Sensitivity of cloud property retrievals to differences in radiative transfer simulations

R.A. Roebeling[1], A. Berk[2], A.J. Feijt[1], W. Frerichs[3], D. Jolivet[1], A. Macke[3] and P. Stammes[1]

[1] Royal Netherlands Meteorological Institute (KNMI) P.O. Box 201, 3730 AE De Bilt, The Netherlands
[2] Spectral Sciences, Inc, Burlington, MA Unites States
[3] Leibniz-Institute for Marine Research (IFM-GEOMAR) Kiel, Germany

July 2005

Sensitivity of cloud property retrievals to differences in radiative transfer simulations

ABSTRACT

Accurate Radiative Transfer Model (RTM) simulations are the basis for retrieval of cloud properties from satellite radiances. Since the relationship between cloud radiances and cloud properties is not linear small differences in simulated radiances can result in large differences in retrieved cloud properties. This paper presents the sensitivity of cloud optical thickness and droplet effective radius retrievals to typical differences in radiative transfer simulations. Four widely accepted RTMs for multiple scattering calculations: Monte Carlo, MODTRAN4v2r0 (beta release), DAK and SHDOM, are intercompared to assess the differences in radiative transfer simulations. For two wavelengths (0.63 and 1.61 μm) plane parallel water cloud simulations are compared for a wide range of cloud properties and viewing geometries. The results show that radiative transfer simulations differ between 3% and 10%, due to differences in model parameterizations, number of streams, scattering phase function and treatment of the forward scattering peak.

The sensitivity of cloud property retrievals to differences in radiative transfer simulations is examined for NOAA16-AVHRR cloud properties retrievals. The retrieval algorithm used is the one planned in the Climate Monitoring SAF of EUMETSAT for meteorological satellites. The sensitivity study reveals that the differences in cloud property retrievals are very sensitive to viewing conditions and cloud characteristics. 3% error in simulated radiances at 0.63 μm accounted for differences in optical thickness up to 40% with increasing optical thickness. 3% error in the simulated radiances at 1.61 μm accounted for about 2 μm differences in the droplet effective radius for clouds with optical thickness greater than 5. The retrieval of cloud optical properties was most uncertain for clouds with optical thickness lower than 5 and greater than 50.

1. Introduction

Clouds strongly modulate the Earths energy balance and its atmosphere through their interaction with the solar and terrestrial radiation. Accurate information on cloud properties and their spatial and temporal variation is crucial for climate studies (King et al. 1997; IPCC 1995). The cloud radiative properties depend predominantly on cloud thermodynamic phase, optical thickness and cloud particle size. Radiative Transfer Models (RTMs) play an important role in the quantification of observed radiances in terms of cloud physical properties.

Radiances observed from meteorological satellites are used to retrieve cloud physical properties by employing RTMs. To retrieve these properties a thorough understanding of the relationship between the radiation characteristics and the physical properties of scattering particles is needed (Hansen and Travis 1974). Several methods have been developed to retrieve cloud optical thickness and cloud particle size from satellite radiances at wavelengths in the non-absorbing visible and the moderately absorbing solar infrared part of the spectrum (Nakajima and King 1990; Han et al. 1994; Nakajima and Nakajima 1995; Watts et al. 1998; Jolivet et al. 2003). The principle of these methods is that the cloud reflectance at the visible wavelength is primarily a function of cloud optical thickness, while the reflection at the near infrared wavelength is primarily a function of cloud particle size (Nakajima and King 1990). The accuracy of the retrieved cloud properties depends, among others, on the surface albedo, 3D cloud effects, multi–layer cloud effects and the presence of aerosols. Other inaccuracies originate from flaws in the RTM that is used to simulate cloud reflectance at given viewing geometries and predefined physical properties. RTMs differ in model parameterization and in the method used to solve the equation of radiative transfer that is either analytical, empirical or statistical (Hansen and Travis 1974). Few studies have been done on the sensitivity of cloud property retrievals to differences in simulated reflectances of commonly used RTMs.

The goal of this study is two fold: first, to assess the accuracy of narrow-band visible radiances simulated by several RTMs and second, to analyze the sensitivity of retrieved cloud microphysical properties to differences in radiances simulated by RTMs. The first part of the study, the model intercomparison, is an integral part of the Climate Monitoring Satellite Application Facility (CM-SAF) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The accuracy of the RTMs is assessed to select a RTM suitable for the retrieval of cloud microphysical properties from NOAA-AVHRR and Meteosat Second Generation radiance. The selected model should simulate the angular dependency of the solar radiation in a cloudy atmosphere with sufficient accuracy and at reasonable computational cost. The second part of the study is useful to examine how uncertainties in radiative transfer calculations affect cloud property retrievals because of the multi wavelength nature of the retrieval algorithms and the non-linear relationship between cloud properties and observed reflectances.

The RTM intercomparison is restricted to homogeneous layers of plane parallel water clouds. The scattering phase function of spherical water cloud particles was obtained through Mie calculations (van de Hulst 1957, Wiscombe 1980). For most plane parallel cloud models, the accuracy of simulated reflectances increases with the angular resolution that is given by the number of discrete zenith angles or Fourier terms and Gaussian points. However at high resolution, the radiative transfer calculations are too expensive. The algorithm of Jolivet et al. (2003) is used to study the sensitivity of cloud property retrievals. This iteration and interpolation algorithm relates Look Up Tables (LUTs) of visible and near-infrared (0.63 and 1.61 μm) reflectances for given optical thickness and droplet effective radius, to observed spectral reflectances. By assuming errors on the LUTs of reflectances the sensitivity of cloud property retrievals is determined.

The outline of the paper is as follows. Section 2 summarizes the RTMs used in the intercomparison. Section 3 describes the procedure for conducting the intercomparison study of four radiative transfer models and analyses the observed model differences. The sensitivity of cloud property retrievals to differences in radiative transfer simulations is presented in Section 4. Finally, Section 5 gives summary and conclusions.

2. Models to simulate radiative transfer for a cloudy atmosphere

a. Methods to solve radiative transfer

The equation of radiative transfer governs the transport of radiant energy in the atmosphere. Applied to the solar spectral range, it balances the loss of radiant intensity caused by extinction plus absorption along a certain direction with the gain of radiant intensity due to scattering into this direction. Several methods have been developed to approximate or solve the equation of radiative transfer in a plane parallel atmosphere. In this paper four well known RTM codes are compared that use different methods to solve the equation of radiative transfer. All codes are suited for simulating narrow-band radiances in a cloudy atmosphere. However, the codes are originally developed and optimized for different applications, for example for modeling radiative transfer in inhomogeneous three-dimensional media. In this section a short description is given of each of these codes.

The Monte Carlo model (Macke et al. 1998) is a forward scheme with a local estimate procedure for radiance calculations. It is a straightforward model that can be extended from one-dimensional to two or three-dimensional calculations (Davis et al. 1985). Monte Carlo treats multiple scattering as a stochastic process. The phase function governs the probability of scattering in a specific direction. Photon packages are emitted from a source (e.g. the sun or a lidar device) and undergo scattering and absorption events inside a predefined three-dimensional cloudy atmosphere until the energy of the package falls below a certain threshold or until the photons escape from the system, are absorbed by particles or by the surface (forward scheme). At each scattering event, the intensity that contributes to predefined sensor viewing angles is calculated (local estimate procedure).

The Doubling-Adding KNMI (DAK) radiative transfer model is developed for narrow band multiple scattering calculations at visible wavelengths in a horizontally homogeneous cloudy atmosphere (De Haan et al. 1987; Stammes 2000). DAK first calculates the reflection and transmission of an optically thin layer, in which no more than two scattering events may occur. Thanks to this restriction the radiative transfer equation can be solved analytically. Next, the reflection and transmission of two identical layers on top of each other can be obtained by computing successive reflections back and forth between the layers. The doubling procedure is continued until the actual optical thickness of the cloud is reached. The cloud is embedded in a multiplayer Rayleigh scattering atmosphere. The DAK model includes polarization.

In the MODerate spectral resolution atmospheric TRANsmittance and radiance code (MODTRAN), the multiple scattering calculations are based on the Discrete Ordinate (DISORT) method (Stamnes et al. 1988). The radiative transfer equation is solved for N discrete zenith angles to obtain N equations for N unknowns. These unknowns may be solved numerically. The MODTRAN single scatter solar radiances are computed separately from DISORT with inclusion of spherical refractive geometry effects; the plane-parallel DISORT single scatter contributions are subtracted from the DISORT solar radiances for generation of the total solar scattering values. The first versions of MODTRAN were optimized for narrow band radiance simulations in a clear atmosphere. The current public-released version of MODTRAN (MODTRAN4v1r1) allows calculations in a cloudy atmosphere. This version accepts the Henyey-Greenstein phase function (Henyey and Greenstein 1941), which is sufficient for modeling irradiances but a poor estimate for predicting radiances. For this study Spectral Sciences, Inc. (SSI) and the Air Force Research Laboratory (AFRL) developed MODTRAN4v2r0, a beta version that accepts Mie generated phase functions. Figure 1 shows an example of the effect of replacing the Henyey-Greenstein phase function in MODTRAN4v1r1 with the Mie generated phase function in MODTRAN4v2r0. The reflectances were calculated at 0.63 and 1.61 μm over a Lambertian surface with an albedo of 0.06 for a water cloud with optical thickness 4, effective radius 10 μm and solar zenith angle 45°. The figure clearly demonstrates that the modification of MODTRAN has a significant influence on the calculated narrow band cloud reflectances.

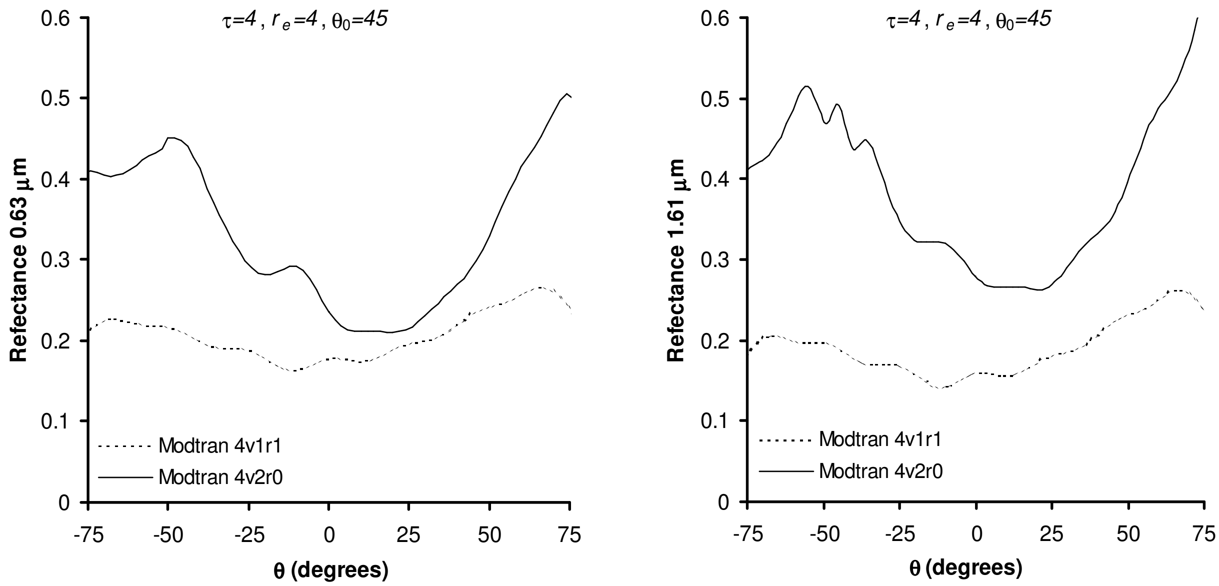


FIG. 1. Examples of MODTRAN4v1r1 (Henyey Greenstein phase function) and MODTRAN4v2r0 reflectance calculations at 0.63 and 1.61 μm. All viewing angles are in the principal plane with negative viewing zenith angles for backscatter. The reflectances are calculated for cloud optical thickness 4, effective radius 10 μm, solar zenith angle 45° over a surface with albedo 0.06.

The Spherical Harmonic Discrete Ordinate Method SHDOM (Evans 1998) is developed for modeling radiative transfer in inhomogeneous three-dimensional media. SHDOM uses an iterative procedure to compute the source function of the radiative transfer equation on a grid of points in space. The angular part of the source function is represented by a spherical harmonics expansion mainly because the source function is computed more efficiently in this way than in DISORT. A discrete ordinate representation is used in the solution process. The number of iterations increases with increasing single scattering albedo and optical thickness. SHDOM can be used for 3 dimensional radiative transfer calculations.

b. Differences in model parameterization

The parameterizations of the RTMs differ with respect to the method applied to truncate the phase function, and the number of streams used for the multiple scattering calculations. In addition, some models consider polarization and/or correct for refraction. A summary of the parameterization of the four codes is given in Table 1.

The scattering phase functions are represented by a finite number of Legendre polynomial expansion terms or tabulated at particular scattering angular bins. For spherical cloud particles a large number of expansion terms is needed to obtain a good representation of the forward peak in the phase function. Empirical techniques have been developed that estimate the contribution of the forward peak to the total scattered energy. The most common method is the delta function approximation (Potter 1970) and the extension to this approximation, the Delta-M method (Wiscombe 1977). In the Delta-M method, the original phase function is represented as a sum of a delta-function in the forward direction and an N-term Legendre expansion for the remainder term; the N Legendre expansion coefficients and the delta-function fraction are defined so that the summed Legendre expansion coefficients are correct up to the N+1 term. Macke et al. (1998) approximate direct forward scattering by linearly extrapolating the phase function value at the first two angular bins to 0°. Direct backscattering is treated correspondingly.

The accuracy of the radiative transfer calculation depends on the number of discrete zenith angles (N) and azimuth angles for which scattering is calculated. MODTRAN and SHDOM refer to these angles by streams, where one stream is equal to two discrete zenith angles. DAK uses Gaussian points for the zenith angles, whereas Fourier terms are used for the azimuth angles. The number of discrete zenith angles needed for accurate simulations depends on the anisotropy of the single scattering phase function. The required computer processing time increases rapidly with an increasing number of angles for MODTRAN and SHDOM or Gausspoints and Fourier terms for DAK. Therefore this number should be set to a value that is just enough to obtain convergence of the radiative transfer calculations. It should be noted that in MODTRAN the nominal maximum number of streams is 16, which is arguably insufficient to simulate multiple scattering of spherical water droplets.

In addition, MODTRAN is the only model that corrects for refraction, which implies that the sphericity of the Earth atmosphere and the bending of solar path are taken into account in the treatment of single scatter solar radiance. This correction is not implemented for multiply scattered solar photons.

TABLE 1. *Radiative transfer models of the intercomparison study, and the reference to the institute and contact person. Indicated are the numerical methods, if polarization and refraction corrections were applied, the zenith angles settings (indicated as streams, Gaussian points or photons) and the method that is applied to calculate and truncate the single scattering phase function.*

Model	Method	Phase function Calculation	Phase function Truncation	Zenith angle settings	Polarization	Spherical Earth Refraction	Reference
Monte Carlo	Ray tracing	Mie	Linear	10^7 - 10^8 photons	no	no	Leibniz-Institute for Marine Research (IFM-GEOMAR), Kiel, Germany. A. Macke: amacke@ifm-geomar.de
DAK	Doubling adding	Mie	none	60 Gausian pnts.	Switched off	no	Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands P. Stammes: stammes@knmi.nl
SHDOM	Spherical harmonics & DISORT	Mie	Delta-M	96 streams	no	no	Program in Atmospheric and Oceanic Sciences University of Colorado, Boulder, USA F. Evans : evans@nit.colorado.edu
MODTRAN4v1r1 [a)]	DISORT 2.0	HG [c)]	Delta-M	16 streams	no	Single Scatter Only	Spectral Sciences, Inc, Burlington, MA, Unites States A. Berk : lex@spectral.com
MODTRAN4v2r0 [b)]	DISORT 2.0	Mie	Delta-M	16 streams	no	Single Scatter Only	Spectral Sciences, Inc, Burlington, MA, Unites States A. Berk : lex@spectral.com

[a)] MODTRAN4v1r1 is the official version; [b)] MODTRAN4v2r0 is a beta version developed for this study; [c)] Henyey-Greenstein phase function

3. Comparison of radiative transfer models

a. Study procedure

All models selected for the intercomparison study other than MODTRAN4v2r0, hereinafter referred to as MODTRAN, solve radiative transfer for solar radiation in the Earth's atmosphere monochromatically; MODTRAN is a band model. MODTRAN is also the only model that considers thermal emission. However, thermal emission does not play a role at the wavelengths considered in this study i.e.: 0.63 and 1.61 μm.

The atmospheric temperature and pressure profiles were obtained from the midlatitude summer atmosphere of Anderson et al. (1986). In DAK, SHDOM and Monte Carlo Rayleigh scattering and absorption by O_3 and NO_2 were included. The Rayleigh scattering coefficient formula is taken from Chandraskehar (1950) and the refractive index of air from Edlen (1953). The O_3 cross-sections are from Bass and Paur (1984) and the NO_2 cross-sections from Schneider et al (1987). In MODTRAN molecular absorption was modeled using band model data calculated from the HITRAN line compilation (Rothman et al. 1986). The CO_2 and water vapour concentrations in the atmosphere were set to zero to exclude CO_2 and H_2O gas absorption lines that are not considered in the DAK, SHDOM and Monte Carlo atmospheres. The underlying surface was assumed Lambertian. Two changes were made in the MODTRAN code to obtain the same parameterization as the other models. Firstly, the sphericity of the Earth was switched off in MODTRAN. Secondly, DISORT in MODTRAN has a limit of 0.99995 for the single scattering albedo (ϖ). This limit is a significant source of discrepancies for multiple scattering calculations at 0.63 μm. To correct for this discrepancy we changed the limit for the single scattering albedo to 0.999998[1]. To demonstrate the impact of modifying the single scattering albedo figure 2 presents the actual and relative difference between original MODTRAN4v1r1_ORG (ϖ=0.99995) and modified MODTRAN4v1r1_MOD (ϖ=0.999998) simulated reflectances. As a reference DAK simulated reflectances are plotted in the figure as well. All simulations are done for water clouds with the Henyey-Greenstein phase function at solar and satellite zenith angles 0°. The figure in the left panel shows significant differences between the original and modified simulations. Compared to MODTRAN4v1r1_ORG the MODTRAN4v1r1_MOD reflectances gradually increase as the optical thickness increases, with a maximum difference of ~10 % at optical thickness 128. In the right panel it can be seen that the MODTRAN4v1r1_MOD reflectances agree well with the DAK reflectances.

The clear sky radiative transfer calculations were done at 0.63 and 1.61 μm to check the description of surface characteristics and atmospheric profiles in all models. The intercomparison is done for a Rayleigh atmosphere with molecular absorption of O^3 and NO^2 and no aerosols over a Lambertain surface with albedo 0.05. The calculations were done for the principal plane (relative azimuth angle between viewing and solar directions is zero or 180°) for three solar zenith angles (θ_0 = 15, 45, 75°) and for viewing angles (θ) between –75° and +75°. We used negative θ for relative azimuth angle 180° and positive θ for relative azimuth angle 0°.

[1] In developing DISORT, the decision was made to simplify code structure and maintenance by not considering the unit single scattering albedo limit. MODTRAN contains the single precision version of DISORT so that allowing a single scattering albedo of 0.999998 pushing the numerical stability limits of the model.

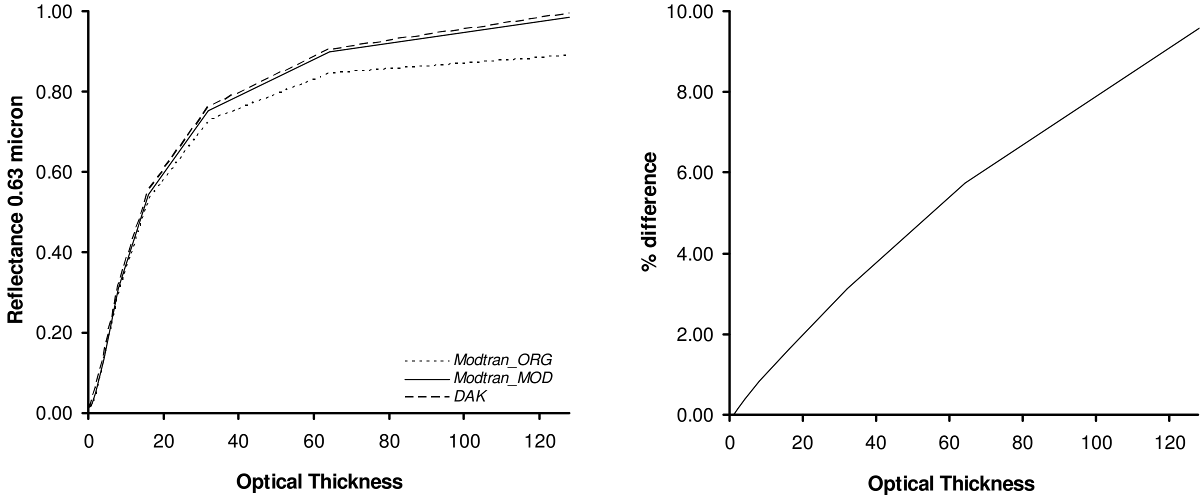


FIG. 2. MODTRAN4v1r1_ORG, MODTRAN4v1r1_MOD and DAK reflectances (left panel) and relative difference between MODTRAN4v1r1_ORG, MODTRAN4v1r1_MOD reflectances (right panel) as function of optical thickness. The reflectances are calculated over a dark surface at 0.63 μm for solar and satellite zenith angle 0°.

The intercomparison for clouds is restricted to plane parallel water clouds that are treated as homogeneous layers. The liquid cloud droplets were assumed to be spherical. For the optical properties of the droplets we employed the modified gamma distribution with specified effective radius (r_e) and effective variance (v_e) (Hansen and Hovenier 1974; Deirmendjian 1969). Mie calculations were done to obtain the scattering phase functions that were employed in the four RTMs. The radiative transfer calculations for clouds were done at 0.63 and 1.61 μm over a surface with albedo of 0.06. In the principal plane normalized reflectances were calculated at both wavelengths for 18 typical cases, which were characterized by different combinations of solar zenith angles (θ_0 = 15, 45, 75°), optical thicknesses (τ = 4, 16, 64) and droplet effective radii (r_e = 4, 10 μm). For plane parallel water clouds the principal plane has sufficient variability in reflected radiances for intercomparing radiative transfer simulations. This was shown from radiative transfer simulations performed over all relative azimuth angles (Feijt 2000). Moreover, the principle plane represents most satellite viewing geometries because it covers almost the full range of scattering angles. In this study scattering angles between 30° -180° are included. Table 2 Summarizes the surface albedo, cloud macro and microphysical properties and atmospheric temperature and humidity profiles that were used for all radiative transfer simulations in this study.

To evaluate the radiative transfer calculations, Monte Carlo was selected as reference model. Monte Carlo simulates arbitrary scattering phase functions and arbitrary sharp cloud structures. The accuracy of Monte Carlo simulations is generally high when sufficient photons are used for the calculations. For this study Monte Carlo calculations were done with 10^7-10^8 photons, which is appropriate to obtain accurate results. The simulated cases were compared by analyzing differences in the mean weighted reflectance over the principal plane, $\overline{R}$:

$$\overline{R} = \frac{\int_{\theta_1}^{\theta_2} R(\theta)\cos\theta \, d\theta}{\int_{\theta_1}^{\theta_2} \cos\theta \, d\theta} \tag{1}$$

where θ is the viewing angle in the principal plane, θ_1 = -75° and θ_2 = +75°. The motivation for applying a weighted mean is to give most importance to the dominating viewing angles of polar orbiting satellites.

The variance to the reference model was analyzed by means of the standard deviation of the model reflectance relative to the Monte Carlo model, integrated over the principal plane and weighted with the cosine of the viewing angles, σR :

$$\sigma R = \sqrt{\frac{\int_{\theta_1}^{\theta_2} \left(\left(\frac{R(\theta)_{\mathrm{ref}} - R(\theta)_{\mathrm{model}}}{R(\theta)_{\mathrm{model}}} * 100 \right) - \overline{\left(\frac{R_{\mathrm{ref}} - R_{\mathrm{model}}}{R_{\mathrm{model}}} * 100 \right)} \right)^2 \cos\theta \, d\theta}{\int_{\theta_1}^{\theta_2} \cos\theta \, d\theta}} \qquad (2)$$

where *Rmodel* is the reflectance of the model and *Rref* the reflectance of the reference model, Monte Carlo.

TABLE 2. Properties of the cloudy atmosphere and the surface of the radiative transfer calculations.

Parameter	Input value
Atm. profiles of pressure and temperature	Midlatitude summer (Anderson *et al.*, 1986)
Atm. profiles of O_3 and NO_2	*MODTRAN:* HITRAN (Rothman et al. 1986). *DAK, SHDOM and Monte Carlo:* O_3 from Bass and Paur (1984) NO_2 from Schneider et al (1987)
Aerosol model	None
Cloud particle	Spherical water droplet
Cloud type	Plane parallel and homogeneous
Cloud base height	1000 m
Cloud top height	2000 m
Droplet single scattering albedo (r_e=10 μm)	0.999998 (0.63 μm) [a)]; 0.992939 (1.61 μm)
Size distribution	Modified gamma
Eff. var. of the size distribution (v_e)	0.15
Surface	Lambertian
Surface albedo	0.060 (0.63 μm); 0.060 (1.61 μm)

[a)] DISORT in MODTRAN4v2r0 has a limit of 0.99995 for the scattering albedo.

b. Accuracy of radiative transfer simulations for a clear atmosphere

Table 3 and 4 give for clear sky the mean weighted reflectances ($\overline{R}$) and standard deviations calculated over the principal plane (σR) for solar zenith angles 15, 45 and 75°. The tables show that the four models produce similar results. These reflectances were simulated for a Lambertain surface with albedo 0.05. The differences are largest at 0.63 μm for solar zenith angle 75°, where a maximum absolute difference of 0.0036 is observed between Monte Carlo (0.1012) and MODTRAN (0.0976). Table 3 shows that the model standard deviations at 0.63 μm are below 2%. The clear sky simulations at 1.61 μm also agree well. Table 4 shows that the absolute differences at 1.61 μm is about five times lower than at 0.63 μm, with a maximum absolute difference of 0.0007. Similar to the 0.63 μm simulations this difference is observed between Monte Carlo and MODTRAN at solar zenith angle 75°. For all simulations the standard deviations at 1.61 μm were below 0.5%. Most differences are the result of small inconsistency in the parameterization of atmospheric profiles. The small absolute differences at both wavelengths support the belief that all models define the surface characteristics and atmospheric profiles consistently. The accuracy of the clear sky simulations is satisfactory for the intercomparison of radiative transfer simulations in a cloudy atmosphere.

TABLE 3. Mean weighted clear sky reflectances ($\overline{R}$) and standard deviation (σR) over the principal plane at 0.63 μm for a surface with albedo 0.05 and solar zenith angles 15, 45 and 75°.

	$\Theta_0=15°$		$\Theta_0=45°$		$\Theta_0=75°$	
	$\overline{R}$	σR	$\overline{R}$	σR	$\overline{R}$	σR
Monte Carlo	0.0656	-	0.0709	-	0.1012	-
Modtran	0.0641	0.20	0.0689	0.29	0.0976	1.85
DAK	0.0650	0.48	0.0704	0.31	0.1036	1.56
SHDOM	0.0646	0.27	0.0695	0.26	0.0987	1.64

TABLE 4. Mean weighted clear sky reflectances ($\overline{R}$) and standard deviation (σR) over the principal plane at 1.61 μm for a surface with albedo 0.05 and solar zenith angles 15, 45 and 75°.

	$\Theta_0=15°$		$\Theta_0=45°$		$\Theta_0=75°$	
	$\overline{R}$	σR	$\overline{R}$	σR	$\overline{R}$	σR
Monte Carlo	0.0503	-	0.0504	-	0.0512	-
Modtran	0.0505	0.09	0.0506	0.14	0.0519	0.32
DAK	0.0502	0.09	0.0503	0.15	0.0515	0.34
SHDOM	0.0504	0.05	0.0505	0.05	0.0513	0.13

c. Accuracy of radiative transfer simulations for a cloudy atmosphere

For a cloudy atmosphere we evaluated the sensitivity of RTM simulations to viewing zenith angle, particle size, optical thickness and effective radius. The results are discussed in this section. Overviews of the overall differences between the compared simulations are listed in table 5 and 6. These tables present for 18 cases over a dark surface at 0.63 and 1.61 μm the average mean weighted reflectance ($\overline{R}(avg)$), the average relative standard deviations ($\sigma R(avg)$) and the relative difference to the reference model. MODTRAN is the only model that simulates higher average reflectances than the reference model (Monte Carlo). The difference is about 2% at 0.63 μm and 7% at 1.61 μm. DAK and SHDOM simulate lower reflectances than the reference model, with differences of about -2% at 0.63 μm and about –1% at 1.61 μm. The negative differences of DAK and SHDOM may be explained by the different treatment of the forward peak in the phase function. Monte Carlo uses a linear approach to handle the forward peak, while SHDOM and MODTRAN use the Delta-M approximation and the forward peak is not truncated for spherical particles in DAK (see section 2). The low average relative standard deviations of DAK (< 1.2%) and SHDOM (< 2.6%) suggest that the differences with Monte Carlo for the individual radiative transfer simulations are within acceptable margins.

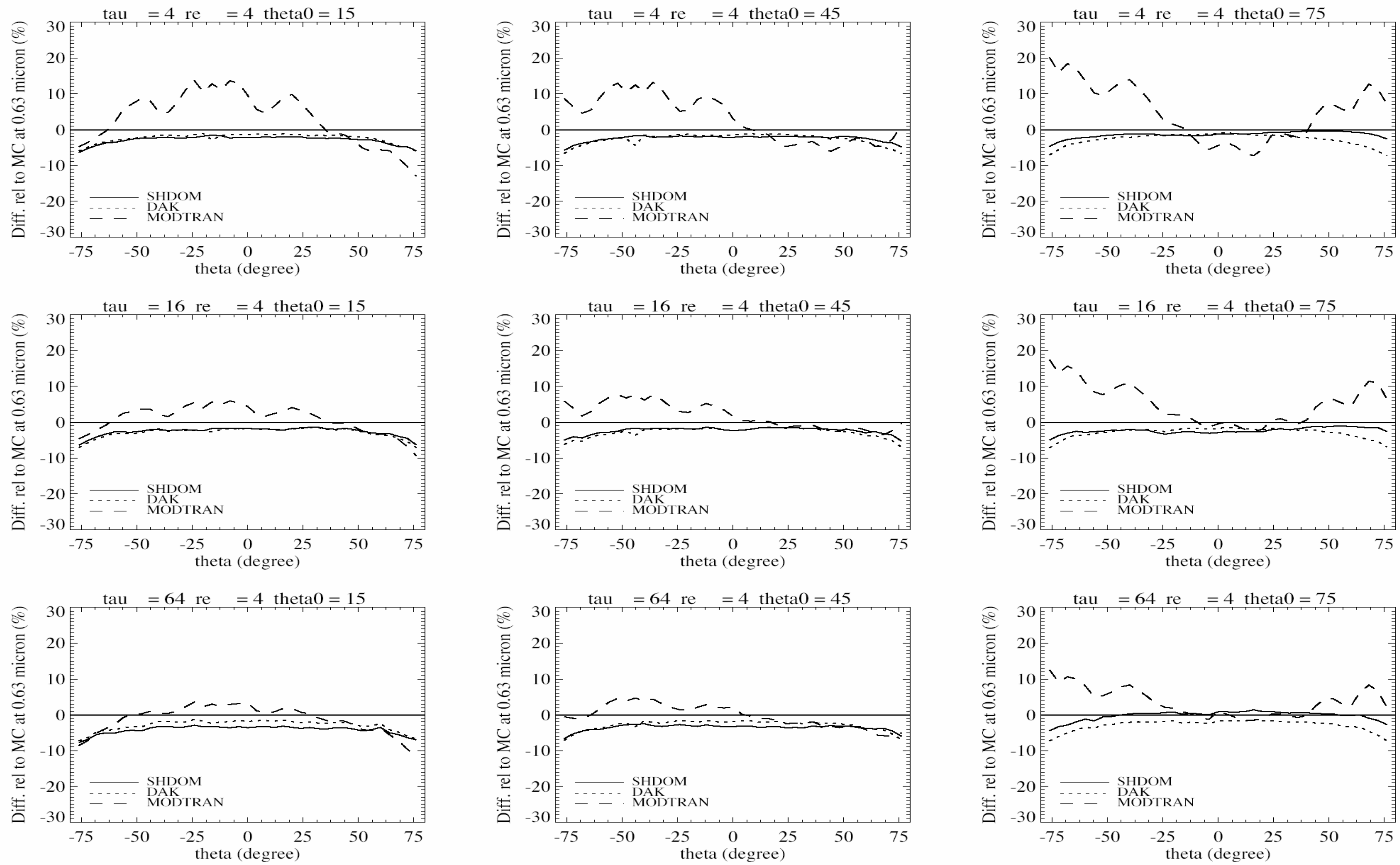
TABLE 5. Average mean weighted cloud reflectance ($\overline{R}(avg)$), the average σR given as a percentage ($\sigma R(avg)$) and the differences of $\overline{R}(avg)$ relative to Monte Carlo $\overline{R}(avg)$ in % (% diff MC) at 0.63 μm for 18 cloud cases over a surface with albedo 0.06.

	Dark surface (0.63 μm)		
	$\overline{R}(avg)$	$\sigma R(avg)$ *in %*	*% diff MC*
Monte Carlo	0.564	-	-
Modtran	0.576	4.38	2.12
DAK	0.551	1.13	-2.38
SHDOM	0.553	0.79	-2.11

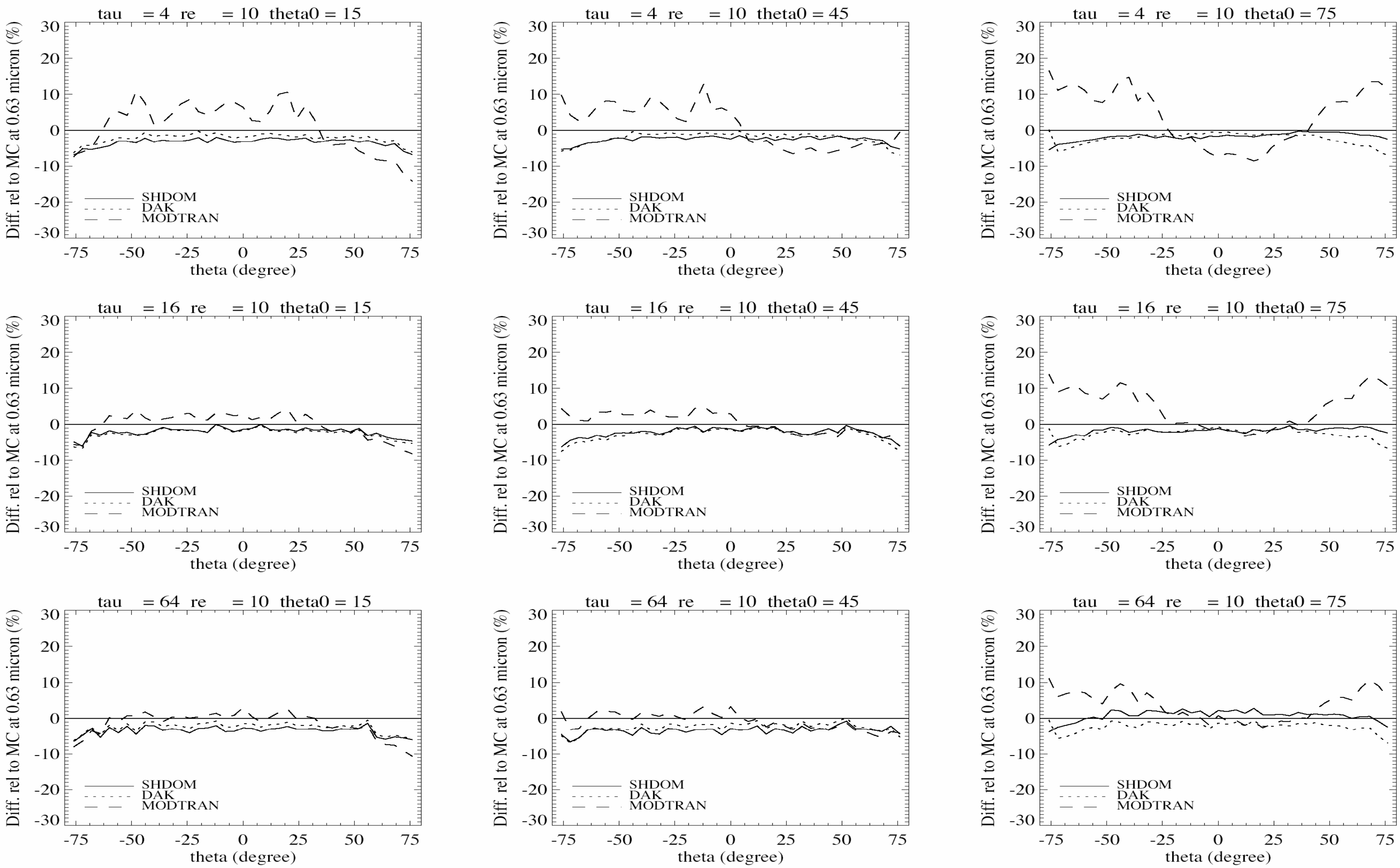
TABLE 6. Average mean weighted cloud reflectance ($\overline{R}(avg)$), the average σR given as a percentage ($\sigma R(avg)$) and the differences of $\overline{R}(avg)$ relative to Monte Carlo $\overline{R}(avg)$ in % (% diff MC) at 1.61μm for 18 cloud cases over a surface with albedo 0.06.

	Dark surface (1.61 μm)		
	$\overline{R}(avg)$	$\sigma R(avg)$ *in %*	*% diff MC*
Monte Carlo	0.578	-	-
Modtran	0.617	4.57	6.83
DAK	0.577	0.42	-0.11
SHDOM	0.577	2.66	-1.32

Figure 3 presents the reflectance distribution differences over the principal plane at 0.63 μm of DAK, SHDOM and MODTRAN relative to the Monte Carlo model. The reflectances are calculated over a dark surface for clouds with optical thickness 4, 16 and 64, solar zenith angles 15, 45 and 75° and effective radius 4 and 10 μm. The differences over the principal plane can be used for estimating the viewing angle dependence of the simulated reflectances. It is apparent that SHDOM and DAK reflectances differences behave similarly relative to the Monte Carlo model. Both models simulate about 2% lower reflectances at viewing angles near ±75° than at nadir. For DAK the reflectance differences relative to Monte Carlo are larger than for SHDOM at solar zenith angle 75°. The differences in SHDOM and DAK simulations are marginally influenced by the chosen particle size. Little influence of particle size would suggest that the different treatments of the forward scattering in the models do not have such a strong effect. The most significant differences relative to the Monte Carlo simulations are observed for MODTRAN. For all presented cases the variations of MODTRAN reflectances relative to Monte Carlo with the viewing angle are larger than for DAK and SHDOM. The differences are largest for effective radius 4 and solar zenith angle 75°. For backscatter directions ($\theta < 0$) MODTRAN simulates higher reflectances than the reference model. The difference increases to 15% at viewing angles that correspond with characteristic features in the phase function, at $\theta_o = 45°$ for example the glory at about $\theta = -45°$ and the cloud rainbow at about $\theta = -5°$. The latter differences can be attributed to the insufficient number of 8 discrete zenith angles (N) in MODTRAN (16 streams). To reproduce specific features of the phase function of spherical cloud particles at least 16 discrete zenith angles (32 streams) are needed. Finally, figure 3 shows that the reflectance distribution differences contain oscillations relative to the Monte Carlo model. The largest oscillations are found for optically thick clouds ($\tau = 64$). Because these oscillations are similar for SHDOM and DAK, it is suggested that these oscillations are explained by numerical noise in the Monte Carlo simulations. At high optical thicknesses the

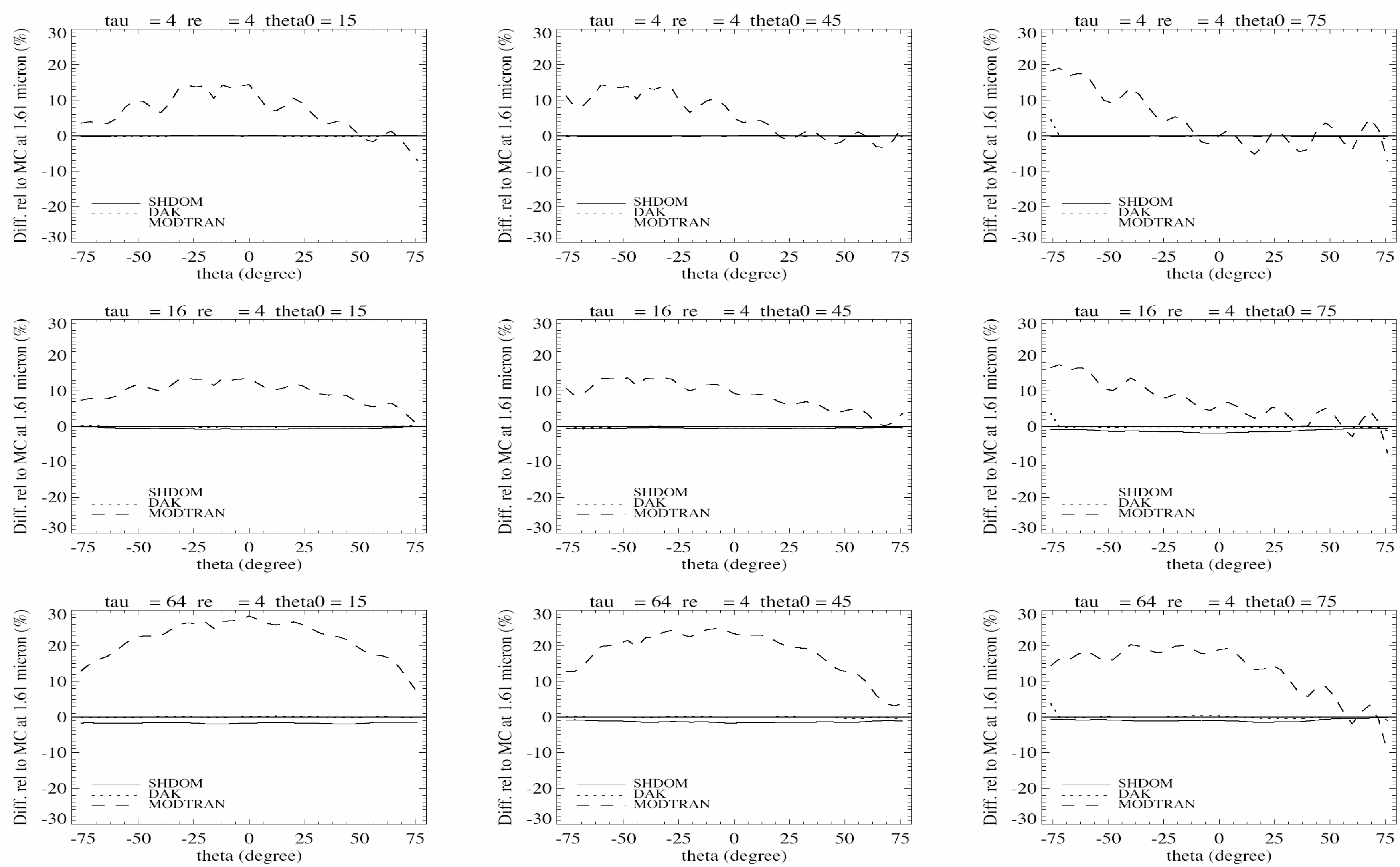

tau = 4 re = 4 theta0 = 15
tau = 4 re = 4 theta0 = 45
tau = 4 re = 4 theta0 = 75
tau = 16 re = 4 theta0 = 15
tau = 16 re = 4 theta0 = 45
tau = 16 re = 4 theta0 = 75
tau = 64 re = 4 theta0 = 15
tau = 64 re = 4 theta0 = 45
tau = 64 re = 4 theta0 = 75
Diff. rel to MC at 0.63 micron (%)
theta (degree)
SHDOM
DAK
MODTRAN

(a)

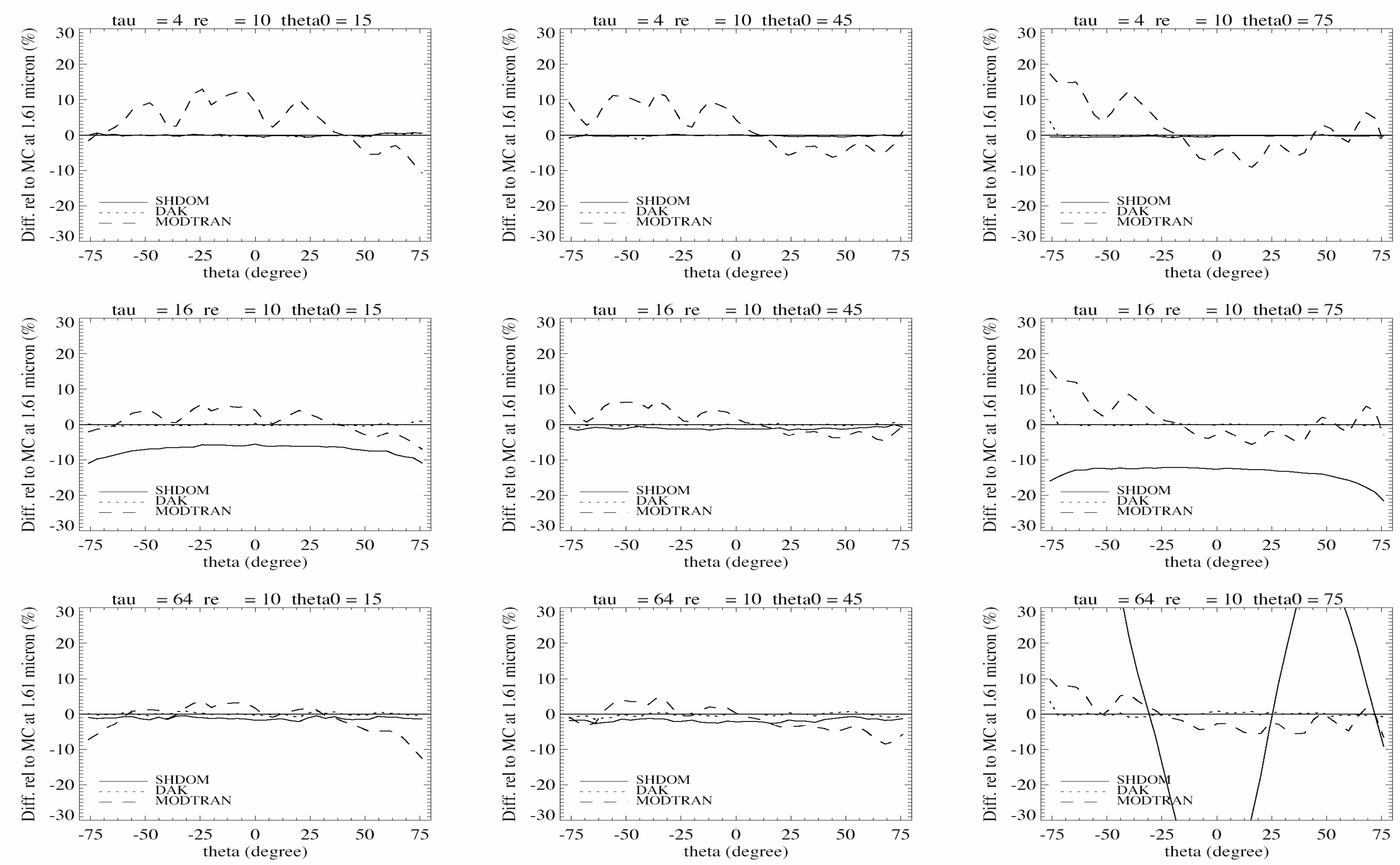


(b)

FIG. 3. Reflectance distribution differences relative to the Monte Carlo model at 0.63 µm. The reflectances are calculated over a dark surface for optical thickness 4, 16 and 64 , solar zenith angles 15, 45 and 75° and effective radii 4 (a) and 10µm (b).


tau = 4 re = 4 theta0 = 15
tau = 4 re = 4 theta0 = 45
tau = 4 re = 4 theta0 = 75
tau = 16 re = 4 theta0 = 15
tau = 16 re = 4 theta0 = 45
tau = 16 re = 4 theta0 = 75
tau = 64 re = 4 theta0 = 15
tau = 64 re = 4 theta0 = 45
tau = 64 re = 4 theta0 = 75
Diff. rel to MC at 1.61 micron (%)
theta (degree)
SHDOM
DAK
MODTRAN

(a)



(b)

FIG. 4. Reflectance distribution differences relative to the Monte Carlo model at 1.61 µm. The reflectances are calculated over a dark surface for optical thickness 4, 16 and 64 , solar zenith angles 15, 45 and 75° and effective radii 4 (a) and 10µm (b).

number of scatter events can reach 200. Therefore, differences that are small for one scatter event (e.g. 0.1%) may grow to ~1.5% in case of 200 scatter events. These differences may be explained by rounding errors, the applied number of streams, or by insufficient photons traced in the Monte Carlo model.

Figure 4 presents, for the same cloud properties as presented in figure 3, the reflectance distribution differences of DAK, SHDOM and MODTRAN relative to the Monte Carlo model at 1.61 μm. The figure shows that SHDOM and DAK reflectance distribution differences at 1.61 μm deviate less than 3% from the Monte Carlo model, and hardly show any viewing angle dependency. Due to the higher absorption of spherical droplets at 1.61 μm than at 0.63 μm multiple scattering plays a less important role. Therefore, we would expect that the observed differences at 1.61 μm would be smaller than at 0.63 μm. From figure 4 it can be seen that for three cases SHDOM simulations at 1.61 μm deviate significantly from Monte Carlo i.e.: τ=16, r_e=10 μm, θ_0 =15°; τ=16, r_e= 10μm, θ_0 = 5° and τ=64, r_e=10 μm, θ_0 =75. Comprehensive analysis of SHDOM simulations revealed that our version of SHDOM becomes unstable at certain optical thicknesses and effective radii. These instabilities occurred both at 0.63 and 1.61 μm wavelengths. Offline SHDOM simulations demonstrated that the problem disappears again for higher optical thicknesses, for example τ = 128. Similar to the reflectance distribution differences at 0.63 μm, MODTRAN tends to overestimate reflectance at 1.6 μm for the negative viewing angles. These differences are unforeseen. The simulated radiances at 1.61 μm are expected to be less sensitive to multiple scattering than at 0.63 μm. Because of the higher absorption of spherical particles at 1.61 μm more energy is lost as the number of scatter events increases. Therefore, it is more likely that the observed differences at 1.61 μm would be smaller than at 0.63 μm. Finally, for small particles (r_e = 4) and high optical thickness (τ = 64) MODTRAN differs up to 25% from Monte Carlo. For clouds with effective radius 4 the differences between MODTRAN and the other models are systematic and can not be explained by numerical noise or insufficient number of streams. However, these systematic differences could manifest if an incorrect and too high single scattering albedo is used. Figure 5 presents DAK simulated reflectances for an absorbing and non-absorbing cloud at 1.6 μm. The difference between the absorbing and non-absorbing clouds (right panel figure 5) is very similar in shape and magnitude to the differences between MODTRAN and the reference model. Hence, it is suggested that the major part of the differences is explained by too low cloud absorption in the beta release of MODTRAN.

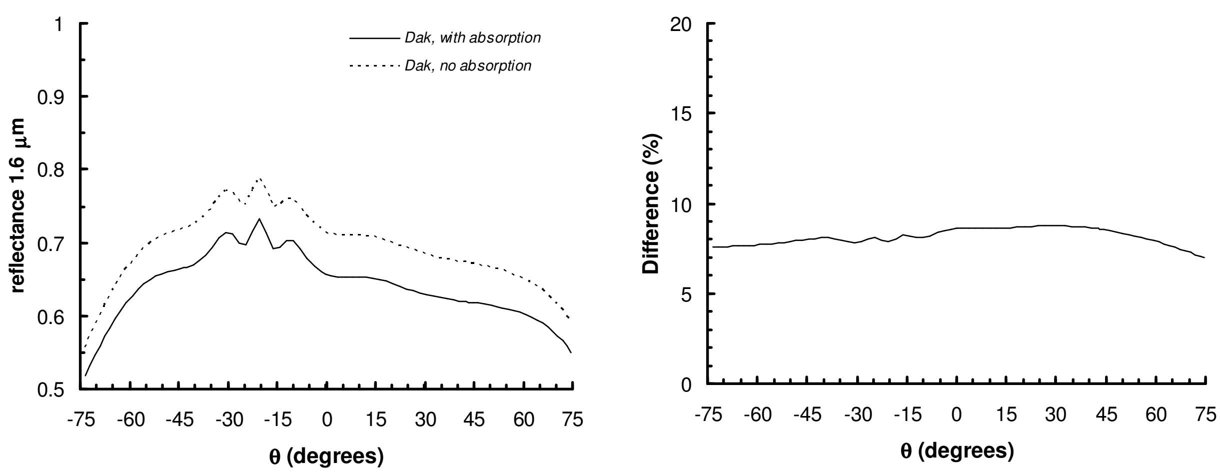


FIG. 5. DAK reflectances at 1.6 μm over the principle plane at θ_0=20 degrees for a water cloud with tau=16 and re = 4 and. The simulations are done for a non-absorbing and an absorbing cloud. The right panel shows the difference between the absorbing and no absorbing cloud.

Figure 6 shows for 0.63 and 1.61 μm the differences between SHDOM, DAK and MODTRAN and Monte Carlo average mean weighted reflectance ($\overline{R}(avg)$) grouped for solar zenith angles 15, 45 and 75°. The error bars shown in this figure represent the average σR given as a percentage ($\sigma R(avg)$). The figure clearly shows that the effect of solar zenith angle on the model simulations is largest for MODTRAN. The effect is strongest at 1.61 μm with about 8% higher reflectances at 15° and 4% higher reflectances at 75°, while at 0.63 μm the difference relative to Monte Carlo is about 4% at 15° and 2% at 75°. However, the simulations at 75° cannot be considered stronger correlated with the Monte Carlo model, because the standard deviations of MODTRAN relative to Monte Carlo are high for all solar zenith angles (> 4%). The difference of DAK and SHDOM relative to Monte Carlo does not show significant solar zenith angle dependence. For the three solar zenith angles the variations of DAK and SHDOM $\overline{R}(avg)$ are within the range of the observed standard deviations at both wavelengths.

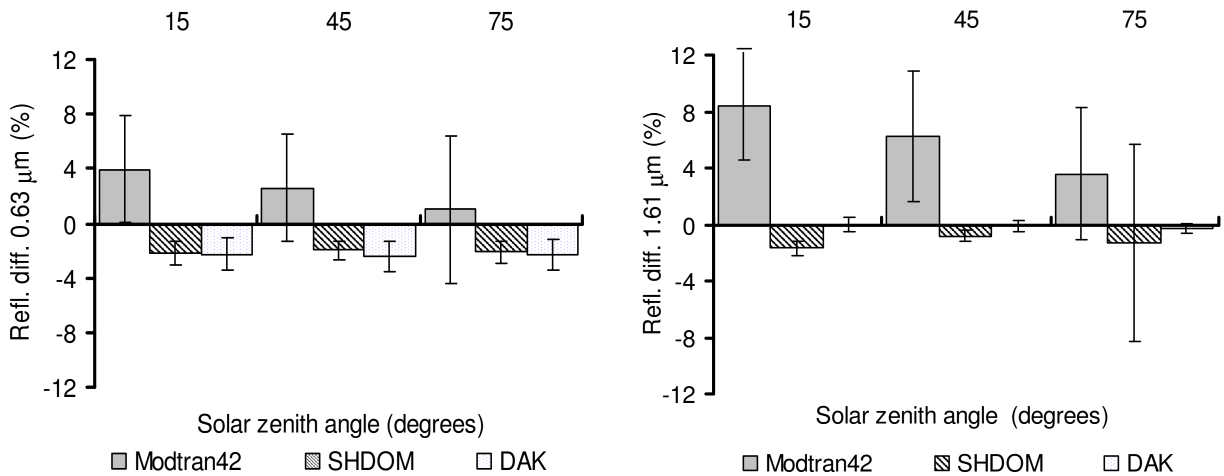


FIG. 6. Averages of model mean weighted reflectances and standard deviations relative to Monte Carlo for solar zenith angles 15, 45 and 75°. The averages are calculated for clouds over a dark surface at 0.63 and 1.61 μm.

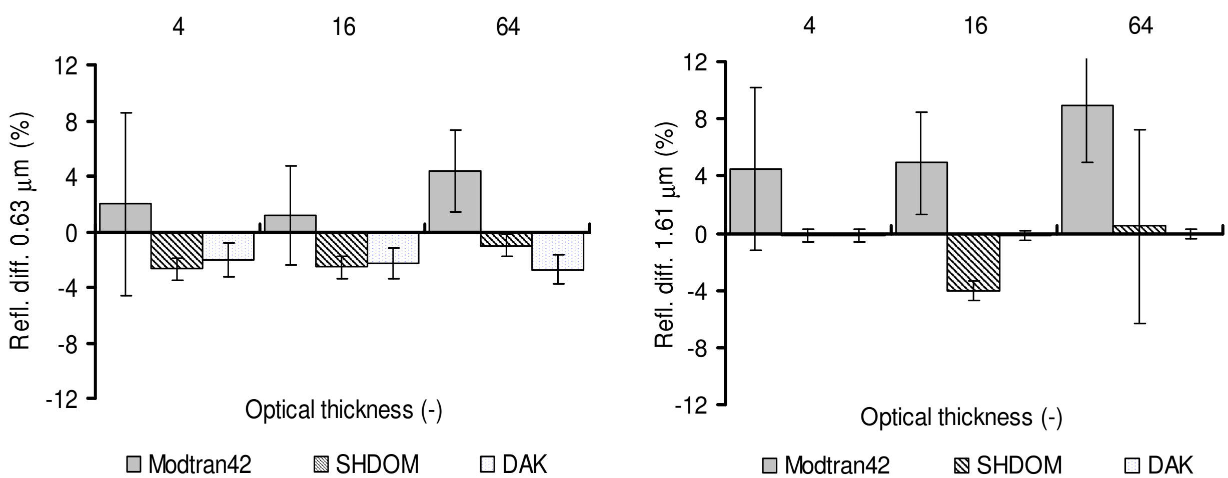


FIG. 7. Same as figure 6 but for optical thicknesses 4, 16 and 64.

Figure 7 shows for 0.63 and 1.61 μm the differences between SHDOM, DAK and MODTRAN and Monte Carlo average mean weighted reflectance grouped for optical thicknesses 4, 16 and 64. At both wavelengths the differences of MODTRAN relative to Monte Carlo show a significant dependence with optical thickness. The difference between MODTRAN and Monte Carlo increases as the optical thickness increases. The effect is strongest at 1.61 μm, with about 8% higher reflectances at τ=64 and 4% higher reflectances at τ=4. The average standard deviations ($\sigma R(avg)$) are highest for τ=4, with about 6% at 0.63 μm and 5% at 1.61 μm.

4. Sensitivity analysis of cloud property retrievals

The sensitivity analysis is done to assess the impact of differences in radiative transfer calculations on cloud optical thickness and droplet effective radius retrievals. For the cloud property retrievals we used the algorithm of Jolivet et al. (2003), an iteration and interpolation scheme that relates LUTs of simulated reflectances for given optical thickness and droplet effective radius to observed reflectances at visible (0.6 μm) and near-infrared (1.6 μm) wavelengths. The LUTs were generated with DAK. The results of this study, however, will be almost insensitive to the selected radiative transfer model because the analysis is done relative to simulated reflectance. The errors in cloud property retrievals arise from differences in radiative transfer calculations and differences in iteration and interpolation scheme. It is useful to determine these errors because of the non-linear relationship between cloud properties and observed reflectances and the simultaneous retrieval of optical thickness and effective radius. Because of the non-orthogonal relationship between droplet effective radius and 1.6 μm reflectances for thin clouds, the retrieval of droplet effective radius was restricted to optical thicknesses larger than 4. The NOAA16-AVHRR image of 13 August 2001, 12:25 UTC over Northern Europe was selected for the sensitivity study. The image is assumed to represent sufficient cloudy situations for a statistically sound analysis. For simplicity it was decided to analyze the sensitivity channel wise, which is a simplification of reality where the errors will occur in both channels simultaneously. The optical thickness and droplet effective radius was retrieved for water clouds with fixed errors put on simulated reflectances in one channel, and with no error in the other channel. These errors were varied between -3% and +3%, corresponding with typical differences that were found in the RTM intercomparison study. Note that the maximum differences of ~25% for MODTRAN and ~10% for DAK and SHDOM are much higher that the typical differences.

Figure 8 presents the NOAA16-AVHRR retrieved cloud optical thickness and droplet effective radius images of 13 August 2001, 12:25 UTC. The prevailing cloud type over the Netherlands and Germany is stratocumulus. While over Denmark and the North Sea convective clouds associated with a frontal occlusion are observed. The stratocumulus clouds are rather homogeneous, with cloud optical thicknesses of about 20-40 and droplet effective radii of about 8-12 μm. The convective clouds are more heterogeneous. The cloud optical thicknesses values range from 10 to 128, whereas the droplet effective radii values range from 8 to 20 μm. The frequency distributions of retrieved optical thickness and droplet effective radius for water clouds are presented in figure 9. The left panel in this figure shows that optical thicknesses have a lognormal distribution and values varying between 0 and 50 for most of the data. The right panel shows that droplet effective radii are normally distributed with the highest frequency at about 8 μm, which is consistent with the values that Feijt (2000) found for stratocumulus clouds over The Netherlands.

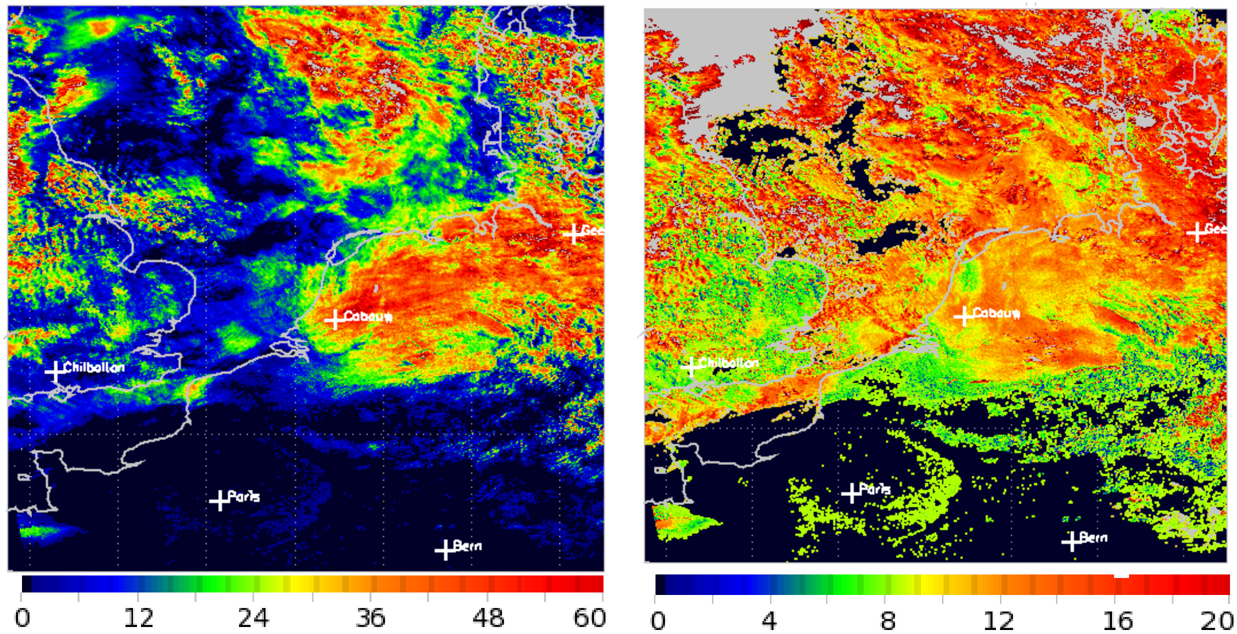


FIG. 8. Retrievals of cloud optical thickness (left) and droplet effective radius (right on 13 August 2001, 12:25 UTC, using NOAA-16 AVHRR visible and near-infrared reflectances. The gray areas represent regions that were identified as ice clouds.

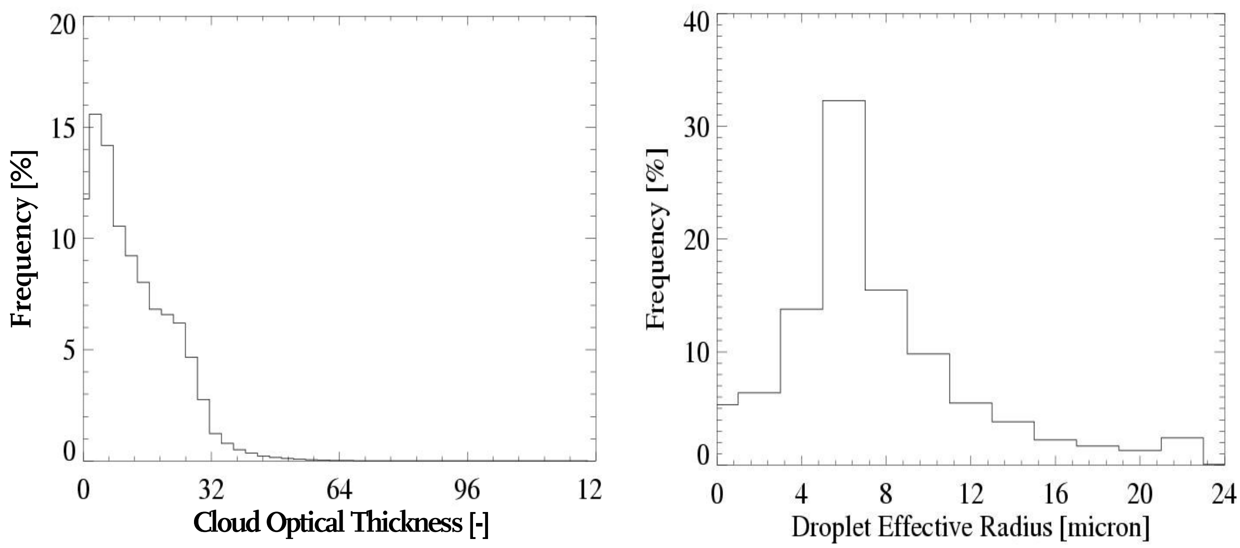


FIG. 9. Frequency distributios of cloud droplet effective radius retrieval (left) and droplet effective radius for water clouds on 13 August 2001, 12:25 UTC, using NOAA-16 AVHRR visible and near-infrared reflectances.

Figure 10 shows the errors in cloud optical thickness due to errors in 0.63 µm and 1.61 µm simulated reflectances. The error bars in the figure represent differences due to the iteration and interpolation scheme of the retrieval algorithm. For clouds with $\tau > 60$ the retrieval of optical thickness is very sensitive to errors in 0.63 µm reflectances. Errors of ±3% in 0.63 µm reflectances can propagate to errors of ±30% in retrieved optical thickness. In contrast, the retrieval of optical thickness is almost insensitive to errors in 1.61 µm reflectances, with errors in retrieved optical thickness being lower than 1%. The error bars indicate the differences due to iteration and interpolation scheme, which slightly increase with cloud optical thickness from zero to ±2% at both 0.63 and 1.61 µm. Figure 11 illustrates that the droplet effective radius retrievals are less sensitive to the wavelength. For errors of ±3% in

0.63 μm reflectances the errors in effective radius are about 0.7 μm. The retrieval of effective radius is a little more sensitive to errors of ±3% in 1.61 μm reflectances with errors varying between 0.8 to 1.5 μm. These errors slowly increase with increasing effective radius. It is remarkable that for both 0.63 and 1.61 μm the errors related to the iteration and interpolation scheme are relatively large, with errors vary between ±0.1 for the ±1% RTM errors and ±0.5 μm for ±3% RTM errors. These errors are probably related to step size in the LUTs that is used for the effective radius simulations. Hence it is suggested to reduce the errors related to the iteration and interpolation scheme by adding more effective radii in the LUTs.

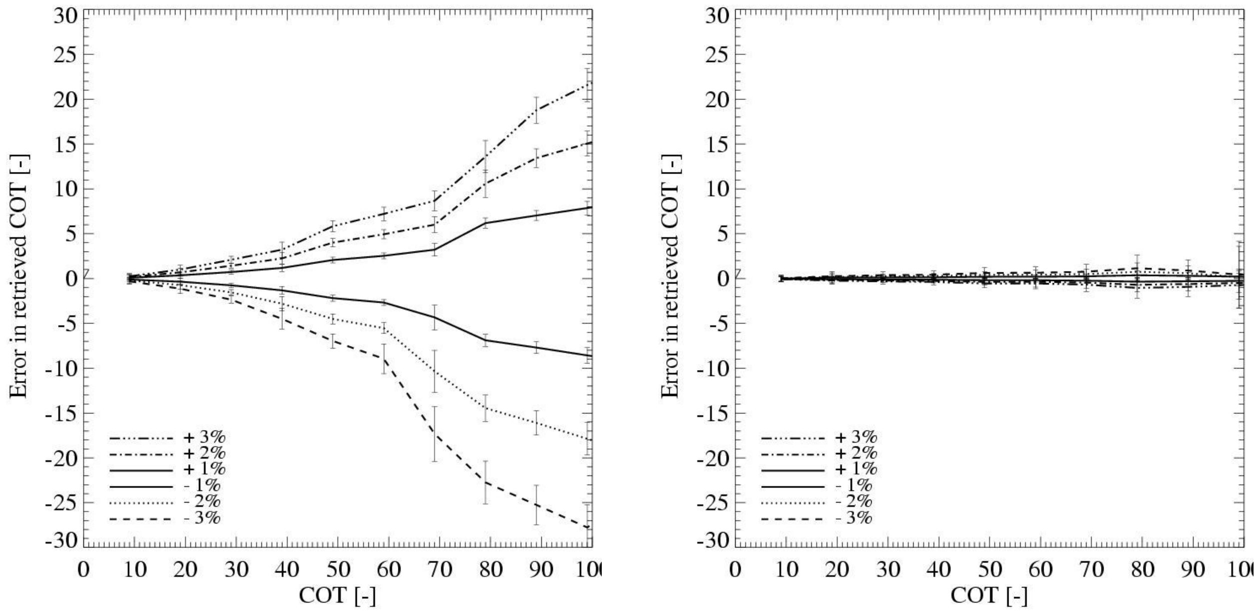


FIG. 10. Error in retrieved cloud optical thickness (-) assuming errors of ± 1, 2 and 3% in the 0.63 (left) and 1.61 μm (right) reflectances. The error bars represent differences due to the iteration and interpolation scheme.

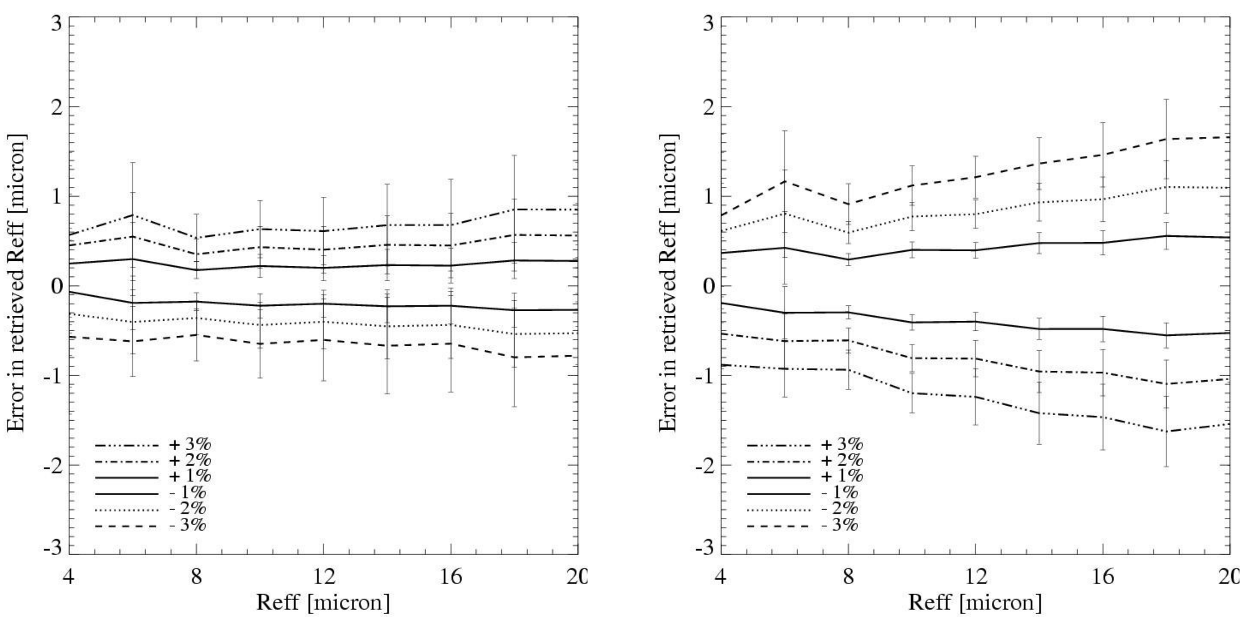


FIG. 11. Error in retrieved droplet effective radius (μm) for water clouds with $\tau > 4$ assuming errors of ± 1, 2 and 3% in the 0.63 (left) and 1.61 μm (right) reflectances. The error bars represent differences due to the iteration and interpolation scheme.

5. Summary and conclusions

This study on the accuracy of RTMs and the sensitivity of retrieved cloud microphysical properties to differences in simulated radiances confirms the need for accurate radiative transfer simulations. Radiative transfer simulations of four models were compared for a cloudy atmosphere for geometrical conditions that represent observations of polar orbiting satellite imagers. The analysis of the simulated radiances provides accurate information on the differences between the compared codes. The importance of accurate radiative transfer calculations is demonstrated by the great sensitivity of cloud property retrievals to relatively small differences in simulated reflectances.

The intercomparison study has demonstrated that SHDOM and DAK are suitable for the radiance calculations of clouds. The simulation results of SHDOM and DAK are similar to the Monte Carlo simulations that were done with 10^7-10^8 photons to ensure accurate simulations. For a clear atmosphere all models show small absolute differences relative to Monte Carlo, while for a cloudy atmosphere considerably larger absolute differences are observed. Since the clear sky simulations are almost identical the cause of the differences for a cloudy atmosphere must lie in the multiple scattering calculation schemes or numerical noise. We can conclude that MODTRAN4v1r1 is not suited for radiative transfer calculations in a cloudy atmosphere because of using the Henyey-Greenstein phase function, which is a poor estimate of the scattering phase function of cloud particles. The implementation of the option to include a user defined phase function in MODTRAN4v2r0 (beta release referred to as MODTRAN) is a large improvement. However, in its present state MODTRAN is still the least accurate model for radiance simulations of clouds. On average MODTRAN simulations deviate less than 3% from the reference model (Monte Carlo), but for individual viewing angles in the principal plane the deviations can increase to nearly 30%. The maximum allowed number of streams in MODTRAN is 16, which is at the lower limit for cloud calculations and explains part of the observed differences. Both at 0.63 and 1.61 μm MODTRAN simulates similar differences relative to the reference model, whereas it is more likely that the differences at 1.61 μm would be smaller than at 0.63 μm due to the higher absorption of cloud particles at 1.61 μm. It is suggested that the differences in MODTRAN reflectances cannot be fully explained by the method for multiple scattering calculations (DISORT). Part of the observed differences may be explained by different or incorrect model parameterization, for example due to differences in the single scattering albedo. Motivated by our results AFGL has released MODTRAN4v3r2, in which cloud radiance calculations are further improved. In the next MODTRAN version (MODTRAN5) the maximum number of streams will be increased to 32. The DAK and SHDOM calculations are similar to Monte Carlo, with mean differences smaller than 3%. However, for individual cases the differences are occasionally much larger. A noticeable finding is that the Monte Carlo has a 3% bias as compared to SHDOM and DAK. This bias may be explained by differences in the treatment of the forward peak of the scattering phase function. Especially for large particles with a strong forward peak this may cause significant differences in simulated radiances. Beside the clarified differences Monte Carlo shows small, non-systematic, oscillations relative to SHDOM and DAK. These oscillations are largest for optical thick clouds ($\tau = 64$), for moderate particles ($r_e = 10$ μm) and for large viewing zenith angles (75°). For these cases the number of multiple scattering events is large (up to 200) and the forward peak is strong, so that small differences in single scattering parameters can easily accumulate to large errors in the reflectances (±2%). Finally, our version of SHDOM becomes unstable at certain optical thicknesses and effective radii. Comprehensive analysis showed that these instabilities occurred at 0.63 and 1.61 μm wavelengths and that the problem disappeared again by choosing another optical thickness or effective radius.

The sensitivity study has shown that small errors in radiative transfer simulations at 0.63 and 1.61 μm can affect retrievals of cloud optical thickness and effective radius strongly. The retrieval of optical thickness shows a large sensitivity to errors in 0.63 μm reflectances. Especially for thick clouds ($\tau > 60$) errors in retrieved optical thickness can increase to 30% due to errors of 3% in the simulated reflectance. Due to the partly orthogonal retrieval of effective radius at 1.61 μm it is only meaningful to retrieve effective radius for clouds with an optical thickness above 4. Compared to the optical thickness a smaller sensitivity is encountered for the droplet effective radius retrievals. However, the effective radius retrievals are sensitive to errors at both wavelengths.

It should be mentioned that several sources of error may affect cloud property retrievals. Besides errors in radiative transfer simulations the instrument calibration is another source of errors. Further, the accuracy of the retrievals depends on the validity of the assumption that homogeneous plane parallel clouds can represent clouds. Added up these effects may result in errors much larger than 3%.

6. Acknowledgments

This work was part of the EUMETSAT co-sponsored Climate Monitoring Satellite Application Facility project. Part of the work was carried out by at University of Kiel. The authors express their appreciation to Gail Anderson of AFRL for assisting in acquisition of a modified version of MODTRAN for this comparison study. The authors like to thank F. Evans of the University of Colorado for his useful comments on the earlier versions of this paper. Finally, we are grateful to H. Hauschildt, S. Meyer and M. Schewski of the University of Kiel for reprocessing a number of SHDOM and MODTRAN4v2r0 simulations.

REFERENCES

Anderson, G. P., S. A. Clough, F. X. Kneizys, J. H. Cheywynd, and E. P Shettle, 1986: AFGL Atmospheric Constituent Profiles (0-120km). Tech. Rep. AFGL-TR-86-0110, 43 pp.

Bass A.M. and R. J. Paur, 1986: The ultraviolet cross-sections of ozone. I. The measurements. II - Results and temperature dependence, In Proc. Quadrennial Ozone Symp., Chalkidiki, Greece, Eds. C. Zefros and A. Ghazi. Reidel, Dordrecht, 606 pp.

Chandrasekhar S., 1960: Radiative Transfer (Dover, New York, 1960).

Davis, J. M. , T. B. McKee and S. K. Cox, 1985: Application of the Monte Carlo method to problems in visibility using a local estimate: an investigation, *Applied Optics*, **24(19)**, 3193-3205.

Deirmendjian, D., 1969: *Electromagnetic Scattering on Spherical Polydispersions.* American Elsevier (New York, 1969), 292 pp.

Edlen, B., 1953: The dispersion of standard air, *J. Opt. Soc. Am.*, **43**, 339-344.

Evans, K. F., 1998: The Spherical Harmonics Discrete Ordinate, Method for Three-Dimensional Atmospheric Radiative Transfer, *J. Atmos. Sci.*, **55**, 429-446.

De Haan, J. F., P. Bosma, and J. W. Hovenier, 1987: The adding method for multiple scattering calculations of polarized light, *Astron. Astrophys.,* **183**, 371-391.

Feijt, A. J., 2000: *Quantitative Cloud Analysis using Meteorological Satellites.* Ph.D. dissertation, Wageningen University, dissertation no. 2896, 186 pp.

Fu, Q., and N. K. Liou, 1992: On the correlated k-Distribution method for radiative transfer in nonhomogeneous atmospheres, *J. Atmos. Sci.,* **49**, 2139-2156.

Han, Q., W. B. Rossow, and A. A. Lacis, 1994: Near-Global Survey of Effective Droplet Radii in Liquid Water Clouds Using ISCCP Data, *J. of Clim.,* **7**, 465-497.

Hansen, J. E., and J. W. Hovenier, 1974: Interpretation of the polarization of Venus, *J. Atmos. Sci.,* **31**, 1137-1160.

Hansen, J.E., and L.D. Travis, 1974: Light scattering in planetary atmospheres, *Space Science Reviews,* **16**, 527 – 610.

Henyey, L. G., and J. L. Greenstein, 1941: Diffuse radiation in the galaxy, *Astrophys. J.,* **93**, 70-83.

Hess, M., R. Koelemeijer, and P. Stammes, 1998: Scattering Matrices of Imperfect Hexagonal Ice Crystals, *J. Quant. Spectrosc. Radiat. Transfer*, **60**, 301-308.

IPCC, 1995: IPCC second assessment Climate change 1995; A report of the Inter-governmental Panel on Climate Change. IPCC, Geneva, Switzerland, 64 pp.

Jolivet D. and A. Feijt, 2003: Cloud thermodynamic phase and particle size estimation using the 0.67 and 1.6 micron channels from meteorological satellites, *Atm. Chem. and Phys.* (accepted).

King, D., and S.-C. Tsay, 1997: *Cloud retrieval algorithms for MODIS: Optical thickness, effective radius, and thermodynamic phase.* MODIS, Tech. Rep. ATBD-MOD-05, 83 pp.

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

Mishchenko, M. I., W. B Rossow, and A. Macke, 1996: Sensitivity of cirrus cloud albedo, bidirectional reflectance and optical thickness retrieval accuracy to ice particle shape, *J. Geophys. Res.,* **101 D12**, 16973 – 16985.

Mishchenko, M. I., J. W. Hovenier, and L. D. Travis, 2000: *Light scattering by non-spherical particles – theory, measurements and applications.* Academic pres, San Diego, 2000, 690 pp.

Nakajima, T., and K. D. King, 1990: Determination of the Optical Thickness and Effective Particle Radius of Clouds from Reflected Solar Radiation Measurements. Part 1: Theory, *J. Atmos. Sci* ., **47**, 1878-1893.

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

Potter, J. F., 1970: The delta function approximation in radiative transfer theory*, J. Atmos. Sci.,* **27**, 943-949.

Rothman, L. S., C. P Rinsland, A. Goldman, S. T. Massie, D. P. Edwards, J.-M. Flaud, A. Perrin, C. Camy-Peyret, V. Dana, J.-Y Mandin, J. Schroeder, A. McCann, R. R Gamache, R. B. Wattson, K. Yoshino, K. V. Chance, K.W. Jucks, L. R. Brown, V. Nemtchinov, and P. Varanasi, 1996: The HITRAN Molecular Spectroscopic Database and HAWKS (HITRAN Atmospheric Workstation): 1996 Edition, *J. Quant. Spectrosc. Radiat. Transfer*, **60**, 665-710.

Schneider,W, G.K. Moortgat, G.S. Tyndall and J.P. Burrows, 1987: Absorption cross-sections of NO2 in the UV and visible region (200-700 nm) at 298 K, *J. Photochem. Photobiol.*, **40**, 195-217.

Stammes, P., 2001: Spectral radiance modelling in the UV-Visible range. *IRS 2000: Current problems in Atmospheric Radiation,* W.L. Smith and Y.M. Timofeyev, Ed., A. Deepak Publ., Hampton, VA, 385-388

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

Van de Hulst, H. C., 1957: *Light scattering by small particles.* John Wiley & Sons. (New York, 1957), 470 pp.

Watts, P. D., C. T. Mutlow, A. J. Baran, and A. M. Zavody, 1998: Study on Cloud Properties derived from Meteosat Second Generation Observations. Final Report, EUMETSAT ITT no. 97/181.

Wiscombe, W. J., 1980: Improved Mie scattering algorithms, Appl. Opt., 9, 1888 – 1896.

Wiscombe, W. J., 1977: The Delta-M Method: Rapid Yet Accurate Radiative Flux Calculations for Strongly Asymmetric Phase Functions, *J. Atmos. Sci.*, **34**, 1408-1422.