JP 2.8 INTERCOMPARISON OF MODELS FOR RADIATIVE TRANSFER IN CLOUDS

Robert .A. Roebeling[1)], D. Jolivet[1)], A. Macke[2)], W. Frerichs[2)], L. Berk[3)] and A. Feijt[1)]
[1)] Royal Netherlands Meteorological Institute, De Bilt, The Netherlands
[2)] Institute for Marine Research at the University of Kiel, Kiel, Germany
[3)] Spectral Sciences, Inc, Burlinton, Unites States

1. INTRODUCTION

Accurate information on cloud properties and their spatial and temporal variation is crucial for climate studies. To date clouds are not well represented in climate models. The radiative effects of clouds depend strongly on cloud properties such as thermodynamic phase, optical thickness and droplet effective radius. Radiances observed from meteorological satellites may be used for the retrieval of cloud physical properties at a global scale. Radiative Transfer Models (RTMs) play a crucial role in the quantification of observed radiances (in the solar spectrum) in terms of cloud physical properties. The accuracy of the retrieved cloud properties is highly dependent on the choice of the radiative transfer code. Several methods have been developed to solve the equation of radiative transfer in a plane parallel atmosphere. The methods are either analytically, empirically or statistically. This paper presents the results of an intercomparison of 5 different radiative transfer codes.

Radiative transfer models simulate, for given viewing geometries, the spectral reflectance (in the solar spectrum) of a cloud with predefined physical properties. The viewing geometries are expressed in terms of the satellite zenith angle (θ_v), solar zenith angle (θ_0) and relative azimuth angle (ϕ). The physical properties concerned are cloud optical thickness (τ), cloud phase, cloud droplet distribution, droplet effective radius (r_e), cloud base height and cloud top height.

The model intercomparison is an integral part of the Climate Satellite Application Facility (CM-SAF) of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). The CM-SAF will provide information on cloud properties for climate studies, derived from NOAA-AVHRR, METOP and MSG channel radiances at a non-absorbing visible and a strongly absorbing near infrared wavelength. Nakajima and Nakajima (1995), Han et al. (1994), Watts et al. (1998) and Jolivet et al. (2000) developed methods to retrieve cloud optical thickness and effective particle radius based on non-absorbing (0.6 μm) and absorbing (1.6 or 3.7 μm) spectral radiances. The reflection of clouds at the non-absorbing channel is primarily a function of the cloud optical thickness. While the reflection function at a water (or ice) absorbing channel is primarily a function of cloud particle size (r_e). The motivation of this intercomparison study is to select a RTM that provides the angular dependency of solar radiation from cloud atmospheres with sufficient accuracy and reasonable computational expenses. The selected model will be used for the retrieval of cloud properties in the CM-SAF.

The outline of the paper is as follows. In section 2 the physical concept of the radiative transfer models is summarised. In section 3 the set up of the intercomparison study is described. Conclusions are drawn in section 4.

2. THE RADIATIVE TRANSFER MODELS

In this section we present the models that are part of the intercomparison study. The models utilise different numerical methods to solve radiative transfer. Uncertainties in the radiative transfer calculations may be introduced due to approximations, the numerical procedure or the number of streams (2*N).

The Monte Carlo model (Macke et al. 1998) threats multiple scattering as a stochastic process. Photon packages are emitted from a source (e.g. the sun) and undergo scattering and absorption events inside a predefined three dimensional cloudy atmosphere until the package's energy falls below a certain threshold or until the photons escape from the system (forward scheme). At each scattering event, the intensity that contributes to predefined sensor viewing angles is calculated (local estimate procedure), which makes the Monte Carlo code efficient for radiance calculations.

The DAK (Doubling-Adding Royal Netherlands Meteorological Institute) radiative transfer model (Stammes, 1994) calculates multiple scattering by means of the doubling-adding method (Van der Hulst, 1980). This method solves radiative transfer monochromatic. The reflection and transmission is calculated for two thin layers. The number of layers is doubled until the whole cloud is described. The reflection and transmission from the combined layer can be obtained by computing successive reflections back and forth between the layers.

In MODerate resolution atmospheric TRANsmittance and radiance code (MODTRAN 4.1) the multiple scattering calculations are based on the Discrete Ordinate (DISORT) method (Stamnes et. al, 1988). The physical processes of DISORT include thermal emission, scattering, absorption and

* *Corresponding author address:* Robert A. Roebeling, Royal Netherlands Meteorological Institute (KNMI), P.O. Box 201, 3730 AE De Bilt, The Netherlands; e-mail rob.roebeling@knmi.nl

bidirectional reflection and emission at the lower boundary. This method solves the radiative transfer equation at 2*N streams to obtain N equations for N unknowns. These unknowns may be solved numerically, and in some cases analytically. The accuracy of the radiance calculations with DISORT depends on the number streams that are used. MODTRAN 4.1 uses a maximum of 16 streams.

The current official release MODTRAN 4.1 simplifies radiative transfer by using the Henyey and Greenstein phase function, which produces large errors in both radiance fields and fluxes. Therefore the Air Force Research Laboratory, Geophysics Directorate (AFGL) developed MODTRAN (4.2b) for this study. In this version the scattering phase function may be approximated by a finite number of Legendre polynomials.

The Spherical Harmonic Discrete Ordinate Method SHDOM (Evans 1998) enables computations of monochromatic or spectral band radiative transfer in a one, two, or three-dimensional medium for either collimated solar and/or thermal emission source of radiation. The source function of the radiative transfer equation is calculated on a grid of points in space with an iterative process. The angular part of the source function is represented with a spherical harmonic expansion, because the source function is more efficiently computed this way than in discrete ordinates. A discrete ordinate representation is used in the solution process because the streaming of radiation is more physically (and correctly) computed in this way.

3. THE INTERCOMPARISON STUDY

In this section we discuss the specifications of the input parameters applied to perform the intercomparison. The models are run with identical input data on atmospheric temperature, humidity profiles and cloud microphysical properties. All models solve or approximate radiative transfer for solar radiation in the Earth's atmosphere monochromatically, and do not consider thermal emission. The incident solar flux is assumed perpendicular to the solar beam. Multiple scattering and polarisation are fully taken into account.

The comparison is restricted to water clouds. The clouds are treated as a plane parallel homogeneous layer. The liquid water cloud particles are assumed to be spherical. The optical properties of the droplets size distribution are parameterised in terms of the effective radius, using a modified gamma distribution with an effective variance of 0.15**.** The scattering phase functions of MODTRAN 4.1 are approximated using the Henyey and Greenstein equation. The scattering phase functions of the SHDOM, DAK, Monte Carlo and Modtran 4.2b are calculated with Mie theory. The atmospheric profiles are taken from the HITRAN database (Kneizys et al. 1996), from which the midlatitude summer is used. The underlying surface is assumed Lambertian.

The radiative transfer calculations are performed at 0.63 and 1.6 μm for clouds over sea, grass and sand surfaces, with a cloud base height of 1000 m and a cloud top height of 2000 m. For each wavelength and each surface type cloud reflectivities are simulated for 27 typical cases. The selected cases are characterised by different combinations of solar zenith angles (θ_0=15,45,75), cloud optical thicknesses (τ=4,16,64) and cloud droplet effective radii (r_e=4,10,16). For each case the reflectivities are calculated for viewing angles (θ_v) between –70 and 70 degrees in the solar plane (solar azimuth angle is zero)

4. SIMULATION RESULTS

In order to evaluate the results of the radiative transfer calculations, the Monte Carlo model is selected as reference model. The Monte Carlo method simulates arbitrary complex scattering phase functions and arbitrary sharp cloud structures. The accuracy of the Monte Carlo methods depends on the number of photons used for the simulations. For this study Monte Carlo simulations are done with 10^7-10^8 photons. This is sufficient to obtain very accurate simulation results that are superior to the DISORT and doubling adding methods

TABLE 1. Average reflectivities (R_λ) at 0.63 and 1.6 μm. The given values are averages of the 27 sea cases. In parentheses is given the difference between Monte Carlo and model reflectivities in %.

Model	***$R_{0.63}$***	***$R_{1.6}$***
Monte Carlo	0.565	0.552
DAK	0.546 (-3.4%)	0.537 (-2.7%)
SHDOM	0.550 (-2.7%)	0.542 (-1.8%)
Modtran 4.1	0.481 (-14.9%)	0.367 (-33.5%)
Modtran 4.2b	0.529 (-6.3%)	0.484 (-12.3%)

Table 1 shows for all models the average reflectivities at wavelength λ (R_λ), weighted with the cosine of the viewing angle. The averages are calculated for the sea cases. From the table it can be seen that both the $R_{0.63}$ and the $R_{1.6}$ values of the DAK, SHDOM and MODTRAN (4.1 and 4.2b) models are lower than the reference model (Monte Carlo). The MODTRAN 4.1 calculations deviate strongly from the reference model. The differences can be explained by the fact that MODTRAN 4.1 uses the Henyey and Greenstein phase function, which is a poor representation of the scattering phase function of spherical droplets. MODTRAN 4.2b, which uses a Mie generated phase function, performs much better than MODTRAN 4.1. Compared to MODTRAN 4.1 the differences reduce by more than 50%. Based on these conclusions it is decided to leave MODTRAN 4.1 out the intercomparison hereinafter. The DAK and SHDOM calculations differ about 4% ($R_{0.63}$) and 3% ($R_{1.63}$) from the reference model. SHDOM performs slightly better than DAK. The large difference between MODTRAN 4.2b and the reference model at 1.6μm

(12%) cannot be explained by the accuracy of the multiple scattering calculations. Due to the high absorption at 1.6 μm the simulated radiances are less sensitive to multiple scattering. It is more likely that the observed differences can be explained by the treatment of Rayleigh scattering or the computation of atmospheric radiance in MODTRAN. This still has to be investigated.

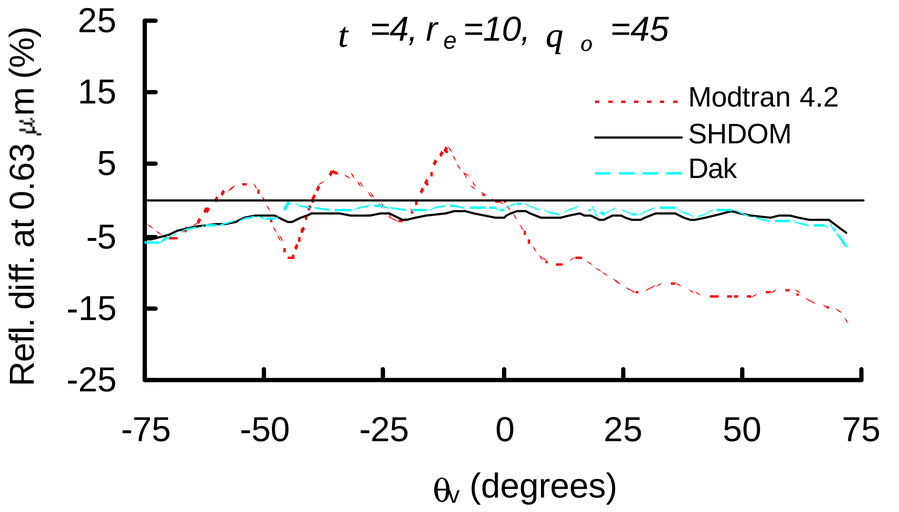

FIG. 1. Model reflectivities relative to Monte Carlo at 0.63 and 1.6 μm as function of θ_v. The calculations are done with a solar zenith angle θ_o = 45 for a water cloud with effective radius r_e=10 μm and optical thickness τ=4.

The influence of the viewing zenith angle on the calculation results can be seen from figure 1. This figure shows the relationship between the simulated reflectivity relative to the reference model, and the viewing angle. From the figures it can be seen that the differences between MODTRAN 4.2b and the reference model show strong oscillations. The largest differences are observed at viewing angles that correspond with characteristic features in the phase function, i.e.: forward peak, cloud bow and glory. The limited number of streams (16) probably causes these differences. In case of forward scattering (θ_v>0) the difference between MODTRAN 4.2b and the reference model increases with the viewing angle, with a maximum difference of 15% at θ_v=70. The DAK and SHDOM calculations at 0.63 μm deviate most from the reference model at large viewing angles. Compared to the reference model the SHDOM and DAK reflectivities at θ_v=70 and -70 are about 2% lower than at nadir (θ_v=0). All models show small oscillations relative to the reference model. These oscillations are non-systematic, and may be caused by the numerical noise.

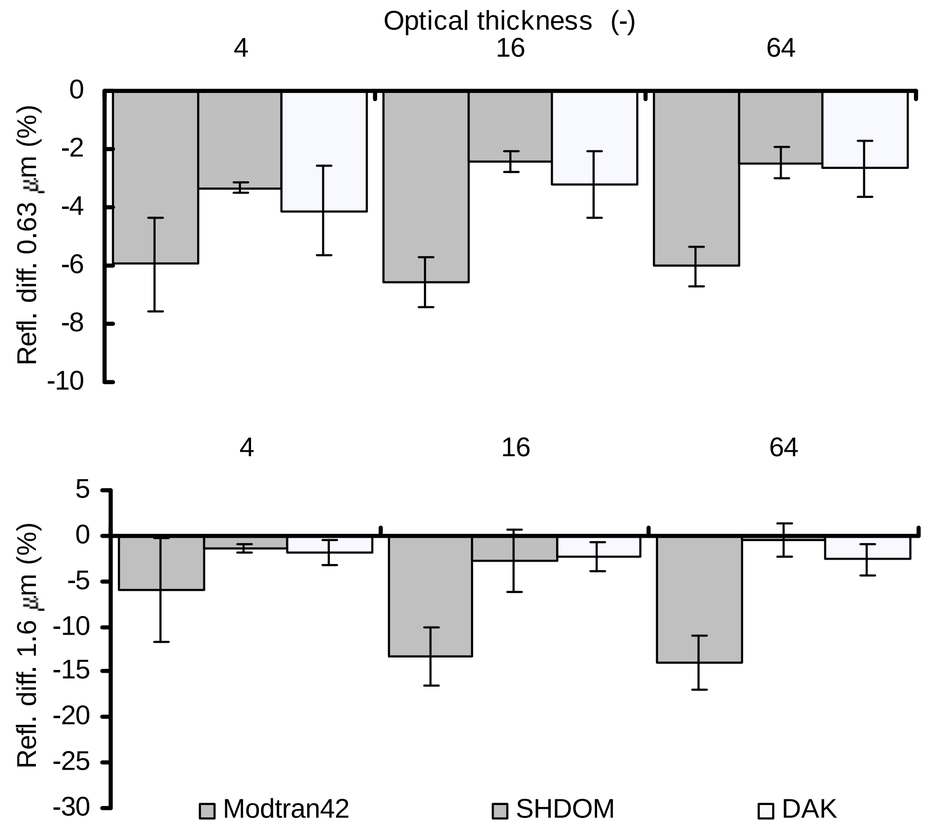

FIG. 2. Averages and Standard Deviations of model reflectivities relative to Monte Carlo as function of τ. The calculations are for all sea cases at 0.63 and 1.6 μm.

Figure 2 shows the average refectivity differences relative to Monte Carlo, as function of the optical thickness. The figure shows that the calculations are marginally influenced by the chosen optical thickness. At 0.63 μm the calculations at large optical thickness are more accurate, which can be seen from the lower average errors and standard deviations in simulated reflectivities. At 1.6 μm the MODTRAN 4.2b errors increases with the optical thickness. Considering the fact the 1.6 μm channel is a strong absorbing wavelength this indicates that there may be a fault in the calculation of the absorption. The SHDOM and DAK reflectivities at 1.6 μm do not reveal any systematic errors related to a low or high optical thickness.

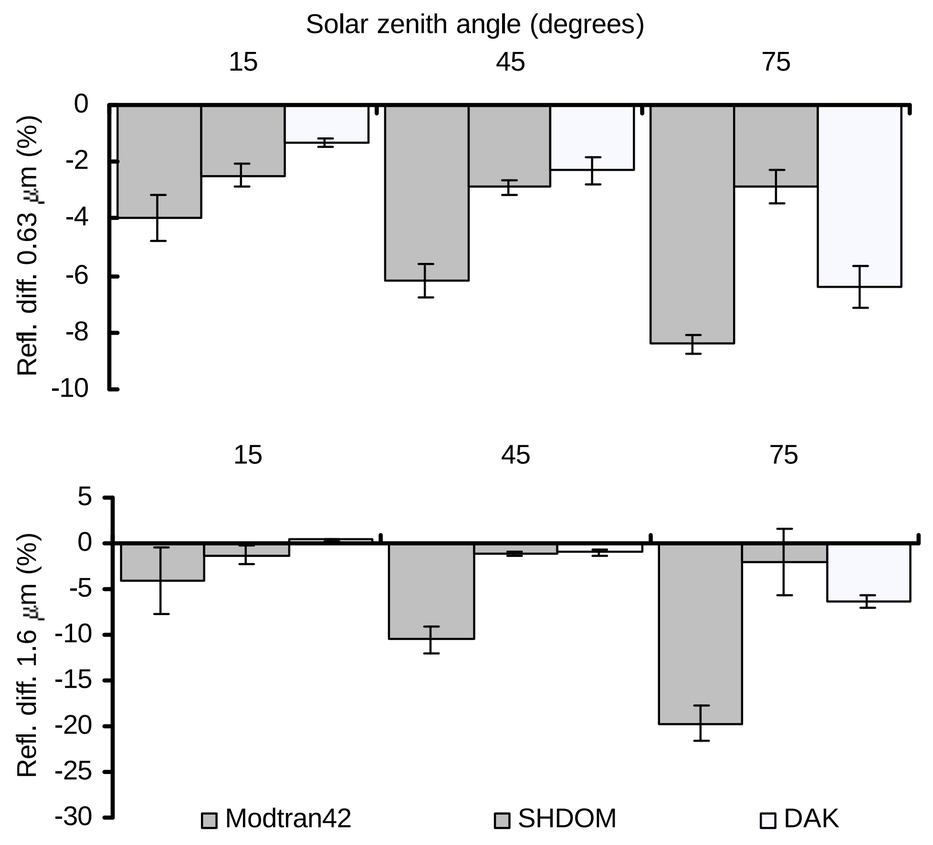

FIG. 3. Averages and Standard Deviations of model reflectivities relative to Monte Carlo as function of θ_o. The calculations are for all sea cases at 0.63 and 1.6 μm.

Figure 3 shows the average reflectivity differences, as function of the solar zenith angle. All models show an increase of the difference with the solar zenith angle. This especially evident for the MODTRAN 4.2b and DAK calculations, where the differences at θ_o>75 are 2-3 times larger than at θ_o>15. Part of the errors in DAK can be attributed to the number of Gaussian mu and Fourier terms that is chosen too low. As results errors occur in the calculations at large solar zenith angles and for the large particles (re=16 μm). The SHDOM results do not significantly vary with the chosen solar zenith angle.

5. CONCLUSIONS

An intercomparison is done for five radiative transfer models for 81 cases at a non-absorbing visible and a strongly absorbing near infrared wavelength. The cases are a good representation of cloud situations that may be observed with imaging satellite instruments. The analysis of the radiative transfer calculations has resulted in accurate information on the applicability of different radiative transfer codes for cloud analysis.

The study has shown that MODTRAN 4.1 is not suited for radiative transfer calculations in a cloudy atmosphere. Due to the use of the Henyey and Greenstein phase function MODTRAN 4.1 is not able to reproduce the anisotropy of the reflected radiation properties. This results in large errors in radiance fields and fluxes.

MODTRAN 4.2b, which allows user defined phase functions, performs much better. On average the simulated radiances are within 12% from the reference model (Monte Carlo). However, MODTRAN 4.2b does not perform as good as the DAK and SHDOM models. The errors at 1.6 μm are larger than at 0.6 μm. This suggests that the difference cannot be fully explained by the method applied for multiple scattering simulations (DISORT). It needs further research to determine whether: i) the calculation of absorption by cloud droplets, ii) the treatment of Rayleigh scattering or iii) the computation of atmospheric radiance, account for part of the observed differences in MODTRAN. In the discrete ordinate method the accuracy of the results is sensitive to the applied number streams. The maximum number of steams (16) used by MODTRAN is 16, which is insufficient to simulate the characteristic features of the phase function of spherical water droplets. For accurate cloud calculations with MODTRAN the number of streams needs to be increased. A similar reasoning applies for the DAK reflectivities, which deviate most from the reference model at large solar zenith angles and for large particles (re=16 μm). This can be explained d to the chosen the number of Gaussian mu and Fourier terms in the doubling adding method, which is too low to accurately simulate the strong forward peak of large particles.

All models are biased towards the Monte Carlo simulations, with more than 2% lower reflectivities. This bias is systematic. In addition there are random variations in the simulated reflectivities. These variations may be attributed to numerical noise that is the result of the differences in the approach to solve the equation of radiative transfer.

Acknowledgements. Financial support for this research was provided by EUMETSAT.

6. REFERENCES

Evans, K.F., 1998: The Spherical Harmonics Discrete Ordinate Method for Three-Dimensional Atmospheric Radiative Transfer.,JoASs, vol 55, pp429-446.

Han, Q., W. Rossow, R. Welch, A. White and, J. Chou, 1995: Validation of satellite retrievals of cloud microphysics and liquid water path using observations from FIRE; J. *Atmos. Science*, **52**, 4183 – 4195.

Hulst, H.C., 1980: "Multiple light scattering", Vols. 1 and 2, Acad. Press, New York.

Jolivet D., A. Feijt, P. Watts, 2000: Requirements for synergetic use of the ERM imager, ESA Contract RFQ/3-9439/98/NL/GD.

Kneizys, F.X., D.C. Robertson, L.W. Abreu, P. Acharya, G.P. Anderson, L.S. Rothman, J.H. Chetwynd, J.E.A. Selby, E.P. Shettle, W.O. Gallery, A. Berk, S.A. Clough and L.S. Bernstein, 1996: The MODTRAN 2/3 Report and LOWTRAN 7 MODEL, pp261.

Macke, A., D. Mitchelland L. von Bremen, 1998: Monte Carlo radiative transfer calculations for inhomogeneous mixed phase clouds, PCE, vol 24-3, pp 237-241.

Nakajima T. Y. and T. Nakajima, 1995: Determination of Cloud Microphysical Properties from NOAA AVHRR Measurements for FIRE and ASTEX regions., *J. of Atmosph. Sciences*, **52**, 4043 – 4059.

Stammes, P., 1994: Errors in UV reflectivity and albedo calculations due to neglecting polarisation, SPIE 2311, 227-235.

Stamnes, K., S.C. Tsay, W. Wiscombe and K. Jayaweera, 1988: Numerically stable algorithm for dis-crete-ordinate-method radiative transfer in multiple scattering and emitting layered media, *Appl Opt*., **27**, 2502-2509.

Watts P.D., 1996: Estimation of cloud droplet size, cloud optical depth and phase from ATSR. IRS'96 Current problems in atmospheric radiation. Deepak. 578-582.