temperature and humidity is used to model the water-vapour absorption. For thin stratocumulus clouds the uncertainty in the solution for cloud LWP is of the order of 50 g m$^{-2}$ but is dependent on the magnitude of the total water column and the vapour loading within the column. This is with the use of an aircraft water-vapour profile, if a satellite retrieval were to be carried out then these uncertainties could increase as a temperature and humidity profile would also need to be derived.

**Multi-channel radiometer.** The multi-channel radiometer (MCR) (Rawlins and Foot 1990) measures radiances in 14 narrow spectral bands between 0.55 µm and 12 µm. The MCR is mounted in a pod on the port wing of the aircraft and can view in the zenith, nadir and at angles out to 60° from the nadir. Internal calibration targets can also be viewed for calibration of the thermal infrared channels. The field of view of the optical system is 1.5°. The incident radiation is split into four streams, two thermal and two solar, and viewed by four detectors. Each detector has a rotating filter wheel with four filters. One complete revolution of a filter wheel takes 4 seconds.

The ideal calibration source for the MCR is one whose spectral power distribution is identical to that of the sources to be observed in the field. When measuring scattered solar energy in the atmosphere, the sun is a suitable calibration source. It is necessary, however, to attenuate the solar irradiance with a diffuser plate which acts as a uniform extended source. On the C130 the sun can be used as the primary calibration source and is viewed through a diffuser plate which forms an integral part of the upper shutter of the port maxi-pod, which can be moved into the MCR view. Radiances incident on the diffusing plate are determined using extraterrestrial irradiance values in conjunction with atmospheric transmission values calculated by LOWTRAN 7 code. The LOWTRAN 7 model (Kneizys et al. 1988) calculates atmospheric transmittance and radiance for a given atmospheric path at a spectral resolution of 20 cm$^{-1}$. This program is used to compute the atmospheric transmission for the direct beam on a slant path using the observed water-vapour profile and solar zenith angle. Ideally a profile from the flight being analysed is used in the computation in LOWTRAN 7, and a model atmosphere assumed for higher levels. Pierlussi et al. (1989) and Pierlussi and Tsai (1987) discuss the molecular band absorption in LOWTRAN 7 and compare the results with a line-by-line model; the agreement is found to be good and so gives confidence in using the LOWTRAN 7 code in the MCR calibration. The calibration runs are generally done at high level (greater than 7 km) to minimize the depth of the atmospheric column between sun and instrument. Once the radiances at the top
of the diffuser plate have been calculated they are combined with the optical response of
the diffuser plate and the spectral response of the filters to obtain the radiances as perceived
by the MCR.

Solar calibrations can only be carried out for a small range of solar zenith angles
because of the problems of shadowing of the diffuser plate by the aircraft superstructure. It
is also prudent to have two means of calibration of the MCR so that errors or deterioration
in the components of any one calibration technique can be monitored. For this purpose a
laboratory calibration source is used; this consists of a highly reflective spectralon plate
(the reflectance properties of which are known) illuminated by a calibrated quartz halogen
tungsten lamp.

The gain of the MCR channels is temperature dependent; therefore one calibration
is not sufficient to characterize the instrument. The MCR is calibrated in flight at every
opportunity, and on the ground using the portable laboratory source. Full details of the
visible and near-infrared calibration of the MCR are given by Taylor (1993).

3. THE RETRIEVAL OF OPTICAL DEPTH AND EFFECTIVE RADIUS

Cloud optical depth, δ, and cloud droplet effective radius, re, can be retrieved using
measurements of the reflectance at two wavelengths in the visible or near-infrared. The
reflectivity in a spectral region of weak liquid-water absorption (e.g. 0.55 μm or 1.25 μm)
is relatively insensitive to changes in re but monotonically increases with increasing δ,
allowing a retrieval of δ by reference to a look-up table of model reflectances for varying
clouds. This retrieved δ can then be combined with the reflectance at a wavelength of
strong liquid-water absorption (e.g. 2.01 μm or 2.26 μm) to retrieve an re. A thorough
description of the scheme is given by Rawlins and Foot (1990) and an improvement to
the scheme, which removed the occurrence of anomalous absorption, often cited by other
authors, is given by Taylor (1992). Other examples of using the retrieval scheme are given
by Taylor (1993) and Taylor (1994). The in situ optical depth can be calculated using an
aircraft profile of LWC (g m⁻³) and re, (μm) to compute δ over the depth of the cloud (z₁
to z₂) using the relation:

\[ \delta \approx \int_{z_1}^{z_2} \frac{3LWC}{2\rho_w r_e} \, dz \] (2)

where ρw (g m⁻³) is the density of liquid water.

4. UNCERTAINTIES IN THE DETERMINATION OF CLOUD OPTICAL DEPTH

Previous results have shown that there is a degree of uncertainty in the retrieval of δ
with the retrieved value often being larger than that measured in situ. In regions of cumulus
intrusion δ often increases above that which can be explained by the increased liquid water
and cloud depth (Taylor 1994). Such high optical-depth retrievals, particularly in clouds
of low cloud-top re, have been described by Nakajima and King (1990) and Taylor (1992,
1993, 1994). In this section a brief description of possible causes for uncertainties in the
retrieval of δ will be given.

To aid in the study the DISORT code developed by Stamnes et al. (1988) has been used.
DISORT is a radiative-transfer code that allows the calculation of azimuth-dependent bi-
directional reflectance in a multi-layered plane-parallel medium. The International Associ-
ation of Meteorology and Atmospheric Physics (IAMAP) Radiation Commission prepared
a numerical comparison of different methods of modelling radiative transfer discussed by
Lenoble (1977). The DISORT code has been tested against the IAMAP results and good
agreement was found.
(a) The variation of Mie parameters

The retrieval scheme, which has been described, and the results, which are presented later in this paper, use a look-up table of reflectance, built up for various combinations of cloud $r_c$, $\delta$ and solar zenith angle, $\theta$. Measured reflectances, made with the MCR viewing in the nadir, are compared with these look-up tables and $\delta$ and $r_c$ are found for the cloud. These look-up tables were constructed from model simulations of single-layer clouds of optical depth $\delta$ and effective radius $r_c$ based on a log-normal droplet distribution. The measurements are made over clouds which have a vertical gradient of $r_c$ and LWC, and not necessarily a linear change in $\delta$ through the cloud.

Figures 1 and 2 show the asymmetry factor, $g$, and the single-scatter albedo, $\omega_0$, as functions of $r_c$ for wavelengths of 0.55 and 1.25 $\mu$m, respectively, computed using Mie theory. Both of these wavelengths can be used in the retrieval of optical depth. At 0.55 $\mu$m $\omega_0$ is unity for all $r_c$; in other words there is no absorption. At 1.25 $\mu$m $\omega_0$ is near unity but decreases slightly as $r_c$ increases. In clouds where $r_c$ decreases through the cloud from top to bottom, at 1.25 $\mu$m the amount of absorption decreases slightly. Twomey (1971) found that for $\omega_0 > 0.999$ the absorption is too weak to modify the reflected or transmitted radiation, but when $\omega_0$ is below that value absorption starts to have an influence. At 1.25 $\mu$m $\omega_0$ drops below 0.999 only for droplet sizes greater than 12 $\mu$m. The effects of changes in $\omega_0$ through the depth of a cloud are therefore likely to be small.

At both 0.55 $\mu$m and 1.25 $\mu$m $g$ changes quite markedly with $r_c$. For larger droplets $> 16$ $\mu$m at both wavelengths $g$ is a constant; $g = 0.87$ at 0.55 $\mu$m and $g = 0.86$ at 1.25 $\mu$m. As one moves to lower $r_c$, in a typical stratuscumulus cloud nearer the cloud base, $g$ decreases. This decrease is most rapid, of the two wavelengths considered, at 1.25 $\mu$m where it drops to 0.76 for an $r_c$ of 2 $\mu$m.

This variation in $g$ with $r_c$ may be important in explaining the tendency of the retrieval scheme to overestimate $\delta$. In computing the look-up tables a single-layer cloud of optical depth $\Delta$ was used with a single droplet size $r_c^m$. This means that at cloud top we have $\delta = 0$ and at cloud base $\delta = \Delta$. In a realistic cloud of optical depth $\Delta$ we have $\delta = 0$ at cloud top and $\delta = \Delta$ at cloud base, but LWC and $r_c$ decrease downward through the cloud. This means that in the real cloud $g$ decreases through the cloud whereas in the single-layer cloud $g$ is constant, the value pertaining to the chosen $r_c$. The decrease in $g$ through the cloud from top to bottom, which occurs in the real cloud but not in the model cloud, represents an increased proportion of the total scattering into the backward hemisphere. Therefore, in a real cloud with varying $r_c$, as a photon progresses through the cloud the probability of it being scattered into the backward hemisphere increases, and hence the reflectance of the realistic cloud of optical depth $\Delta$ will be greater than the single-layer cloud of optical depth $\Delta$ in which $g$ is constant. This increased reflectance will be perceived by the retrieval scheme as a single-layer cloud of greater optical depth, $\Delta + x$. The value of $x$ will be dependent on the nature of the real cloud.

One can see from Figs. 1 and 2 that $x$ will be smallest for clouds where $r_c$ at cloud top is large and hence less change in $g$ through the depth of the cloud. The value of $x$ will be largest for clouds of low cloud-top $r_c$ at wavelengths of 1.25 $\mu$m. In other words the error in optical-depth retrieval will be larger for a cloud with cloud-top $r_c$ of 6.0 $\mu$m than for a similar depth cloud where the $r_c$ at cloud top is 12 $\mu$m. The vertical gradient of $r_c$ is, therefore, paramount in determining the errors in the retrieved optical depth, and the shallower the gradient of $r_c$ with height the more accurate the retrieval will be.

Using DISORT the reflectance at 1.25 $\mu$m, normal to the cloud top, of two clouds of optical depth $\delta = 30$ has been modelled. In one case the cloud is a single-layer `slab' cloud with constant $r_c$. In the other case a more realistic cloud with ten levels is modelled where
$r_e$ decreases with depth through the cloud in the same manner as described in section 5. Figure 3 shows the reflectance at 1.25 $\mu$m for this cloud as a function of $r_e$. For the slab cloud this is the effective radius throughout the depth of the cloud whereas for the real cloud it is the effective radius at cloud top.

The results of the modelling show that for small cloud-top $r_e$ the 'real' cloud reflectance is larger than the slab cloud, whereas for larger cloud-top $r_e$, where the change in asymmetry factor through the cloud is less, the reflectance for the two clouds tends to the same value. A larger reflectance of the realistic cloud would be interpreted by the retrieval scheme as being due to a larger optical depth, and hence the retrieved optical depth would be an overestimate of the true value. It should be noted that these calculations have only been carried out for a single vertical gradient of $r_e$ within the cloud and that they may differ
for other cases. In stratocumulus, however, an increase in $r_e$ and LWC with height is the normal.

Using a simple two-stream approximation (Houghton 1986), with irradiances $F \uparrow$ and $F \downarrow$, and assuming we have pure scattering, $\omega_0 = 1$, then the radiative-transfer equation for solar radiation incident on a uniform cloud can be given as:

$$\frac{dF \downarrow}{d\delta} + (F \downarrow - F \uparrow)(1 - f) = 0$$

(3)

$$\frac{dF \uparrow}{d\delta} + (F \downarrow - F \uparrow)(1 - f) = 0.$$  

(4)

Here $f$ is the fraction of the scattered radiation which in one scattering event goes into a forward direction. Given these relationships the cloud albedo, $A$, and transmissivity, $\tau$, become

$$A = \frac{\delta(1 - f)}{1 + \delta(1 - f)}$$

(5)

$$\tau = \frac{1}{1 + \delta(1 - f)}.$$  

(6)

The fraction $f$ can be expressed in terms of the asymmetry factor as

$$f = \frac{g + 1}{2}.$$  

(7)

Taking values from Figs. 2 and 3 one finds that for a cloud with $r_e$ of 5 $\mu$m a difference in $\delta$ of 15% will arise between the slab and real clouds, with the real cloud giving the larger optical depth. This simple two-stream approach shows that the variability $g$ within the cloud may be significant in accounting for some of the differences observed in $\delta$ between the retrievals and the in situ calculations.
(b) In situ measurements

Another source of error could be in the calculation of $\delta$ from the aircraft profiles. This has been carried out using the LWC measured by the Johnson–Williams probe. Calculations using the FSSP integrated liquid water consistently gave even lower optical depths as the FSSP tends to underestimate the water content, sometimes by as much as 50%. There is still considerable debate as to the absolute accuracy of LWC measurement, and further work in this area is required to clarify the problem. An independent measurement of LWP can be made using microwave radiances, and these values are generally more consistent with measurements from the Johnson–Williams probe.

It is clear from the results of the retrievals and the arguments presented that an accurate optical depth could only be reliably retrieved, using visible or near-infrared wavelengths, if the vertical structure of $r_e$ were known. This suggests, therefore, that using visible or near-infrared wavelengths to retrieve $\delta$ may not be the best technique and other methods should be considered.

5. Effect of cloud inhomogeneity on the retrieval of cloud properties

The retrieval of cloud droplet $r_e$ and cloud $\delta$, using MCR reflectances, described in previous papers and presented above, has used a look-up table of reflectances for varying cloud and solar conditions which was constructed using a vertically homogeneous cloud sheet. However, terrestrial clouds contain significant vertical variation in both LWC and $r_e$, as is shown in Fig. 12; it is therefore necessary to study what effect this variation is likely to have on cloud reflectance at the wavelengths used in the MCR retrieval.

Observations have shown that in stratocumulus both cloud liquid water and $r_e$ are linear functions of height. Following the method of Nakajima and King (1990) the liquid water, $w$, can be written in the form:

$$w(z) \simeq Az + B$$

and $r_e$ in the form:

$$r_e(z) \simeq az + b.$$  

(8) (9)

If one assumes that the extinction efficiency factor equals 2 (the large-drop approximation), the cloud optical thickness between level $z$ and the top of the cloud can be estimated as follows:

$$\delta \simeq \frac{3}{2\rho} \int_z^{\infty} \frac{w(z')}{r_e(z')} \, dz' \simeq \frac{3Ar_e}{2\rho_0 a^2} \left( 1 - \hat{r} + \frac{w_l r_b - w_b}{w_l - w_b} \ln \hat{r} \right)$$

where $\rho$ is the density of liquid water, $w_l$ and $w_b$ the LWC at cloud top and base, respectively, $r_l$ and $r_b$ the effective radius at cloud top and base, respectively, and $\hat{r}$ the normalized effective radius defined by

$$\hat{r} = r_e(z)/r_l.$$  

(10) (11)

If we assume that $w_b = 0$ then the normalized optical depth is given as:

$$\hat{\delta} = \frac{\delta}{\delta_e} \simeq \frac{1 - \hat{r} + \hat{r}_b \ln \hat{r}}{1 - \hat{r}_b + \hat{r}_b \ln \hat{r}_b}$$

(12)

where $\delta_e$ is the total optical depth of the cloud. It can be seen from this equation that $\hat{\delta}$ does not depend on the LWC and is solely determined by $\hat{r}$ at cloud base. In this work $\hat{r}_b = 0.5$.
and the droplet distribution is defined as a log-normal distribution of the form:

\[
n(r) = \frac{C}{(2\pi)^{1/2} \sigma r} \exp \left\{ - \left( \frac{(\ln r - \ln r_0)^2}{2 \sigma^2} \right) \right\}
\]

(13)

where \( C \) is a constant, \( r_0 \) the mode radius and \( \sigma \) the standard deviation of the droplet distribution (\( \sigma = 0.35 \) in these calculations). The effective radius is given by (Hansen and Travis 1974)

\[
r_e = r_0 \exp(5\sigma^2/2) \Rightarrow r_0 = \frac{r_e}{\exp(5\sigma^2/2)}.
\]

(14)

The choice of \( \hat{r}_b = 0.5 \) is within the range of microphysical measurements presented in the literature (Slingo et al. 1982; Albrecht et al. 1988), although the results presented are not very sensitive to its exact value.

The reflectance normal to the cloud top was calculated at 1.25 and 2.26 \( \mu m \) using DISORT for a cloud of ten levels, at equal effective-radius intervals, for all combinations of \( \delta_c = 4, 8, 12, 20, 25, 30, 40 \) and 50, \( r_t = 4, 6, 8, 10, 12, 14, 16 \) and 20 \( \mu m \) and for \( \theta = 15^\circ, 30^\circ \) and 60°. The cloud layer was modelled as overlying a Lambertian surface with an albedo of 0.05. Gaseous absorption within and above the cloud was neglected.

In order to study the effect of vertical structure on the optical depth retrieved by the MCR the reflectances for the vertically inhomogeneous clouds modelled with DISORT have been input to the program which is usually used to retrieve optical depth from MCR reflectances. The model reflectances are fed in to the MCR retrieval program as if they were aircraft measured reflectances. The MCR retrieval program uses a look-up table of reflectances that was constructed assuming that the cloud is vertically homogeneous; therefore we will in effect be computing what the MCR retrieval scheme would produce were the aircraft to fly over a horizontally homogeneous cloud with the same vertical structure as that modelled in DISORT.

Figure 4 shows the ratio of MCR retrieved optical depth to the total optical depth of the cloud as a function of \( r_t \) and for \( \theta \) equal to 30°. Little change in the pattern of retrievals was observed at different solar zenith angles so for brevity they are not shown.

It should be noted that some of the combinations of \( r_t \) and \( \delta_c \) shown are not physically realistic and unlikely to be observed in real clouds. For example, if we consider a vertically homogeneous cloud with the same droplet size throughout as that at the top, \( r_t \), and choose some arbitrary thickness of 100 m, then when the droplet radius at cloud top is 4 \( \mu m \) a value of \( \delta_c = 12 \) or above would require a very large number of droplets (in excess of 1000 cm\(^{-3}\)), a concentration which is not observed in the real atmosphere; even in the most polluted air, droplet concentrations may only reach 600 cm\(^{-3}\). Even if we ignore the unrealistic combinations of \( \delta_c \) and \( r_t \) we can see from Fig. 4 that for small \( r_t \) the retrieval scheme overestimates the cloud optical depth considerably, in quite an erratic manner, by between 30% and 50%. The erratic nature of the retrieved optical depth is due to the multiple-value problem whereby the combination of reflectances at 1.25 \( \mu m \) and 2.26 \( \mu m \) can be representative of several different combinations of \( r_e \) and \( \delta \); the exact value being output by the program is dependent on the iterative scheme being used.

As the value of \( r_t \) increases, the error in the retrieved cloud optical depth decreases to within \( \pm 10\% \) for \( 8 < r_t < 15 \mu m \); note that an optical depth of 4 with this size of droplet would require a very low droplet concentration and is unlikely to be observed in reality. As the value of \( r_t \) increases further to values in excess of 15 \( \mu m \) the accuracy of the retrieved optical depth decreases to \( \pm 20\% \). Modelling studies with DISORT showed the magnitude of the error in retrieved optical depth to be dependent on \( r_t \), the optical depth of the cloud itself, and \( \theta \).
Figure 4. Ratio of the multi-channel radiometer retrieved optical depth to the total cloud optical depth as a function of cloud-top effective radius for a solar zenith angle of 30° for varying transmissivities, τ.

(a) The effect of cloud-top slope on the MCR retrieval scheme

The DISORT code can only handle the case of horizontally homogeneous clouds. However, an estimate of the effects of a sloped cloud surface can be obtained by altering the geometry of the sun with respect to the viewing angle of the MCR, and noting how the reflectance and hence retrieved $r_e$ and $\delta$ are affected.

Figure 5 shows the geometry used for these simulations where cloud-top slope is varied through $\pm 10^°$ to the horizontal. For example, to simulate the MCR nadir view of a cloud sloped up at $10^°$ into sun with $\theta$ equal to $30^°$ the DISORT model is run with $\theta$ equal to $40^°$ and the reflectance at $10^°$ at the same azimuth as the sun is calculated. The reflectance calculated at the two wavelengths (1.25 $\mu$m and 2.26 $\mu$m) for these sloped clouds is then fed into the retrieval scheme with the fixed solar geometry of $30^°$. In this way it is possible to simulate what the retrieval scheme would give for a sloping cloud top which is assumed to be flat. The results of this simulation are shown in Fig. 6 where the cloud angle is as defined in Fig. 5.

At a slope of $-10^°$ (i.e. cloud slopes away from the sun) we observe that the retrieved optical depth is reduced to $\approx 26$, a reduction of 23.5% to that retrieved if the cloud were flat. For the same cloud slope the reduced reflectance, relative to the horizontal cloud case, has caused an increase in retrieved $r_e$ of $\approx 4.5\%$. A cloud slope of $+10^°$ has the opposite results on the retrieved microphysical properties with an increase in $\delta$ and a decrease in $r_e$.

A slope in stratocumulus cloud top of $\pm 10^°$ has not, on a large scale, been observed by the authors in their observations. However, the smaller-scale inhomogeneities in the tops of stratocumulus caused by cumulus intrusion or strong convection within the main cloud deck can have slopes of this magnitude and possibly larger. The field of view of the MCR is only $1.5^°$ and it is, therefore, likely that such features would be seen quite clearly. The typical length-scale over which the MCR measurement is averaged is around 80 m. These results suggest, therefore, that inhomogeneity in the cloud top can cause errors in retrieved optical depth of $\pm 23\%$ and a retrieved effective radius of $\pm 5\%$; and that if the cloud top is
very disturbed (e.g. by a cumulus cloud intruding from below) larger errors caused by the assumption that the cloud is horizontal may well occur. It is important to note that the errors due to cloud slope are largest for the retrieval of cloud optical depth which is retrieved at a wavelength of weak liquid-water absorption. The change in $r_e$ is smaller as this is retrieved at a wavelength where there is strong liquid-water absorption. These simulations have not considered the effects of shadowing on the retrievals, a problem that is likely to occur for low-sun angles. It should also be noted that in these simulations of clouds with inclined tops the value of $r_e$ is constant on surfaces parallel to the tops, whereas in real clouds it is constant on horizontal surfaces. This is not likely to induce a large error where the horizontal gradient is low. Errors associated with cloud-top inhomogeneity are likely to be smaller with satellite instruments because of the larger field of view. However satellite measurements will have the additional problems of scene determination and sub-pixel clouds.

Studies using two-dimensional radiative calculations carried out by Duda et al. (1994) showed that retrieved optical depths for low-sun cases can differ from the actual cloud optical depth by 20–50%. They conclude, in agreement with the modelling studies presented here, that retrieved cloud optical properties can be significantly affected by changes in cloud geometry.

6. **Combining microwave and near-infrared data to retrieve optical depth**

As described earlier, by using the two channels (89 and 157 GHz) of the MARSS it is possible to retrieve LWP for both nadir and zenith views through the atmosphere. Although the calibration of the MARSS during the Atlantic Stratocumulus Transition Experiment
(ASTEX) was not ideal, the error characteristics are well understood and are incorporated into the retrieval scheme following Rodgers (1976).

LWP (g m⁻²) measurements made with the MARSS can be combined with the MCR retrieved \( r_e (\mu m) \), to compute a cloud optical depth, \( \delta_{\text{com}} \), using the relation

\[
\delta_{\text{com}} = \frac{3\text{LWP}}{2r_e}.
\]

Here \( r_e \) is that of cloud top as retrieved from the MCR data not the \( r_e \) integrated through the depth of the cloud as used in the \textit{in situ} measurements, Eq. (2). The steps taken in the retrieval are firstly to retrieve an effective radius using the MCR reflectances. In order to obtain an effective radius, a cloud optical depth is retrieved using the MCR. The MCR \( r_e \) is then combined with the LWP, retrieved from microwave radiometer radiance measurements, to obtain a new optical depth. If the cloud being measured is optically thin (\( \delta < 8 \)) then the \( r_e \) retrieved by the MCR may be in error and hence \( \delta \) from the combined measurements may be in error also. It is important, therefore, to monitor the quality of the individual components, i.e. \( r_e \) and LWP before computing \( \delta \).

The field of view of the MCR is 1.5° with an integration time of 820 milliseconds. In contrast the MARSS has a field of view of 10° but has a much shorter integration time of 80 milliseconds. These factors combine such that the difference in the length of cloud sampled by the two instruments in any one second when flying at altitudes of 300 m above cloud, typical for these data, is not large. The MCR integrates measurements over a horizontal distance of around 80 m whereas the MARSS integrates over a distance of around 60 m. This difference may introduce some error in to the combined instrument retrieval but it is not likely to be large as the scale of the clouds is generally larger than this difference of 20 m. It should be noted that the \( r_e \) used here is that retrieved from the MCR data which are representative of that in the top 10% of the cloud layer (Rawlins and Foot 1990) due to the strong absorption at the wavelengths used. This will introduce some error in to the retrieved optical depth as \( r_e \) varies through stratocumulus cloud. If one takes a cloud of 225 m thick with cloud \( r_e \) varying from 10 \( \mu m \) to 5 \( \mu m \) from cloud top to base
and a LWC profile which varies from 1.0 g m\(^{-3}\) to 0.1 g m\(^{-3}\) from top to base then one can compute the LWP of this cloud (137.5 g m\(^{-2}\)) and its optical depth (24.8). If one now uses the LWP and computes an optical depth using varying \(r_e\) and using Eq. (15) then this approximate optical depth can be compared with the true optical depth, giving an insight into the sensitivity of the choice of \(r_e\). This calculation has been done for this simple cloud and it was found that using an average \(r_e\) for the top 10% of the cloud, the depth to which typically the MCR is sensitive, results in an overestimate of \(\delta\) by around 10%.

The accuracy of the retrieval of \(r_e\), using the MCR radiances, is in part dependent on the optical depth that is first retrieved using the MCR data. However, results of comparisons of the retrieved \(r_e\) with \textit{in situ} microphysical measurements (Taylor 1992, 1993, 1994) have shown agreement typically to within 1.5 \(\mu\)m. This dual-instrument technique could be further refined if the raw near-infrared and microwave radiometer data were combined at an early stage in some optimal nonlinear scheme which iterated to the best solution.

7. AIRCRAFT MEASUREMENTS

During June 1992 the MRF C130 Hercules took part in ASTEX (Albrecht 1993; Martin \textit{et al.} 1994; Taylor and McAffie 1994). Throughout the measurement phase the aircraft was based on the island of Santa Maria. The major objective of the experiment was to study the break-up of subtropical marine stratocumulus into trade-wind cumulus, and find its effect on the atmosphere and ocean. Sixteen scientific sorties were flown over a 26-day period, totally 126 hours flying time. In the Azores local noon was one hour behind GMT.

In this paper, results from two flights in stratocumulus near the Azores will be presented. The stratocumulus flown in during ASTEX was generally very inhomogeneous. Large cumulus cloud cells were often observed to penetrate the main stratocumulus deck. In many cases these cumulus cells seemed to be maintaining the stratocumulus with their tops spreading out like anvils. The effects on the clouds’ radiative properties were clearly visible to the eye. Viewed from above, the stratocumulus was brighter in circular regions where the cumulus clouds were penetrating the main deck. These cumuli were quite active and often penetrated the main cloud deck by several hundred metres. On other occasions strong gravity-wave activity was apparent in the cloud tops where these cumulus clouds had punched into the inversion, and gravity waves had spread out as a result.

(a) Case 1: Flight A212 on 16 June 1992

Over the few days preceding flight A212 a plume of continental air had been observed approaching the Azores from the north-east. On 16 June 1992 the satellite imagery showed a marked difference in cloud structure and microphysics between the incoming continental airmass and the maritime airmass over the Azores. The terms continental and maritime being decided upon by virtue of the air’s back trajectory. Despite the fact that the air had been over the ocean for 36 hours (based on a trajectory analysis using the UKMO Unified Model) it still maintained a strong continental influence. Figure 7 shows the mean-sea-level pressure and 850 mb heights for 00 GMT 16 June 1992 from the UKMO Unified Model analysis. The measurements presented here were taken at 36°N 19°W in the north-easterly airflow. The aerosol concentration in the layer beneath the cloud, as measured by the PCASP, was \(\sim 1450\) cm\(^{-3}\).

The C130 flew an eight-hour sortie on this day, stacks were flown in the maritime and continental airmasses and in the transition region. The AVHRR* channel 3 (3.7 \(\mu\)m) reflectance image for 1610 GMT is shown in Fig. 8. The 3.7 \(\mu\)m reflectance is very sensitive

* Advanced Very High Resolution Radiometer
to droplet size, the smaller the droplets the greater the reflectance. The high reflectances (white pixels) of the clouds in the continental air indicate smaller droplets than in the clouds of lower reflectance (black pixels) in the maritime air. There was no upper-level cloud, as observed by the aircraft, so changes in reflectivity are due to changes in the microphysics of the stratocumulus. The aircraft flew a run above cloud which was coordinated with this overpass; this track is shown on the image.

The cloud in the continental airmass had a high droplet concentration of around 280 cm$^{-3}$ and some of the smallest droplets observed at cloud top, during this experiment, between 4 and 6 μm. The $r_e$ only decreased by $\sim 2$ μm through the depth of the cloud. The optical depth of the cloud sheet, as calculated from the profile through the layer, was 16.6; this is slightly lower than that retrieved using the MCR reflectances at 1.25 μm which gives a value between 20 and 25 for most of the run, Fig. 9. The cloud was observed to be around 600 m thick. A retrieval of $r_e$ has been carried out for this run above cloud and this is shown in Fig. 9; also in this figure is shown the in situ $r_e$ measured by the FSSP in a later run just below cloud top. The run in cloud was flown in the same direction as the above-cloud run but 15 minutes later. The in situ $r_e$ varies by less than 2 μm along the run, showing that the cloud was relatively homogeneous in the horizontal. The retrieved optical depth shows a decrease in $\delta$ towards the end of the run associated with a thinning of the cloud, a break was observed ahead but the run terminated before passing over it. The low retrieved optical depths at the end of the run have resulted in spurious retrievals of $r_e$. The agreement between the MCR and the FSSP values of $r_e$ is very good; the mean (and standard deviation) of $r_e$ from the FSSP and MCR are 5.3 (0.6) and 5.1 (1.3) respectively, and clearly show that the retrieval scheme works over continental clouds with small $r_e$.

Figure 7. Mean-sea-level pressure (mb) and 850 mb height (dam) from the UKMO Unified Model analysis for 00 GMT 16 June 1992.
A profile through the continental cloud studied during this flight gave $\delta$ equal to 16.6; calculated using measurements of LWC from the Johnson–Williams probe and the FSSP $r_e$. Using the technique described above a retrieval of $\delta$ using combined near-infrared and microwave radiometry has been carried out. Figure 10 shows $\delta$ retrieved from the MCR reflectances alone (upper panel), that retrieved using the radiances from the combined microwave and near-infrared radiometers (middle panel), and the difference between the two retrievals (lower panel). This cloud was relatively uniform in that there was no evidence of any cumulus clouds intruding into the stratocumulus and there were no visible breaks. Towards the end of the run the cloud thinned and this is observed in both retrievals. The combined retrieval gives an optical depth that is slightly larger than that retrieved using the MCR data alone. The difference in the means of the two retrieval techniques is 5.03; the standard deviation of the differences is 6.7, but this is large due to the spikes at the beginning and end of the time series. Both retrievals give $\delta$ greater than that calculated from the in situ profile. Given the uncertainties in the retrieved LWPs, using the MARSS microwave radiances, and the estimated accuracy of the MCR retrieval (under ideal conditions the accuracy of $\delta \sim 5$ (Rawlins and Foot 1990; Taylor 1992)) these results are in good agreement. The agreement between the two retrieval schemes in this particular case is due to the little change in $r_e$ with height, around 2 $\mu$m, and the horizontally homogeneous cloud field which showed no large-scale variability, i.e. no cumulus intrusion. This case acts as a comparison with the other two cases where cumulus intrudes into the stratocumulus, and the vertical variation of $r_e$ is larger.
Figure 9. The multi-channel radiometer (MCR) retrieved optical depth at 1.25 μm and MCR retrieved effective radius using 2.01 μm for cloud on 16 June 1992. The Forward Scattering Spectrometer Probe (FSSP) in situ effective radius measured just below cloud top is shown as a dotted line.

(b) Case 2: Flight A208 on 10 June 1992

On 10 June 1992 a high-pressure system was centred west of the Azores causing light northerly winds in the operating area. Figure 11 is the UKMO Unified Model analysis for 00 GMT 10 June showing mean-sea-level pressure and 850 mb heights. The data presented were obtained at 33°N 20°W near the centre of the high-pressure area. A back-trajectory analysis showed that the air had been over the ocean for the last 36 hours and this, combined with the relatively low aerosol concentrations of ~ 190 cm⁻³, suggests this is a maritime airmass. The C130 flew a series of runs and profiles in the vicinity of a sharp edge in an otherwise extensive semi-infinite stratocumulus sheet. The maritime nature of the airmass was confirmed by the observation of some drizzle when flying below the cloud layer.

The profile of LWC, as measured by the Johnson–Williams probe, and rₑ as measured by the FSSP, is shown in Fig. 12. The maximum rₑ is 8.4 μm, near cloud top, some 3 μm larger than in case 1. After this initial profile through the cloud a series of runs at various levels were flown below, in, and above the cloud. A sharp edge to the cloud sheet was observed and this was crossed on all runs, perpendicular to the line of the transition which was orientated along the wind. The in-cloud run was flown near the middle of the stratocumulus layer so is not ideal for the verification of the remotely retrieved rₑ which retrieves the value at or near cloud top (Taylor 1993). The in-cloud data when corrected to cloud top using the profile of rₑ in Fig. 12 have a mean value of 8.1 μm.

The retrieved δ at 1.25 μm, and the retrieved rₑ, at 2.01 μm, are shown in Fig. 13 for the run above cloud. The optical depth is quite variable, ranging from 5 near the beginning of the run rising to around 65 at 400 seconds into the run. In this region bright cumulus tops were observed penetrating the main stratocumulus cloud deck. On a few occasions spikes in excess of 80 are observed. At around 600 seconds into the run, δ drops to below 5 and this coincides with the edge of the stratocumulus cloud sheet. The retrieved rₑ also shows large variability, rising from around 8 μm at the beginning of the run to 10 μm in the region of larger δ at 400 seconds. At the end of the run the retrieved rₑ increases
Figure 10. Top panel: retrieved optical depth using the multi-channel radiometer (MCR) reflectance at 1.25 $\mu$m; middle panel: using the Microwave Airborne Radiometer Scanning System (MARSS) liquid water paths and MCR retrieved effective radii at 2.01 $\mu$m; and bottom panel: the difference in these two retrievals (MARSS and MCR) – MCR, for flight A212 on 16 June 1992.

rapidly as the edge is crossed at 600 seconds. This is attributed to a failure in the retrieval scheme that occurs for $\delta$ less than 5. At low $\delta$ there arises a regime where, for a given pair of reflectances at 1.25 and 2.01 $\mu$m, there are multiple combinations of $\delta$ and $r_e$ that give the same reflectances (Nakajima and King 1990; Taylor 1993). This results in erroneous solutions dependent on the order in which a retrieval programme searches through its look-up table. In this case the scheme finds the higher $r_e$ value first. The retrieval scheme presented here does not work for $\delta$ lower than 5.

During an initial profile into the cloud, $\delta$ was calculated using the profile of a Johnson–Williams probe LWC and FSSP $r_e$. The cloud was only 200 m thick and an optical depth of 5.5 was calculated which is, in general, lower than that retrieved using the MCR data. The results have shown that the MCR has a tendency to overestimate $\delta$, and this is confirmed in the top panel of Fig. 14 which shows the retrieved $\delta$ at 1.25 $\mu$m using MCR reflectance measurements from the above-cloud run. There is evidence of some localized large increases in $\delta$ associated with cumulus clouds within the main stratocumulus sheet. The mean optical depth calculated using combined near-infrared and microwave mea-
Figure 11. Mean-sea-level pressure (mb) and 850 mb height (dam) from the UKMO Unified Model analysis for 00 GMT 10 June 1992.

Figure 12. Profiles of liquid-water content (LWC) and effective radius \( r_e \) as measured by the Microwave Airborne Radiometer Scanning System through the cloud of 10 June 1992.

measurements (middle panel of Fig. 14) outside of the regions of cumulus intrusion is 5.35, which compared with the value of 5.5 calculated during the profile is in good agreement. In the regions of the cumulus intrusion the optical depth derived from near-infrared and microwave data reaches a maximum of \( \sim 15 \), as opposed to the value of 60 retrieved from the MCR data alone. This is clearly seen in Fig. 14 (lower panel) which shows the difference between the two retrieval schemes (MCR – MARSS and MCR). If it is assumed that the largest cumulus extend from the top of the surface mixed layer to the top of the stratocumulus cloud, a depth of 640 m, and that they have an adiabatic increase of LWC,
then using the range of $r_e$ measured during several straight and level runs intersecting cumulus cells, the maximum possible optical depth is calculated to be of the order 25. With the available instrumentation one cannot determine the vertical extent of the cumulus clouds intruding into the stratocumulus deck that was flown over during this run above cloud top, but a value of $\delta$ of 60, as retrieved from the MCR data alone, is too large. Although there is considerable uncertainty in the absolute accuracy of the MARSS LWPs, due to uncertainties in the water-vapour column and surface effects, the sensitivity of the MARSS retrieval along a run is high, of the order of 3–6 g m$^{-2}$, showing that the changes in $\delta$ observed with the MCR alone were anomalous.

(c) Case 3: Flight A146 on 11 November 1991

Flight A146 took place in the South Atlantic around 11°S 12°W as part of the First ATSR (Along-Track Scanning Radiometer) Tropical Experiment (FATE) (Saunders 1993). A retrieval of $r_e$ and $\delta$ using near-infrared reflectances for this case have been presented by Taylor (1994) who noted that the mean of the remotely retrieved $r_e$ was within 1.5 $\mu$m of the in situ measurements, the mean value being 10.5 $\mu$m. However, the remotely retrieved $\delta$, using near-infrared reflectances alone, was larger than that measured in situ.

Figure 15 shows the retrieved $\delta$ using the original MCR technique and the new combined MCR and MARSS technique (upper panel). The lower panel shows the difference in these two retrieval techniques (MCR—MARSS and MCR). The large spike in the centre of the figure is due to a data break. The results show that $\delta$ calculated using MARSS LWP and MCR $r_e$ is less variable. Furthermore the large increases in $\delta$ at around 40 and 180 seconds from the start of the run seen in the MCR retrieval are not observed. These large increases in $\delta$ were well correlated with cumulus clouds intruding into the main cloud deck which were observed during a run near cloud top immediately after the above-cloud run. Figure 16 shows the LWC measured using the Johnson–Williams probe during a run near cloud top. The LWC is higher at 50 and 200 seconds where cumulus clouds are penetrating the main stratocumulus deck.

The stratocumulus retrieved $\delta$ using the MCR reflectance at 1.25 $\mu$m is very variable,
ranging from 100 to 40. Calculations of $\delta$ based on the adiabatic LWC and cloud thickness suggest a maximum $\delta$ of 100 for the case of cumulus intruding into stratocumulus. When considering the adiabatic LWC over the depth of the stratocumulus alone a maximum $\delta$ of 65 is predicted. The LWCs measured in the cumulus regions are lower than the adiabatic values, so the optical depth should still be lower than retrieved. The remotely retrieved $\delta$, using the MCR data alone, in the region of cumulus intrusion are larger (by around 25%) than those that would be predicted.

The combined MARSS and MCR retrieved $\delta$ shows an increase in the region of the cumulus intrusion, but the sharp transitions seen in the MCR retrieval and the very high values are not observed. The combined retrieval of $\delta$ has resulted in values nearer those measured in situ from an aircraft profile. The MARSS radiances are insensitive to changes in droplet size and to variations in solar illumination due to cloud-top structure. Therefore, it is possible that the large optical depths observed with the MCR are due in part to variability in cloud-top structure.

This example has shown that the MCR retrieved $\delta$ is very sensitive to variability in the cloud top as was suggested by the modelling results. In this case errors in $\delta$ of 22% are observed which may be attributed to cloud-top variability.
8. THE REPRESENTATION OF VERTICALLY INHOMOGENEOUS CLOUDS IN RADIATION MODELS

It has been shown that $r_c$ and $\delta$ retrieved from the MCR data when viewing a vertically inhomogeneous cloud are not necessarily the same as the real cloud optical depth and the cloud-top effective radius. In particular for optically thin clouds the differences between retrieved and real cloud microphysical properties can be significant.

Having made these observations, an important question to be answered is how should these retrieved microphysical parameters be input to a radiation model? Should the retrieved values of $r_c$ and $\delta$ in some way be corrected before being used in radiation models? Nakajima and King (1990) developed a scheme whereby the remotely retrieved $r_c$ was corrected to that at cloud top. However, this may not necessarily be the correct thing to do if the retrieved parameters are to be used to model a cloud field.

The very fact that under some conditions the retrieved $r_c$, using MCR reflectances, is lower than that at cloud top tells us that the MCR is 'seeing' deeper into the cloud. In
these conditions, therefore, it is reasonable to hypothesize that the radiative properties of
the complex vertically varying cloud sheet can in some way be represented by the retrieved
parameters.

To test this hypothesis the retrieved \( r_e \) and \( \delta \) from MCR data were used to construct an
equivalent single-layer (slab) cloud, and the irradiance from both the real and slab cloud
were compared by modelling with DISORT. The term ‘real’ is used to describe a model
cloud where there is vertical variation of droplet size as observed in stratocumulus. The
term ‘slab’ is used to describe a model cloud where there is only one value of droplet size.

In these simulations only realistic combinations of \( \delta \) and \( r_e \) in the real cloud have been
used. The albedo, transmittance and absorptance of the real (vertically inhomogeneous
cloud) and the slab cloud (one layer with MCR retrieved \( r_e \) and \( \delta \)) are shown in Fig. 17 at
wavelengths of 1.25 \( \mu \)m and 2.26 \( \mu \)m.

These results show that, to a good approximation, one can represent a vertically in-
homogeneous cloud with varying \( r_e \) and \( \delta \) by the equivalent single-layer cloud constructed
using the retrieved \( r_e \) and \( \delta \) from MCR reflectances.

It should, however, be noted that these results are at the two wavelengths used for
the MCR retrieval, namely 1.25 and 2.26 \( \mu \)m. In order to test this hypothesis further the
radiation code developed by Slingo and Schrecker (1982) was used to allow irradiances
over a wider spectral range (0.25–4.0 \( \mu \)m) to be calculated. The Slingo and Schrecker
code uses height as its vertical coordinate whereas DISORT, used before, has a vertical
coordinate of optical depth. An assumption that the two clouds, real and slab, were of
the same geometrical thickness was, therefore, made to ease the modelling. The MCR
retrieved \( r_e \) and \( \delta \) were used to compute a total LWP for the slab cloud, using the relation
given in Eq. (15).

The results of modelling the real and slab clouds with the Slingo and Schrecker code
showed that the good agreement observed at the two discrete wavelengths of 1.25 and
2.26 \( \mu \)m was no longer observed. This result is not altogether unexpected. It has already
been shown that the MCR retrieved \( \delta \) is often significantly different to the total cloud \( \delta \),
which suggests a non-conservation of liquid water if we use this value to construct an
equivalent slab cloud.

Using radiances at microwave frequencies it is possible to retrieve LWP. The Slingo
and Schrecker radiation code has been run with the real (vertically inhomogeneous) cloud
and a slab cloud using a conserved LWP (which would be available from microwave radiometry) and the MCR retrieved $r_c$. Table 1 shows the microphysical properties of the vertically inhomogeneous cloud and $r_c$ retrieved with the MCR used in the slab cloud (the LWP in both clouds was kept the same).

The results of this modelling are shown in Fig. 18 for the five cases with varying microphysical properties. These results show that, with the exception of the last case in Table 1, the real cloud can be well represented in the Slingo and Schrecker radiation code with a single-layer slab cloud of the same LWP and $r_c$ as given by the MCR retrieval. This is particularly the case for the cloud absorptance, which shows very good agreement. The largest differences in albedo and transmittance have occurred where the real cloud had a

![Graphs showing albedo, transmittance, and absorptance comparisons between real and slab clouds at 1.25 µm and 2.26 µm wavelengths.]

Figure 17. Hemispherically averaged albedo, transmittance and absorptance for the real and slab cloud for both 1.25 µm and 2.26 µm.
Figure 18. Hemispherically averaged albedo, transmittance and absorptance for the real and slab cloud modelled using the Slingo and Schrecker (1982) model.
<table>
<thead>
<tr>
<th>Total cloud optical depth</th>
<th>Cloud-top effective radius (µm)</th>
<th>Multi-channel radiometer effective radius (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>8</td>
<td>8.3</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
<td>13.1</td>
</tr>
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<tr>
<td>12</td>
<td>6</td>
<td>7.29</td>
</tr>
</tbody>
</table>

Total δ of 12 and \( r_c \) of 6 µm; here the errors in transmittance and albedo were of the order of 16%. As was discussed earlier, this case is at the limit of the MCR retrieval schemes applicability; with both \( r_c \) and \( δ \) being low.

9. CONCLUSIONS

The retrieval of cloud-top effective radius has been shown to be possible in a wide variety of clouds (Taylor 1992, 1993, 1994) and good agreement to within 1.5 µm is found with in situ measurements. Cloud optical depth when retrieved using reflectances in the visible or near-infrared part of the spectrum often has larger values than the in situ measurements. This overestimate has been shown to be due, in part, to the vertical variability of LWC and \( r_c \) in stratocumulus and also to inhomogeneity in the cloud-top structure caused by cumulus intrusion.

A technique combining both microwave LWP and near-infrared retrieved \( r_c \) has been presented for obtaining a remote measure of cloud optical depth. The results for the three cases presented are in good agreement with the in situ measurements, and show less sensitivity to cloud-top inhomogeneity. The difference in \( δ \) from these two techniques is on occasion very significant. Further study is required to test this technique over many more clouds. If such errors in \( δ \), retrieved at visible wavelengths, are commonplace, then this has serious consequences for satellite-derived measurements used in climate studies. Satellite retrievals of \( δ \) are not likely to be affected by small-scale features like individual cumulus clouds, but sloping cloud tops and larger-scale inhomogeneities may be significant in affecting the retrieved optical depth. Albedo depends nonlinearly on \( δ \), therefore averaging the effect of a random distribution of cloud-top slopes over a pixel may not result in zero net effect. The combined retrieval of \( δ \) is not an absolute measurement, as the MCR is giving only a measure of the cloud-top \( r_c \). Changes in the vertical structure of the clouds away from the classical stratocumulus profile with increasing liquid water and \( r_c \) with height will have an effect on the retrieval scheme. However, this effect is not considered to be large as the microwave measurements of LWP are sensitive to the entire cloud depth, and the MCR is measuring the \( r_c \) of the radiatively significant upper portion of the clouds. Further modelling studies are required to study this point fully.

These results show the advantage of utilizing the information from different spectral regions in order to optimize the retrieval of cloud properties. Although the uncertainty in the absolute measure of LWP from microwave radiometers, such as that flown aboard the MRF C130, is large (of the order of ±50 g m\(^{-2}\) for stratocumulus clouds) the sensitivity along any particular measurement run is high. Other instruments using different microwave frequencies may result in better measurements of the LWP. This technique shows promise as an alternative way of retrieving \( δ \) which is not sensitive to the complex inhomogeneities.
of real clouds. The new instruments that are planned to fly on the NOAA* K, L and M polar orbiters will include both near-infrared channels and microwave channels similar to those used in this study. This will allow the techniques described above to be applied to remotely sensed data and hence provide the possibility of a global data set of these cloud parameters.

A simple modelling study has shown that the remotely retrieved \( r_e \) and LWP can be combined to represent a complex vertically inhomogeneous cloud layer as a single cloud layer, provided the cloud layer observed has a classical stratocumulus profile of increasing liquid water and \( r_e \) with height.

This work stresses the need for further study into the combination of instruments working in different regions of the electromagnetic spectrum. Clearly one measurement cannot reveal all that is to be known about the cloud field, and it is only through the careful combination of information from different sensors that the difficult problem of characterizing clouds can be tackled.

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