Sensitivity of Remotely Sensed Effective Radius of Cloud Droplets to Changes in LOWTRAN Version

J. P. TAYLOR

United Kingdom Meteorological Office, Meteorological Research Flight Royal Aerospace Establishment, Farnborough, Hants, United Kingdom

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ABSTRACT

A method of retrieving effective radius and optical depth of stratocumulus from narrowband near-infrared radiances was recently presented by Rawlins and Foot. Their retrieval scheme used LOWTRAN 5 to calculate atmospheric corrections, and the results showed that the remotely retrieved effective radii were significantly larger than those measured in situ with a PMS Forward Scattering Spectrometer Probe. LOWTRAN 7 has recently been developed and is used in this work for all atmospheric corrections. In this note, the major differences between LOWTRAN 5 and LOWTRAN 7 at near-infrared wavelengths are discussed, and it is shown that the retrieved effective radii using LOWTRAN 7, for two flights during the FIRE87 campaign, are in much better agreement with the in situ measurements.

1. Introduction

Rawlins and Foot (1990, hereafter RF90) described a method to determine the optical depth (δ) and effective radius of the drop size distribution (r_e) of stratocumulus clouds using a narrowband multichannel radiometer (MCR). Their results showed that the effective radius retrieved remotely was larger than that measured in situ with a Particle Measuring Systems Forward Scattering Spectrometer Probe (FSSP); on average, the retrieved r_e was about 25% larger and in some extreme cases, 50% larger than the measured in situ r_e. Similar results showing large differences between remotely sensed and in situ effective radius measurements have also been shown by Twomey and Cocks (1989). Nakajima et al. (1991) detail results from measurements made using the NASA ER-2 aircraft and the University of Washington C-131A aircraft during the First ISCCP Regional Experiment (FIRE) campaign. They use LOWTRAN 5 for atmospheric corrections and find that remotely sensed effective radii are consistently larger than those measured in situ, their results being in agreement with those of RF90.

A number of workers have reported differences between theoretical and measured solar radiances, particularly in the near-infrared region in clouds. These discrepancies have manifested themselves as an anomalous absorption of broadband radiation and a reduction in narrowband reflectance from those predicted. Stephens and Tsay (1990) provide an overview of the subject of absorption of solar radiation by water clouds and in particular, they address this problem of anomalous absorption.

The retrieval scheme described in detail in RF90 is a multiwavelength scheme—optical depth and cloud droplet effective radius being retrieved simultaneously using a combination of narrowband channels on the MCR. Optical depth was typically retrieved using a wavelength of 1.25 μm, and this optical depth was then used in the simultaneous retrieval of effective radius at wavelengths of either 1.55, 2.01, or 2.26 μm.

In the retrieval method of RF90, the values of cloud reflectivity were found for the MCR channels by correcting for the transmission of the atmosphere in the slant path of the direct solar beam to cloud top and the vertical path from cloud top to aircraft level for the reflected radiance. Based on Monte Carlo calculations of effective pathlength, an extra pathlength of one-third of the average cloud thickness was added to take into account the multiple scattered paths within the cloud. The atmospheric transmission model LOWTRAN 5 (Kneizys et al. 1980) was used for these corrections, with an atmospheric temperature and humidity profile measured with the aircraft. The radiometer data and retrieval technique used in this note are identical to those used by RF90, with the one exception that LOWTRAN 7 (Kneizys et al. 1988) is used to calculate the atmospheric transmission corrections.

The differences between the two versions of LOWTRAN at near-infrared wavelengths are first outlined

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Corresponding author address: Jonathan P. Taylor, U.K. Meteorological Office, Meteorological Research Flight, Royal Aerospace Establishment, Farnborough, Hants, GU14 6TD United Kingdom.

before going on to compare the retrieval of effective radius and optical depth using the two model versions.

2. Differences between LOWTRAN 5 and 7

The LOWTRAN 5 code calculates atmospheric transmittance, with a spectral resolution of 20 cm^{-1} from 350 to 40 000 cm^{-1} (0.25–28.5 μm). The total transmittance at any given wavenumber averaged over a 20-cm^{-1} interval is given by the product of the average transmittance due to four components, namely molecular-band absorption, molecular scattering, aerosol extinction, and molecular-continuum absorption.

The LOWTRAN 7 code calculates atmospheric transmittance, atmospheric radiance, single-scattered solar and lunar radiance, direct solar irradiance, and multiple-scattered solar and thermal radiance. The spectral resolution of the model is 20 cm^{-1} in steps of 5 cm^{-1} from 0 to 50 000 cm^{-1} (0.2 μm to infinity). A single parameter-band model is used for molecular-line absorption, and the effects of molecular continuum absorption, molecular scattering, aerosol and hydrometeor absorption, and scattering are included.

The new separate band models used for modeling molecular absorption, included in the LOWTRAN 7 code, are detailed in Pierluissi et al. (1989) and Pierluissi and Tsai (1987); a summary of their work is given here. Each molecular absorber has its own band model with 20 cm^{-1} resolution using an analytic transmission function τ with defining spectral parameters repeated at 5-cm^{-1} intervals, defined as

$$\tilde{\tau} = \exp[-(CW)^a] \qquad (1)$$

$$W = \left(\frac{P}{P_0}\right)^n \left(\frac{T_0}{T}\right)^m U, \qquad (2)$$

where P and T are vertical profiles of pressure and temperature, and U and W are the absorber amount and equivalent absorber amount, respectively.

Pierluissi et al. (1989) compared the new band model for water vapor absorption, as used in LOWTRAN 7, and the old band model in LOWTRAN 5 with transmittance data obtained from a line-by-line model FASCOD (Clough et al. 1986). The rms transmittance difference between FASCOD and the new band model used in LOWTRAN 7 was found to be only 2.06%, compared to 20.76% for a similar comparison between FASCOD and the old band model.

In addition, the results of intercomparisons between LOWTRAN 5 and the new band models that have been used in LOWTRAN 7 and carried out by Pierluissi et al. (1989) highlighted the following points.

- LOWTRAN 5 had difficulty in following absorption near band heads, as well as missing some bands at higher wavenumbers.
- In LOWTRAN 5 the pressure dependence of absorber amount is assumed to be independent of spectral region, and a constant exponent n of 0.90 is used. However, the pressure dependence actually varies considerably across the spectrum, the mean value of the coefficient is 0.90, but it varies from 0.67 in the range 16 340–17 860 cm^{-1} to 1.14 for 350–1000 cm^{-1}. The approximation made in LOWTRAN 5 is therefore inadequate, and in LOWTRAN 7 more accurate tabulated values, which are a function of wavenumber, are used.
- In LOWTRAN 5 the temperature dependence of absorber amount is assumed to be independent of spectral region and a constant exponent m of 0.45 is used. However, the temperature dependence varies considerably across the spectrum, from 0.51 in the range 16 340–17 860 cm^{-1} to -2.63 for 350–1000 cm^{-1}. In the new band models in LOWTRAN 7 the temperature dependence of absorber amount is represented by tabulated values that are a function of wavenumber, and hence this temperature dependence is modeled more accurately in LOWTRAN 7.

The new band models that represent the individual components of the uniformly mixed gases (CO_2, N_2O, CH_4, CO, O_2, and N_2) developed by Pierluissi and Tsai (1987) represent the transmission function in the same way as the new band model for water vapor absorption. In these new band models, all the parameters were determined using line-by-line generated transmission spectra. The authors validated, where possible, the new band models with laboratory measurements. The new band models were found to be an improvement over the single model used to represent the uniformly mixed gases in LOWTRAN 5 and were subsequently included in all later versions of LOWTRAN, hence they also will have made a significant improvement in LOWTRAN 7. A more detailed analysis of the two LOWTRAN models at near-infrared wavelengths is given in Taylor (1991).

In view of the substantial improvements included in LOWTRAN 7, it is therefore of interest to use LOWTRAN 7 in the retrieval scheme for cloud drop effective radius and optical depth and to compare the results with those obtained using LOWTRAN 5.

3. Retrieval of optical depth and effective radius

A total of 11 flights were completed by the C130 of the Meteorological Research Flight during the FIRE87 campaign (Albrecht et al. 1988) to study stratocumulus. The data presented is from two flights, which were part of the intensive field observation program of the marine stratocumulus component of FIRE.

Details of the calibration of the MCR during FIRE87 are detailed in RF90. Solar calibrations are routinely carried out at high levels, typically in excess of 6 km,

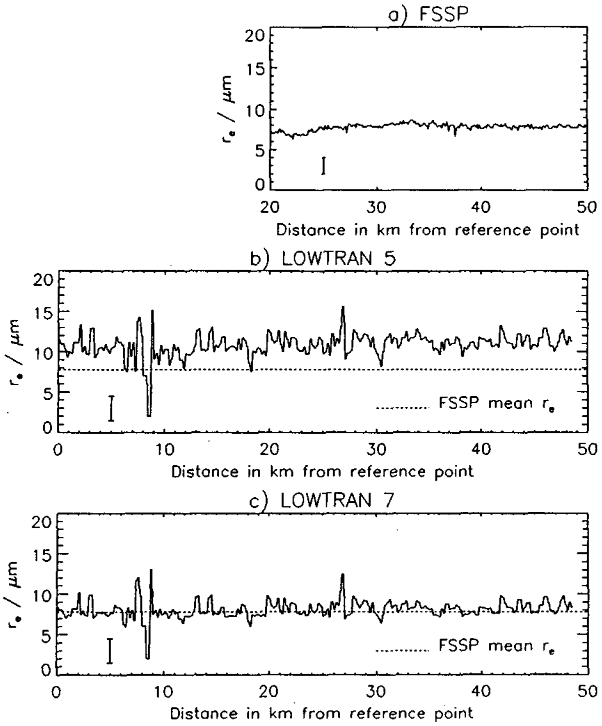

FIG. 1. Effective radius (a) measured with FSSP 1818:42–1823:42 UTC, (b) retrieved with MCR channel D3 (1.55 μm) with LOWTRAN 5 atmospheric corrections 1750:37–1758:44 UTC, and (c) retrieved with MCR channel D3 (1.55 μm) using LOWTRAN 7 atmospheric corrections 1750:37–1758:44 UTC for the 5 July flight.

so as to reduce absorption by atmospheric gases to a minimum. For this reason, no significant difference in radiometer gain was found between using LOWTRAN 7 and LOWTRAN 5 for atmospheric corrections since the changes in transmission between the two models for the relatively weak absorber path were negligible. MCR gains used in this study are therefore kept the same as those used in RF90.

a. Results from observations on 5 July 1987

The cloud tops during this flight varied from 600 to 700 m, and cloud bases from 300 to 450 m. Figure 1a shows the effective radius of the droplet spectrum as calculated from the in situ FSSP data on 5 July during a run at an altitude of 580 m, a level just below cloud top. This in situ run was flown along the same ground track as the above cloud run Figs. 1b and 1c, distances along the track being referenced to a point at the beginning of the above cloud run.

This figure shows that the variation in r_e of the cloud over this run of approximately 30 km is small, the mean effective radius for the run being 7.8 μm. Figure 1b is the r_e retrieved from MCR data at a wavelength of 1.55 μm using LOWTRAN 5 to correct for all atmospheric absorption. This run was at a height of 1100 m and was vertically above the cloud where the in situ FSSP effective radii were measured on a subsequent run. The mean r_e value from this retrieval was 10.8 μm, some 3.0 μm larger than the in situ measurements. Finally, in Fig. 1c, the same radiometer data are used as for Fig. 1b, but with r_e calculated with atmospheric corrections carried out using LOWTRAN 7. The error analysis of RF90 showed that the retrieval scheme should be capable of determining optical depth and effective radius to within about ±5 and ±1.5 μm, respectively. The absolute accuracy of the FSSP is estimated at ±1.0 μm for the range of droplet sizes measured here (Dye and Baumgardner 1984; Cerni 1983). In the figures error bars are shown that represent the absolute accuracy in the parameter concerned.

There is better agreement between the in situ measurements with those predicted using LOWTRAN 7 rather than LOWTRAN 5. The modeled atmospheric absorption increases by approximately 15% using LOWTRAN 7 compared with using LOWTRAN 5. The retrieved r_e, using LOWTRAN 7 corrections, has a mean of 8.1 μm, only 0.3 μm larger than the in situ measurements and well within the accuracy of the FSSP and MCR. Details of retrievals of r_e using wavelengths of 1.55 μm, 2.26 μm, and 2.01 μm are included in Table 1 for both 5 and 13 July 1987. These all show that when LOWTRAN 7 was used the remotely sensed r_e was in better agreement with the in situ measurements than those obtained using LOWTRAN 5.

The FSSP data from various runs during the flight showed that the r_e variations near cloud top were not significant for the interpretation of most MCR mea-

TABLE 1. Mean (and standard deviation) of in situ and remotely retrieved effective radius measurements r_e (μm) averaged along a run for flights on 5 and 13 July. The estimated accuracy for the FSSP and remotely retrieved values are ±1 and ±1.5 μm, respectively.

	Retrieval wavelength (μm)						
	LOWTRAN 5			LOWTRAN 7			
Flight date	2.26	2.01	1.55	2.26	2.01	1.55	FSSP
5 July 1987	—	10.6 (1.0)	10.8 (1.5)	—	9.1 (0.8)	8.1 (1.1)	7.8 (0.4)
13 July 1987	9.1 (0.5)	9.7 (0.5)	10.0 (0.9)	8.2 (0.4)	7.9 (0.4)	7.4 (0.7)	7.6 (0.6)

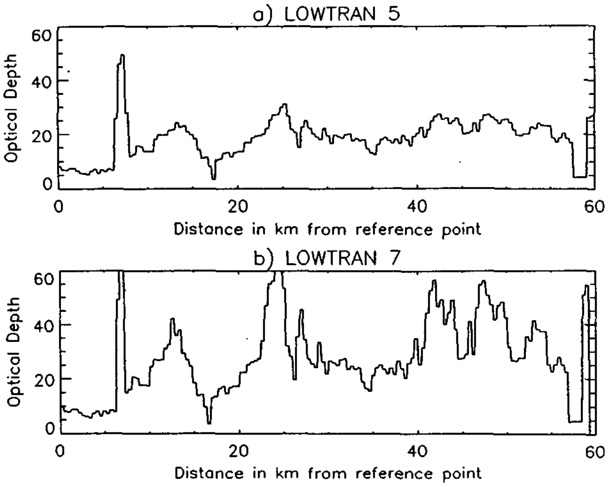

FIG. 2. For 5 July: optical depth retrieval using (a) MCR channel D1 (1.25 μm) with LOWTRAN 5 atmospheric corrections 1749:10–1759:10 UTC and (b) MCR channel D1 (1.25 μm) using LOWTRAN 7 atmospheric corrections 1749:10–1759:10 UTC for the 5 July flight.

surements; that is, the cloud sheet was reasonably homogeneous.

Figure 2 shows the optical depth of the cloud sheet retrieved using a reflected radiance at a wavelength of 1.25 μm: (a) using LOWTRAN 5 corrections and (b) using LOWTRAN 7 corrections. It is noticeable that the retrieval using LOWTRAN 7 shows much larger variations in optical depth than those shown using LOWTRAN 5. This is due to the water vapor band and continuum absorption now modeled in LOWTRAN 7; these differences could be reduced by using a channel in the visible wavelength region, say 0.55 μm, which is free of water vapor absorption. Here 1.25 μm has been used as in RF90 to retrieve cloud optical depth to highlight the differences between using LOWTRAN 5 and LOWTRAN 7. The magnitude of the optical depths increases slightly when LOWTRAN 7 is used in the retrieval but remains in broad agreement with the approximate adiabatic values of optical depth inferred from aircraft reports of cloud thickness. These inferred optical depths were estimated from collocated aircraft runs above and below the cloud to measure the thickness. This gave an adiabatic water content at cloud top, and a linear increase of liquid water content with height was assumed (and normally observed) from which a corresponding maximum optical depth was inferred (see RF90 Fig. 9). The larger variation in optical depth using LOWTRAN 7 suggests that the accuracy of the retrieval scheme will decrease as the clear-air absorption increases and the radiance is reduced.

b. Results from observations on 13 July 1987

The cloud tops during this flight varied from 550 to 650 m, and the bases from 300 to 400 m. As with the flight on 5 July, a similar set of runs has been analyzed, the stratocumulus cloud sheet was reasonably homogeneous and FSSP data showed little variation in the effective radius of the cloud tops along a run.

Figure 3, in three parts, shows the r_e: (a) measured in situ at a height of 580 m using the FSSP; (b) using the 1.55-μm channel with LOWTRAN 5 atmospheric corrections; and (c) using the 1.55-μm channel with LOWTRAN 7 atmospheric corrections. It should be noted that part (a) is for the period 1654:01–1658:16 UTC, a shorter period than parts (b) and (c), which are both for a subsequent run above cloud at a height of 1200 m from 1748:42 to 1758:42 UTC. Although the time separation of the in situ run to the above-cloud run, where the remote measurements were made, is on the order of 60 minutes, observations of the cloud droplet effective radius near cloud top throughout the flight showed little variation, and the FSSP effective radii shown here are believed to be representative of the cloud flown over for the retrieval. The mean r_e values are 7.6 μm, 10.0 μm, and 7.4 μm for the FSSP, and the remote retrievals using LOWTRAN 5 and LOWTRAN 7, respectively.

This clearly shows that, in common with the flight on 5 July, the retrieval using LOWTRAN 7 gives r_e values in closer agreement with those measured in situ.

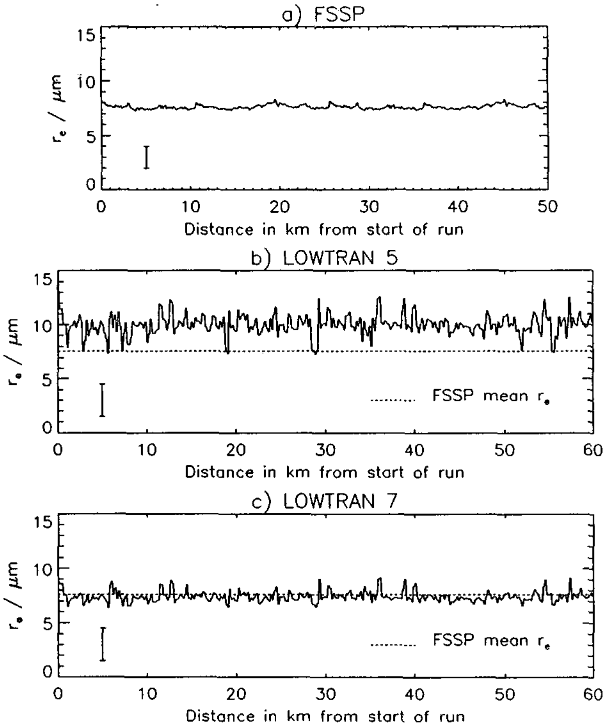

FIG. 3. Effective radius (a) measured with FSSP 1654:01–1658:16 UTC, (b) retrieved with MCR channel D3 (1.55 μm) with LOWTRAN 5 atmospheric corrections 1748:42–1758:42 UTC, and (c) retrieved with MCR channel D3 (1.55 μm) using LOWTRAN 7 atmospheric corrections 1748:42–1758:42 UTC for the 13 July flight.

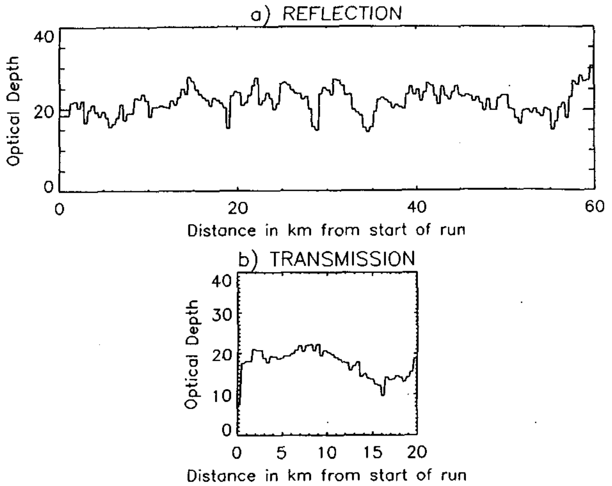

FIG. 4. Optical depth retrieval using (a) MCR channel D1 (1.25 μm) with LOWTRAN 7 atmospheric corrections looking at reflectance of the cloud top for 1748:42–1758:42 UTC and (b) MCR channel D1 (1.25 μm) using LOWTRAN 7 atmospheric corrections looking at transmission through the cloud for 1834:54–1838:20 UTC for the 13 July flight.

Figure 4 shows the optical depth of the stratocumulus retrieved using a wavelength of 1.25 μm with LOWTRAN 7 atmospheric corrections. Figure 4a is that retrieved using reflectance measurements for the same run as detailed in Figs. 3b and 3c. Figure 4b shows the optical depth retrieved using transmission measurements looking up through the cloud during a shorter run at a height of 304 m from 1834:54 to 1838:20 UTC. The broad agreement between transmission and reflectance retrievals of optical depth gives confidence in using reflectance measurements that are of more importance if retrievals by satellite are considered.

4. Conclusion

Rawlins and Foot concluded that radiances in the window and absorption channels were measured with absolute accuracies of ±10% and ±15%, respectively, and that these accuracies translated to an ability to determine optical depth, δ, and r_e to within about ±5 and ±1.5 μm, respectively.

The retrieval of r_e with the MCR is best carried out using wavelengths of 1.55 and 2.26 μm where there is moderately strong liquid water absorption and weak water vapor absorption. In LOWTRAN 7 there is CO_2 absorption at 1.55 μm and CH_4 and N_2O absorption at 2.26 μm; this absorption is weak and is accounted for in the retrieval. Retrievals using a wavelength of 2.01 μm are also useful, since this wavelength shows the greatest cloud absorption and hence the largest discrimination of drop size. However, this wavelength suffers from the disadvantage of being affected strongly by CO_2 absorption and, to a lesser extent, by water vapor absorption. For completeness retrievals using wavelengths of 2.26 μm, 2.01 μm, and 1.55 μm are summarized in Table 1.

The accuracy of r_e measurement by the FSSP is believed to be on the order of ±1 μm for the range of droplet sizes encountered in this experiment. From this it can be concluded that the retrievals of r_e using LOWTRAN 7 to correct for atmospheric absorption result in values of r_e that agree with the in situ measurements to within the experimental accuracy of the instruments.

In this note, as in RF90 the FSSP, in situ data are taken from runs in the tops of the cloud sheet. A correction of one-third of the depth of the cloud is added to the radiation pathlength in calculating the atmospheric absorption using LOWTRAN. This approximation is the major weakness of this retrieval scheme, and further studies are being made as to the depth into the cloud for which the remotely retrieved effective radii are valid.

These results are of importance in explaining the cloud absorption anomaly discussed in Stephens and Tsay (1990). The results presented here show that there is no anomalous absorption and, furthermore, that the anomalous absorption discussed by Stephens and Tsay (1990) may be an artifact arising from the use of less-developed radiation models. It should be noted that many users have based their calculations on versions of LOWTRAN 5 and its predecessors. There is a need for more radiometer measurements to be compared with LOWTRAN 7 and for in situ cloud microphysics data to verify our findings; in particular, cases with a larger range of effective radii need to be studied.

The ability to use narrowband reflectances derived from global satellite data to retrieve cloud drop effective radius would be of great advantage to climate studies. In the near future, the Advanced Very High Resolution Radiometer-3 will fly on a NOAA polar-orbiting satellite (1993/94); this will have 1.6-μm and 0.9-μm channels; these may be suitable for retrieval of r_e and optical depth of uniform cloud layers. However, the potential of satellite retrievals is limited by the field of view of the instruments and by atmospheric attenuation. These limitations suggest further studies that would be relevant to satellite applications, in particular, the effects of nonhomogeneous cloud sheets, mixed-phase clouds, subpixel clouds, intervening atmospheric absorption, and subvisual cirrus. Hence, there is a need for further aircraft measurements of both clear and cloudy spectral radiances in the atmosphere to be carried out above and below a wide variety of cloud types, and then compared with model predictions.

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