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Abstract

This report presents a study on the determination of the required number of azimuth (Fourier terms) and zenith (Gaussian μ) integration points in order to obtain a cloud reflectance as calculated by the Doubling Adding KNMI (DAK) radiative transfer model with an absolute accuracy within 0.005. Cloud reflectance calculations at 0.632 and 1.605 μm are performed for a plane parallel water cloud having an optical thickness, τ, of 10, overlying a surface with albedo 0.10, for effective radii of 5-24 μm. Relative azimuth angles are 90, 120, 150, and 175° and (cosines of) zenith angles are 0.2-0.8. A two-parameter Gamma size distribution is applied. Fourier terms and Gaussian μ points are varied from 20-200 for each zenith and relative azimuth angle. Results indicate that accurate cloud reflectance calculations at 0.632 μm can be performed by taking 60-80 Fourier terms and 40-60 Gaussian μ points for most effective radii and viewing geometries investigated. However, for effective radii of 16 and 24 μm, 140-180 Gaussian μ points are required. For the reflectance at 1.605 μm, 40-60 Fourier terms and 40-60 Gaussian μ points suffice. At both wavelengths, the given values strongly increase when the backscatter viewing geometry is approached. In addition to the convergence study, the effect of a change in the variance of the size distribution, v_{eff}, and the error due to neglecting linear polarization in modeled cloud reflectances is examined. An absolute change in v_{eff} of 0.05 results in a maximum relative difference in calculated cloud reflectance of $\sim$4%. Neglecting linear polarization in the 0.632 μm cloud reflectance calculations causes an averaged relative difference of 0.1-0.3%, with a maximum of $\sim$1%, depending on the effective radius.

1. Introduction

Radiative transfer models play an important role in the retrieval of cloud physical parameters from satellites, such as cloud optical thickness and cloud particle size. The way in which the radiative transfer equation is solved, differs between the various existing models. These different approaches have, in turn, an impact on the accuracy of the simulated reflectances (e.g. Roebeling et al. 2005). The Doubling Adding KNMI radiative transfer model (DAK) (De Haan et al. 1987; Stammes 2001) simulates the short-wave reflection at the top of the atmosphere, assuming plane-parallel homogeneous clouds over a Lambertian surface. Within the Satellite Application Facility on Climate Monitoring (CM-SAF), a longterm dataset of cloud physical properties, CPP, (Roebeling et al. 2006) is constructed for the area of Europe and northern Africa using visible and near-infrared reflectances of the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) onboard the METEOSAT-8 satellite. Measured reflectances from the SEVIRI 0.6 and 1.6 μm channels are compared to Lookup Table values generated by DAK. The accuracy of a DAK simulation is among others dependent on the number of Fourier terms and Gaussian μ points, being the azimuth and zenith angle integration points, respectively. The objective of this study is to determine the required number of these points in order to obtain an absolute accuracy of the cloud reflectance within 0.005, which is considered a typical error in the reflectance measurements of satellites.

2. Methods

2.1. *DAK settings*

In DAK, the computation of reflectances in the atmosphere requires a specification of the number of points in both the zenith angle and the azimuth angle integration. The number of points needed for convergence of the reflectance values depends on the effective radius of the cloud particles and the viewing geometries. In this study, variations in Fourier terms and Gaussian µ points were applied to a standard cloud case. This standard simulation case consisted of a plane-parallel water cloud with cloud base at 2 km and a geometrical thickness of 1 km. The optical thickness of the cloud, τ, and the surface albedo, A_s, were set at 10 and 0.10, respectively. Atmospheric pressure, temperature and trace gas profiles were taken from the US Air Force Geophysics Laboratory (AFGL) mid-latitude summer profiles, thereby accounting for Rayleigh scattering by air molecules and absorption by ozone. There was no linear polarization included in the standard calculations. Reflectances were calculated for cosines of solar and viewing zenith angles, (μ_0, μ), of 0.2, 0.4, 0.6, and 0.8. In order to be certain of sufficient accuracy at all viewing geometries, simulations were performed at $\mu = \mu_\circ$, because this geometry is more sensitive to errors. Relative azimuth angles, φ-$\varphi_\circ$, were taken at 90, 120, 150, and 175°. Effective radii, r_{eff}, of the spherical water droplets were 1, 3, 5, 8, 12, 16, and 24 µm, assuming a two-parameter Gamma size distribution (Deirmendjian 1969) with an effective variance, v_{eff}, of 0.15 for all r_{eff} values. Mie calculations were carried out using the Meerhoff Mie Program (De Rooij and van der Stap 1984). The refraction indices for water particles were taken from Downing and Williams (1975). The resulting phase functions at λ=0.632 µm and λ=1.605 µm are presented in Figure 1. All DAK calculations were performed accounting for multiple scattering. Cloud reflectances were simulated at 0.632 and 1.605 µm, being near the center wavelengths of the SEVIRI 0.6 and 1.6 µm channels and outside of water vapor and CO_2 absorption lines.

2.2. *Convergence study approach*

The major part of this study was the determination of the optimum number of Fourier terms and Gaussian µ points. For each r_{eff} and azimuth angle step the number of Fourier terms (n_{Fourier}) was varied from 20 to 200 with a step size of 20. In order to ascertain that observed differences were due to the variation in n_{Fourier} only, the number of Gaussian µ points was set sufficiently high, namely at 20 for calculations with r_{eff} of 1 and 3 µm. For r_{eff}=5-12 µm, 60 Gaussian µpoints were used, whereas for effective radii of 16 and 24 µm this number was further increased to 100. Since at r_{eff}=24 µm the difference in simulated reflectances between n_{Fourier}=200 and n_{Fourier}=300 was negligibly small, it was assumed that for all effective radii convergence had taken place at n_{Fourier}=200. Subsequently, the absolute difference between the reflectance at n_{Fourier}=n and n_{Fourier}=200, $R_{\text{n}} - R_{200}$, was calculated. Convergence was assumed at an absolute reflectance difference $\leq$ 0.005 for all calculations. This criterion was chosen in order to keep the relative error in simulated cloud reflectances smaller than the satellite measurement errors, which are typically a few percent (Nakajima and King 1990). The convergence in Gaussian µpoints, n_{Gauss}, was examined analogously to the Fourier term convergence. Results from the Fourier term convergence study were taken in order to ascertain that n_{Gauss} was the only varying factor.

2.3. *Sensitivity study approach*

In addition to the Fourier and Gauss convergence analyses, the effect of a varying v_{eff} on the modeled reflectance was studied. It is of importance to investigate this effect, since a larger value of v_{eff} implies that the size distribution becomes broader. Especially the larger particles of the size distribution can influence the calculated reflectance significantly when varying v_{eff}. More information on v_{eff} is given by Hansen and Travis (1974). Since in the convergence studies v_{eff}=0.15 was applied, the effect of a change in v_{eff} on reflectance simulations was investigated by setting v_{eff} to 0.10 and 0.20 for effective radii of 5, 8, 12, 16, and 24 µm for all viewing geometries. The number of Fourier terms and Gaussian µpoints were taken from the corresponding convergence study results.

Further, the effect of neglecting linear polarization was studied for the 0.632 µm reflectance. In principle, polarization has to be included when calculating the reflectance, since in second-order scattering (and less in higher-order scattering) the incident light is polarized and affects the scattered intensity. Therefore reflectances for effective radii of 5, 8, 12, 16, and 24 µm were simulated with and without including linear polarization at (cosines of) zenith angles between 0.2 and 1.0 and φ-$\varphi_\circ$ between 90 and 175°.

3. Results

3.1. *Fourier term convergence analysis*

Figures 2 and 3 show the convergence for r_{eff}=12 µm and µ=µ$_\circ$ values between 0.2 and 0.8 for λ=0.632 and 1.605 µm, respectively. It is evident that differences at n_{Fourier}=20 are largest for azimuth angles of 150 and 175°. Further, at both 0.632 and 1.605 µm the difference R_{n}-R_{200} oscillates around a certain value. It is most prominent for the backscatter region at higher solar zenith angle (low $\mu_\circ$). The results for r_{eff}=5-24 µm at λ=0.632 µm and λ=1.605 µm are summarized in Tables 1 and 2, respectively. Reflectance simulations for r_{eff}=1 µm did not show any change with increasing n_{Fourier}. Therefore it is very likely that convergence has already taken place at n_{Fourier} lower than 20. For r_{eff}=3 µm the calculations converged around n_{Fourier}=40. Due to the vicinity of the backscatter peak, the largest number of Fourier terms was required at relative azimuth angles of 175°. It should be noted that the number of required Fourier terms at an azimuth angle of 180° are significantly higher than the values presented here.

Table 1: Number of Fourier terms in azimuth at λ=0.632 µm required for convergence (R_{n}-R_{200} $\leq$ 0.005) at different r_{eff}. Values presented are maximum for the range µ=µ$_\circ$=0.2-0.8, φ-$\varphi_\circ$=175° and 150°.

r_{eff} [µm]	φ-$\varphi_\circ$=175°	φ-$\varphi_\circ$=150°
5	120	40
8	180	60
12	180	60
16	180	60
24	180	80

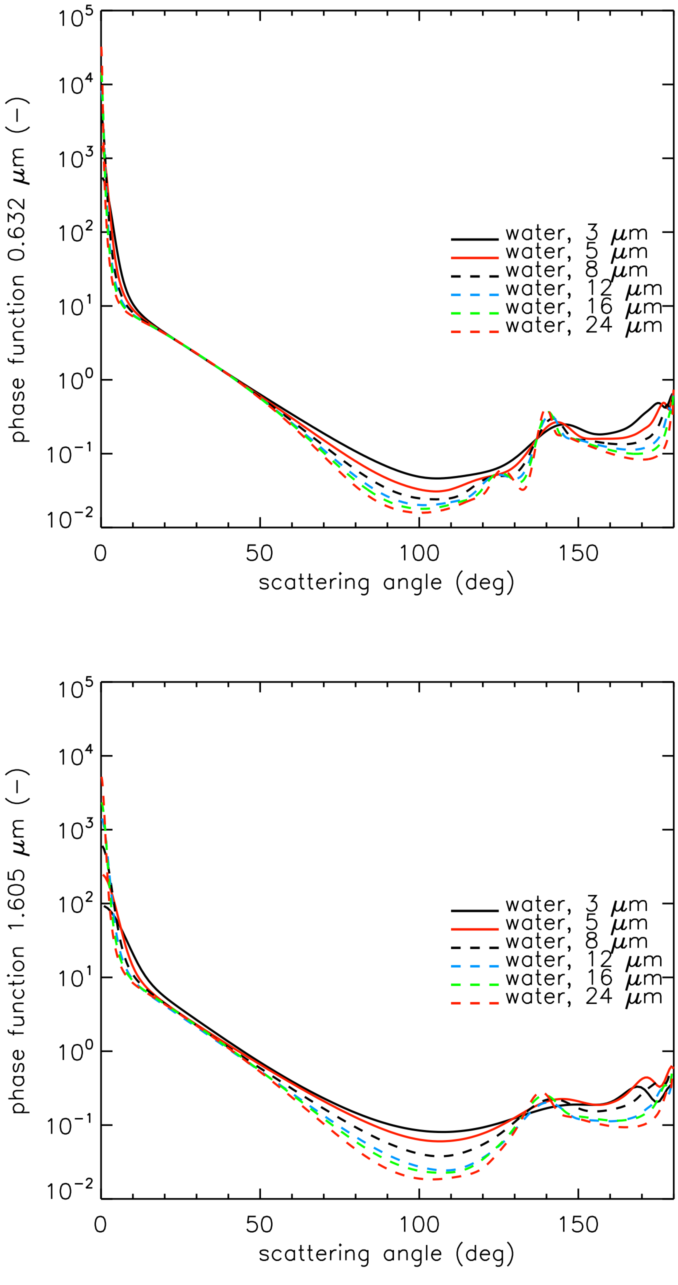

Figure 1: Mie phase functions for spherical water droplets at r_{eff}=3-24 µm, v_{eff}=0.15, λ=0.632 µm (upper panel) and λ=1.605 µm (lower panel). Refractive indices are taken from Downing and Williams (1975).

Table 2: Number of Fourier terms in azimuth at λ=1.605 µm required for convergence (R_{n}-$R_{200} \leq$ 0.005) at different r_{eff}. Values are for µ=µ$_\circ$=0.2-0.8, φ-$\varphi_\circ$=175° and 150°.

r_{eff} [µm]	φ-$\varphi_\circ$=175°	φ-$\varphi_\circ$=150°
5	80	60
8	80	40
12	140	40
16	180	40
24	180	60

3.2. *Gaussian µ point convergence analysis*

Figure 4 and 5 clearly show the rapid convergence of cloud reflectance with increasing n_{Gauss}. At high solar zenith angles, the difference $R_{\mathrm{n}} - R_{200}$ is large at 60 Gaussian µ points (0.05-0.06), but an increase towards n_{Gauss}=80 decreases this difference by a factor of 2-3. Results for the convergence study are summarized in Table 3 and 4. From the Tables it follows that the number of n_{Gauss} required for an accurate simulation strongly increases with r_{eff}, especially at 0.632 µm. At 1.605 µm, calculations converge more rapidly for r_{eff}=5-12 µm. As for the Fourier convergence, using an azimuth difference angle of 175° requires a larger number of Gaussian µ points than at smaller azimuth difference angles.

Table 3: Number of Gaussian points in µ at λ=0.632 µm needed for convergence ($R_n - R_{200}$ ≤0.005) at different r_{eff}. Values presented are maximum for the range µ=µ$_\circ$=0.2-0.8, φ-$\varphi_\circ$=175° and 150°.

r_{eff}[µm]	φ-$\varphi_\circ$=175°	φ-$\varphi_\circ$=150°
5	80	60
8	80	60
12	100	60
16	140	140
24	180	180

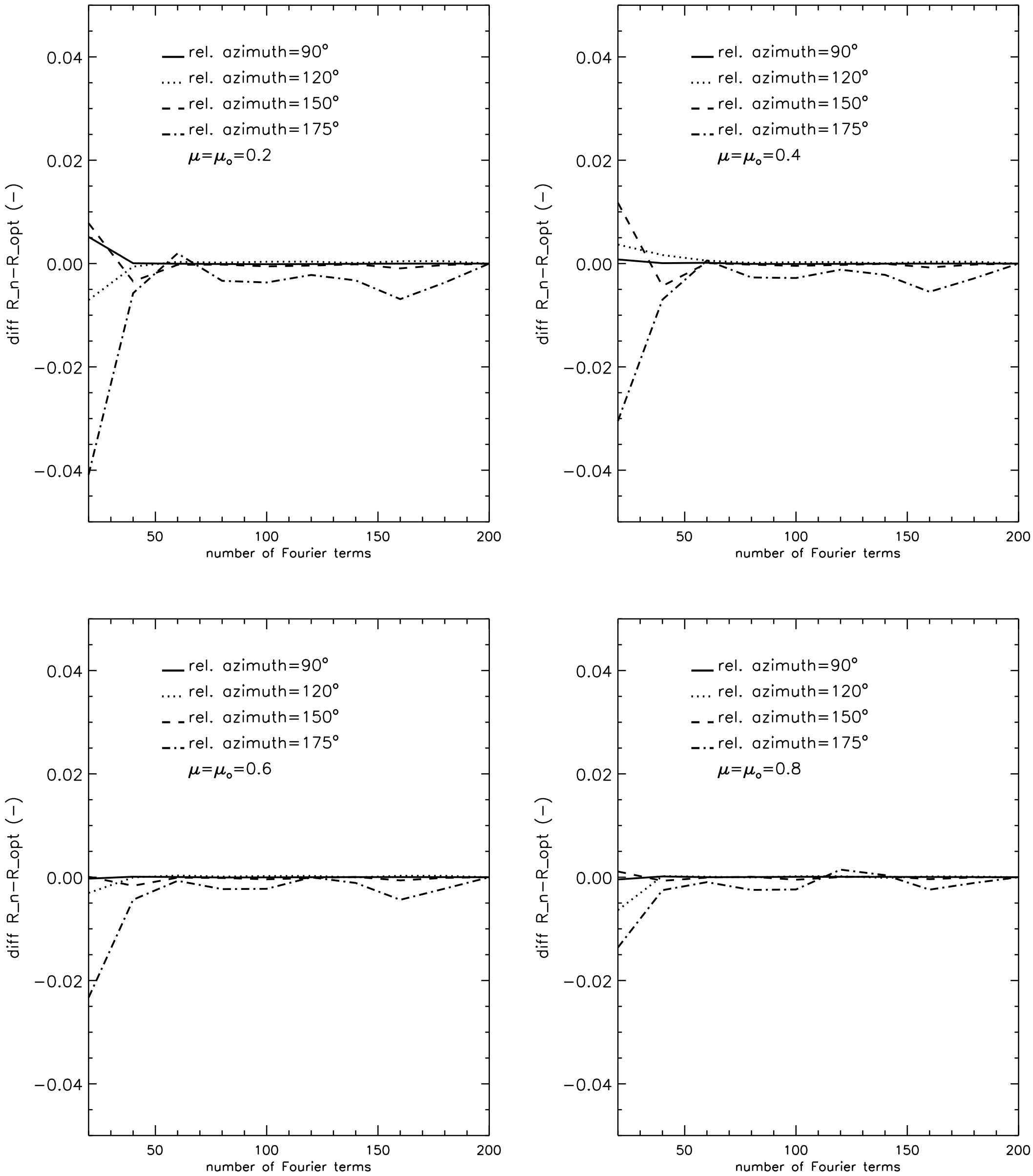

Figure 2: Absolute difference in cloud reflectance at λ=0.632 µm compared to reflectance at assumed convergence point (200 Fourier terms), $\mu=\mu_\circ$=0.2-0.8, r_{eff}=12 µm, azimuth angle difference 90 (solid), 120 (dotted), 150 (dashed) and 175° (dashed-dotted).

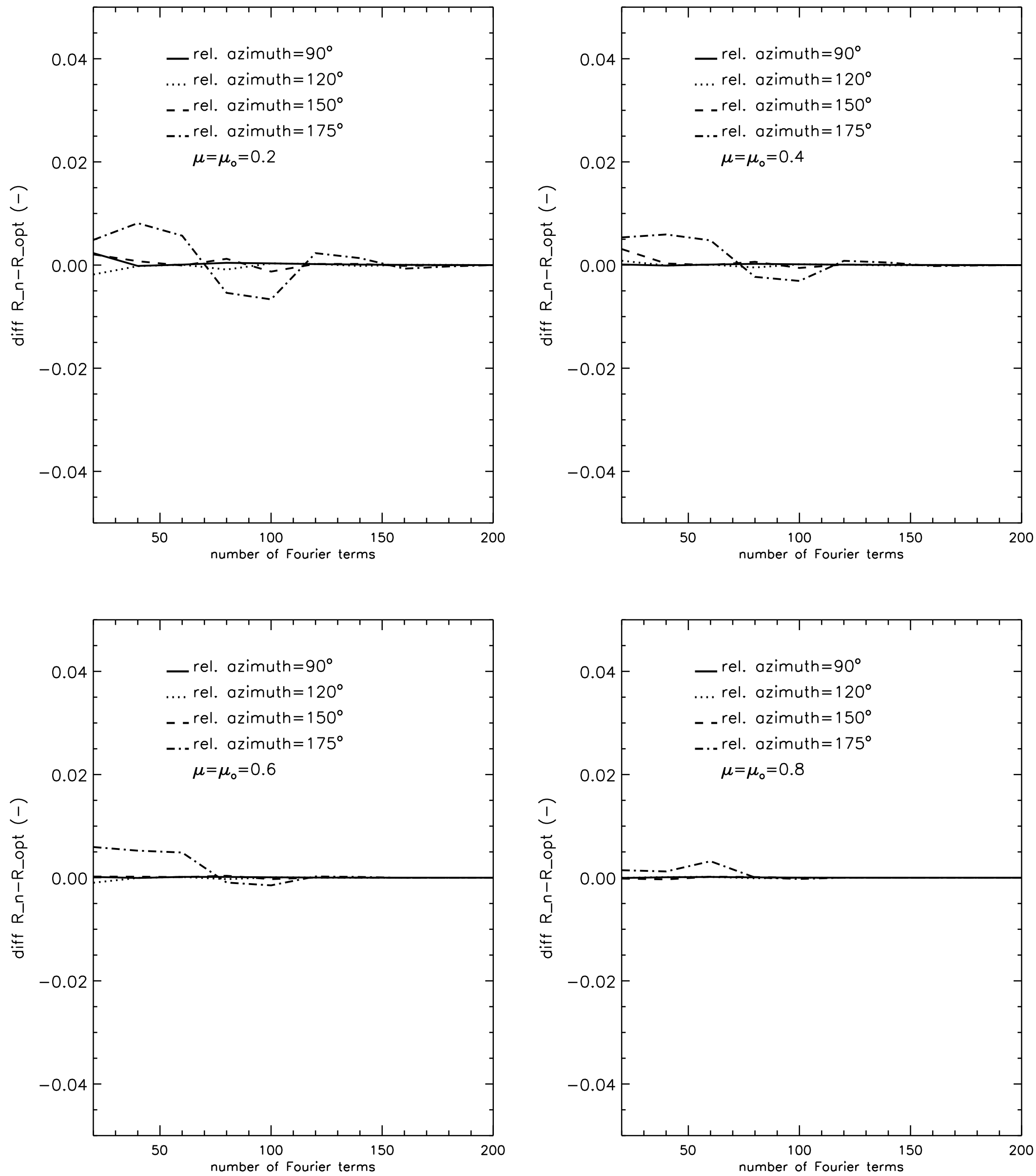

Figure 3: Absolute difference in cloud reflectance at λ=1.605 µm compared to reflectance at assumed convergence point (200 Fourier terms), μ=$\mu_\circ$=0.2-0.8, r_{eff}=12 µm, azimuth angle difference 90 (solid), 120 (dotted), 150 (dashed) and 175° (dashed-dotted).

Table 4: Number of Gaussian points in μ at λ=1.605 needed for convergence ($R_n - R_{200} \leq$0.005) at different r_{eff}. Values presented are maximum for the range μ=μ$_\circ$, φ-$\varphi_\circ$=175° and 150°.

r_{eff}[μm]	φ-$\varphi_\circ$=175°	φ-$\varphi_\circ$=150°
5	20	20
8	20	40
12	40	40
16	40	40
24	60	40

3.3. *Effect of varying v$_{eff}$*

In general, for the 0.632 μm reflectance the effect of varying v_{eff} is small. Differences were calculated as absolute ($R_{\text{X}} - R_{0.15}$) as well as relative differences, $\frac{R_{0.10}-R_{0.15}}{R_{0.15}}$, for all geometries (μ=μ$_\circ$, φ-$\varphi_\circ$), with suffix X referring to the value of v_{eff}, being 0.10 or 0.20, and suffix 0.15 referring to the standard value of v_{eff}. The results are summarized in Table 5.

Table 5: Maximum absolute and relative differences between modeled 0.632 μm cloud reflectances using v_{eff}=0.10, 0.15, and 0.20, standard water cloud case applied.

r_{eff} [μm]	$R_{0.10} - R_{0.15}$	$\frac{R_{0.10}-R_{0.15}}{R_{0.15}}$ [%]	$(R_{0.20} - R_{0.15})$	$\frac{R_{0.20}-R_{0.15}}{R_{0.15}}$ [%]
5	-0.0041	-0.58	0.0045	0.63
8	-0.0095	-1.06	0.0073	0.82
12	-0.0053	-0.91	0.0059	1.02
16	-0.0052	-1.07	0.0047	0.96
24	-0.0157	-3.82	0.0146	3.56

It follows from the Table that absolute differences are generally in the order of 0.005-0.01. When a look is taken at the relative differences, it follows that from 5-16 μm differences are typically in the order of 1%. However, at 24 μm the relative difference has increased to 3.56% for v_{eff}=0.20 and -3.82% for v_{eff}=0.10.

3.4. *Effect of neglecting linear polarization*

Table 6 presents the differences of cloud reflectance calculations at λ=0.632 μm performed with and without linear polarization included. Obviously, the effect of neglecting linear polarization is small at all effective radii. The maximum relative difference is 1.05% at r_{eff}=8 µm. To obtain a general indication of the effect of neglecting linear polarization, absolute differences were averaged over all zenith and azimuth angles. The results are presented in the last column of Table 6. It is evident that this averaged relative difference is almost negligible, with values of 0.1-0.3%.

Table 6: Maximum absolute, maximum and mean relative difference in 0.632 µm cloud reflectance modeled with and without linear polarization included.

r_{eff}[µm]	max. abs. diff.	max. rel. diff. [%]	mean rel. diff. [%]
5	0.0032	0.42	0.12
8	0.0063	1.05	0.32
12	0.0035	0.45	0.13
16	0.0037	0.48	0.15

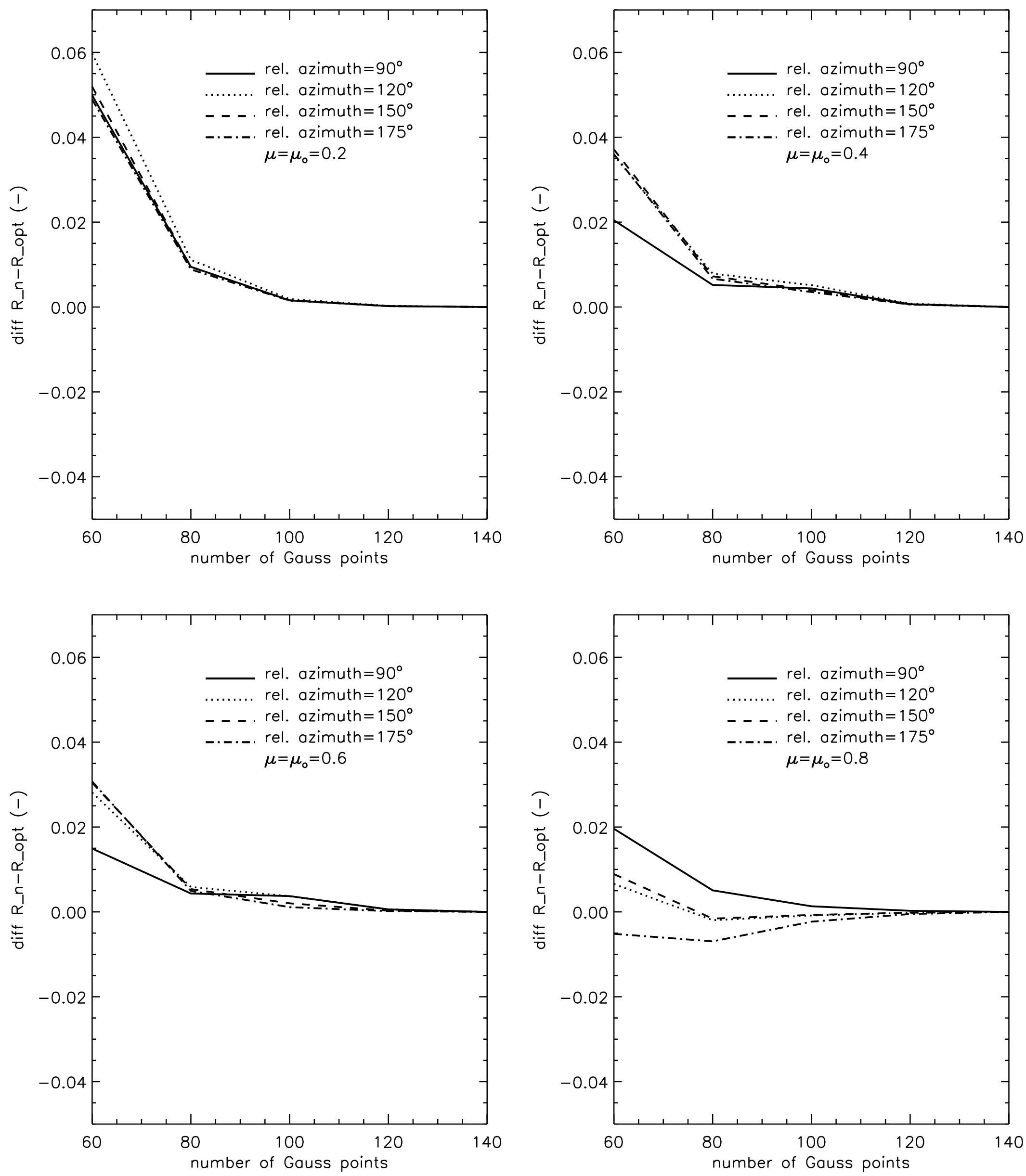

Figure 4: Absolute difference in cloud reflectance at λ=0.632 µm compared to reflectance at assumed convergence point (200 Gauss points in µ), $\mu=\mu_\circ$, $r_{\rm eff}$=12 µm, azimuth angle difference 90 (solid), 120 (dotted), 150 (dashed) and 175° (dashed-dotted).

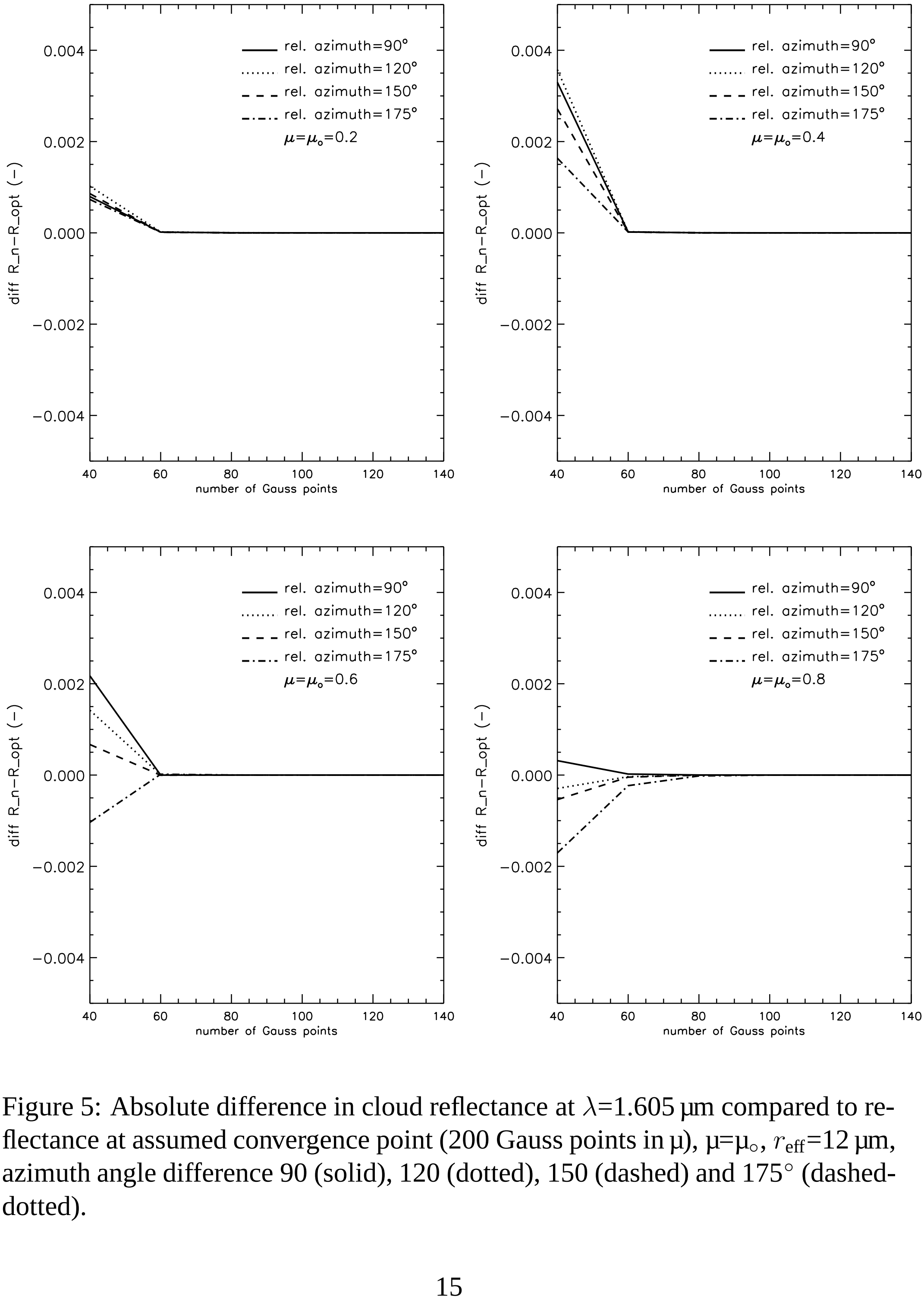

Figure 5: Absolute difference in cloud reflectance at λ=1.605 μm compared to reflectance at assumed convergence point (200 Gauss points in μ), $\mu=\mu_\circ$, r_{eff}=12 μm, azimuth angle difference 90 (solid), 120 (dotted), 150 (dashed) and 175° (dashed-dotted).

4. Summary

The analysis presented focused on finding the required number of Fourier terms and Gaussian µ points to accurately model cloud reflectances at 0.632 and 1.605 µm by the Doubling Adding KNMI (DAK) radiative transfer model. The convergence study was restricted to a standard water cloud case with an optical thickness of 10 and a surface albedo of 0.10.

At 0.632 µm, for most effective radii and viewing geometries 60-80 Fourier terms suffice, whereas at 1.605 µm the required number of Fourier terms decreases to 40-60. The required number of Gaussian µ points is 40-60 for most effective radii investigated at both 0.632 and 1.605 µm. It should be stressed that due to the vicinity of the backscatter peak, at both wavelengths the number of Fourier terms and Gaussian µ points strongly increases for φ-$\varphi_\circ$ approaching 180°.

The effective variance of the two-parameter Gamma size distribution was varied between 0.10 and 0.20 and the absolute and relative difference in cloud reflectance to values with v_{eff}=0.15 was calculated. The largest relative difference was found for r_{eff}=24 µm, having a value of $\sim$4%.

Lastly, the effect of neglecting linear polarization was investigated. The relative difference between cloud reflectance calculations at 0.632 µm performed with and without linear polarization appeared to be small with a maximum relative difference of $\sim$1% and mean relative differences of 0.1-0.3%, which indicates that linear polarization can be neglected in cloud reflectance calculations.

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