



# Evaluation of ground-based remotely sensed liquid water cloud properties using shortwave radiation measurements

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## ABSTRACT

Water cloud optical and microphysical properties are required for a better understanding of the impact of aerosols on the solar radiation feedback. The introduced retrieval technique provides droplet concentration, effective radius and optical thickness on a basis of ground-based remote sensing observations and a vertical cloud model. Mainly cloud radar, microwave radiometer and ceilometer observations are used in this approach. The model assumptions are related to a sub-adiabatic approach, in which cloud mixing processes are predefined to be homogeneous. A gamma droplet size distribution with a fixed shape parameter is considered to relate the observations with the retrieval products. The technique is applied on a water cloud case and the uncertainties in relation to the model assumptions and errors in the measurements are determined. The greatest uncertainty in the retrieval of droplet concentration is related to the fixed shape parameter, which requires in-situ data for validation processes to quantify the results. The optical parameters are less sensitive to the model assumptions and they are evaluated with a radiative closure experiment. They are used as input for radiative transfer calculations in order to compare the simulations with radiation measurements at the ground. There is a relatively good agreement between the simulated and measured radiation considering the horizontal cloud inhomogeneity, although a bias of around 5% still exists. Therefore the technique might be a suitable approach of retrieving quantitative cloud optical properties independently from radiation observations.

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## 1. Introduction

The microphysical and optical properties of liquid water clouds are important parameters for studying cloud–radiation interactions. The amount of liquid water droplets, their particle size and the vertical cloud extent characterize the scattering and absorption features of the cloud, which in return have an impact on the shortwave radiation budget. The synergy and the high temporal resolution of ground-based remote sensing measurements enable the observations of the effect of water cloud properties on the surface radiation on a regional scale. The central aim is to retrieve the relevant cloud parameters from remote sensing observations and to evaluate these using surface solar radiation measurements.

Observations of millimeter-wave radar and microwave radiometer are indispensable for studying the microphysical properties of low level water clouds. A number of remote sensing retrieval techniques provide either radar-only retrievals or combine millimeter-wave radar with microwave radiometer measurements (Frisch et al., 1995, 1998, 2002). These algorithms generally assume a log-normal model of droplet distribution with a fixed width parameter to relate the radar reflectivity factor with liquid water content in order to derive profiles of effective radius.

This paper discusses an alternative retrieval technique of microphysical and optical cloud properties that includes an evaluation study of the optical properties using short wave radiation measurements from the ground. The remote sensing observations of radar reflectivity, microwave radiometer estimated liquid water path and cloud geometrical thickness from lidar and radar are used as input data for a thermodynamic

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cloud model from Boers et al. (2006). The algorithm requires the assumption of a droplet size distribution and its geometric standard deviation. It retrieves droplet concentration, optical thickness and vertical profiles of effective radius on the basis of a homogeneous mixing process, where evaporation affects the particle size. The cloud liquid water content is parameterized through the ratio of liquid water path measured by microwave radiometer and the adiabatic one. The technique is applied on a water cloud case study and the sensitivity to uncertainties in the measurements and the model assumptions are discussed. The derived optical parameters are evaluated by means of a radiative closure experiment. The retrieved effective radii and optical thickness for the case study are used as input for radiative transfer calculations to simulate transmittance and to compare them with radiation observations at the ground.

## 2. Retrieval of liquid water cloud microphysical and optical properties

### 2.1. Droplet concentration

The retrieval technique of droplet concentration combines different ground-based remote sensing measurements with a thermodynamic model, which is introduced by Boers et al. (2006). In this model the cloud is described by a single-mode droplet size distribution  $n$  and its moments are given by  $\langle r^a \rangle = N^{-1} \int r^a n(r) dr$ . The droplet concentration  $N$  is the zeroth moment and is defined by

$$N = \int_0^\infty n(r) dr \quad (1)$$

The liquid water content (LWC) for a droplet distribution can be expressed by:

$$LWC(h) = \frac{4}{3} \pi \rho_w N \langle r^3 \rangle = f(h) LWC_{ad}(h) = f(h) \rho_a A_{ad} h \quad (2)$$

with  $h$  as height above cloud base,  $\rho_w$  density of water,  $\rho_a$  density of air,  $A_{ad}$  is the adiabatic lapse rate of liquid water content mixing ratio and the subscript  $ad$  refers to the adiabatic value of the variable. The cloud LWC is defined by a function  $f(h)$  of height multiplied with the adiabatic liquid water content. This function  $f(h)$  represents the sub-adiabatic fraction and describes the variation of LWC with height from the cloud base (cb) to the cloud top (ct). Furthermore  $f(h)$  can be attributed to variations in the droplet concentration ( $N$ ) or in the third moment ( $\langle r^3 \rangle$ ) of the assumed droplet size distribution or in both (Eq. (2)). The uncertainty of the alteration of  $N$  or volume radius ( $\langle r^3 \rangle$ ) can be explicitly solved by a predefined mixing process. The measured cloud radar reflectivity factor in case of Rayleigh approximation is defined by:

$$Z(h) = 64N \langle r^6 \rangle \quad (3)$$

We can relate the reflectivity factor with our description of LWC of the cloud by using the well-known relation between the third moment and the sixth moment of the size distribution (e.g. Atlas, 1954; Frisch et al., 1998). Considering in this

formulation the variation of the volume radius with height the relationship between the moments results in:

$$\langle r^6 \rangle = k_6 f^2 \langle r^3 \rangle_{ad}^2; N = N_{ad} \quad (4)$$

The constant coefficient  $k_6$  depends on the shape parameter of the assumed droplet size distribution  $n$ . Substituting the sixth moment and third moment with the reflectivity (Eq. (3)) and LWC (Eq. (2)) relation results in a functional form of radar reflectivity depending on the height:

$$Z(h) = k_6 \left( \frac{6\rho_a A_{ad}}{\pi\rho_w} \right)^2 \frac{1}{N} f^2(h) h^2 \quad (5)$$

The height dependency of the parameters is defined by the radar range gate resolution with cloud base as the lowest gate and cloud top as the highest gate in the cloud. This height grid is used as the vertical resolution for all following derived properties. In the equation above  $f(h)$  is attributed to variations in the third moment of the droplet size distribution and we assume a constant droplet concentration with height. This implies a homogeneous mixing procedure, which means that when dry air is entrained and LWC is reduced the droplets become smaller, but the total amount remains the same. The functional form of the radar reflectivity factor (Eq. (5)) can be used for an estimation of droplet concentration. The unknown sub-adiabatic fraction function  $f(h)$  can be estimated by an integrated approach of Eq. (5) with  $iZ := \int_{cb}^{ct} Z(h) dh$ , because the ground-based remote sensing observations do not provide direct measurements of the variation of LWC with height ( $f(h)$ ), but the total integrated water (liquid water path) over the cloud depth is given by the radiometer observations. Considering our definition of LWC (Eq. (2)) the liquid water path (LWP) can be described by:

$$LWP = \rho_a A_{ad} \int_{cb}^{ct} f(h) h dh \quad (6)$$

the integral can be estimated by:

$$LWP \leq \underbrace{\frac{1}{2} \rho_a A_{ad} H^2}_{LWP_{ad}} \max_{h \in [cb, ct]} f(h) \quad (7)$$

where  $H$  is the geometrical thickness of the cloud and the adiabatic liquid water path ( $LWP_{ad}$ ) can be calculated from the cloud base conditions. Eq. (7) can be solved to:

$$F_c := \frac{LWP}{LWP_{ad}} \leq \max_{h \in [cb, ct]} f(h) \leq 1 \quad (8)$$

The term  $F_c$  describes the mixing-status or the degree of sub-adiabaticity in the cloud. If  $F_c$  is equal to one the cloud is considered to be adiabatic. But most clouds are on average not adiabatic (Kim et al., 2005); because mixing processes with environmental dryer air reduces the LWC and the cloud could become quasi-adiabatic (close to adiabatic) in the lower part and sub-adiabatic in the upper part. The variety of possible vertical profiles of LWC is large and difficult to characterize, whereas with Eq. (8) the maximum value of our unknown sub-adiabatic fraction  $f(h)$  can be confined. The restriction to the maximum value of  $f(h)$  and the fact that LWC is close to zero at

cloud base are appropriate for the definition of a parameterization of LWC with height. A simple parameterization is given with the assumption that  $f(h) = \max(f(h)) = F_c = \text{const.}$ , which means that  $f(h)$  reaches its lower bound of the maximum at each height bin and the dilution from adiabaticity is constant. This parameterization of  $f(h)$  is used in the integration of Eq. (5) and after solving the droplet concentration  $N$  results in:

$$N = C_N k_6 \left( \frac{\rho_a A_{ad}}{\rho_w} \right)^2 i Z^{-1} F_c^2 H^3 \quad (9)$$

with  $C_N = 12\pi^{-2}$ .

## 2.2. Extinction and optical thickness

The derivation of the optical parameters is depending on the method described in Section 2.1 and it is also partly presented in (Boers et al. (2006)). The optical extinction can be expressed, assuming large particles sizes compared to the wavelength, in the following form:

$$\sigma_{\text{ext}}(h) = 2\pi N(h) \langle r^2(h) \rangle \quad (10)$$

According to Eqs. (3) and (4) and to the homogeneous mixing process the optical extinction can be related to LWC by using the relationship of the second and the third moments of the droplet size distribution:

$$\langle r^2(h) \rangle = k_2 f^{\frac{2}{3}}(h) \langle r^3 \rangle_{ad}^{\frac{2}{3}}; N = N_{ad} \quad (11)$$

with  $k_2$  depending on the shape parameter of the assumed droplet size distribution. Substituting the second moment in Eq. (10) using Eq. (11) and LWC (Eq. (2)) results in a functional form of optical extinction depending on the height:

$$\sigma_{\text{ext}}(h) = 2\pi^{\frac{1}{3}} k_2 \left( \frac{\rho_a A_{ad}}{4\rho_w} \right)^{\frac{2}{3}} N^{\frac{1}{3}} f^{\frac{2}{3}}(h) h^{\frac{2}{3}} \quad (12)$$

with our assumption of  $f = \max(f(h)) = F_c = \text{const.}$  The cloud optical thickness  $\tau = \int_{z_b}^z \sigma_{\text{ext}}(h) dh$  results in:

$$\tau = \frac{6}{5} \pi^{\frac{1}{3}} k_2 \left( \frac{\rho_a A_{ad}}{4\rho_w} \right)^{\frac{2}{3}} N^{\frac{1}{3}} F_c^{\frac{2}{3}} H^{\frac{5}{3}} \quad (13)$$

Now we can substitute  $N$  with Eq. (9):

$$\tau = C_\tau k_2 k_6^{\frac{1}{3}} \left( \frac{\rho_a A_{ad}}{\rho_w} \right)^{\frac{4}{3}} i Z^{-\frac{1}{3}} F_c^{\frac{4}{3}} H^{\frac{8}{3}} \quad (14)$$

with  $C_\tau = \frac{6}{5} 12^{\frac{1}{3}} \frac{4}{3} \pi^{-\frac{1}{3}}$ . In this approach the optical thickness can be derived from the integrated radar reflectivity, which is an additional possibility to lidar based retrieval techniques of cloud optical properties (Boers et al., 2000). The advantage of using radar reflectivity is that the lidar signal especially for water clouds rapidly attenuates by the presence of any liquid water clouds and it provides only information at or slightly above cloud base. The optical thickness limit for the lidar is

around 3 with an error in extinction within the cloud of about 50% (Ansmann et al., 1992).

## 2.3. Effective radius

The effective radius is defined as the ratio between the third moment and the second moment of the size distribution and in relation to our assumptions it follows to:

$$r_{\text{eff}}(h) = \frac{\langle r^3(h) \rangle}{\langle r^2(h) \rangle} = k_2^{-1} f^{\frac{1}{3}}(h) \langle r^3 \rangle_{ad}^{\frac{1}{3}} \quad (15)$$

On the basis of the homogeneous mixing process we have assumed that the effective radius is varying with height. Substituting  $\langle r^3(h) \rangle$  by using Eq. (11) results in:

$$r_{\text{eff}}(h) = \pi^{-\frac{1}{3}} k_2^{-1} \left( \frac{\rho_a A_{ad}}{4\rho_w} \right)^{\frac{1}{3}} N^{-\frac{1}{3}} f^{\frac{1}{3}}(h) h^{\frac{1}{3}} \quad (16)$$

with  $f(h) = F_c$  and substituting  $N$  it results in:

$$r_{\text{eff}}(h) = C_{r_{\text{eff}}} k_2^{-1} k_6^{-\frac{1}{3}} \left( \frac{\rho_a A_{ad}}{\rho_w} \right)^{-\frac{1}{3}} i Z^{-\frac{1}{3}} F_c^{-\frac{1}{3}} H^{-1} h^{\frac{1}{3}} \quad (17)$$

with  $C_{r_{\text{eff}}} = 12^{-\frac{1}{3}} \frac{4}{3} \pi^{\frac{1}{3}}$ . Since we assume a constant droplet concentration with height and the LWC increases linearly with height through  $f = \max(f(h)) = F_c = \text{const.}$ , the effective radius increases with height (homogeneous mixing), which is also in agreement with the observations (Stephens and Platt, 1987).

## 2.4. Basic uncertainties in the retrieval algorithm

The retrievals rely on an integrated approach of the vertical variation of the unknown function  $f(h)$ , which requires a parameterization of LWC with height (Eq. (2)). In this approach the LWC is approximated by a linear function ( $F_c$ ) of the lower bound of the maximum of  $f(h)$  (Eq. (8)), which is the ratio of LWP measured from microwave radiometer and adiabatic LWP. Assuming a linear profile of LWC with height is straightforward in comparison to the alteration of LWC through entrainment processes observed in in-situ measurements (Sassen et al., 1999). This could lead to uncertainties in the retrieval parameter, because any other function of  $f(h)$  could be used to describe the variation of LWC with height. The characterization of LWC profiles is difficult and there are no direct ground-based remote sensing measurements of the distribution of liquid water available. However the approximation of LWC used in this approach contains the important property that clouds deviate from adiabatic conditions. The degree of sub-adiabaticity ( $F_c$ ) has a strong impact on the retrievals and it is one of the basic uncertainties and is considered in the interpretation of the retrieval results.

Another source of error in this retrieval technique is related to the fixed shape parameter with height (through  $k_2$ , and  $k_6$ ) of an assumed droplet size distribution. This assumption is necessary in order to calculate any moment of the DSD and to relate them to the ground-based remote sensing observations. In the application on a water cloud case (Section 4) a gamma size distribution is used, because it adequately models

distributions of in-situ measurements of water cloud droplet size distributions (Miles et al., 2000). The definition is:

$$n(r) = \frac{D^\nu}{\Gamma(\nu)} r^{\nu-1} e^{-Dr} \quad (18)$$

where  $\Gamma$  is the gamma function,  $\nu$  the shape parameter and  $D$  the scale parameter. According to the relation between the sixth and the third moments (Eq. (4)) the parameter  $k_6$  results in:

$$k_6 = \frac{(\nu + 3)(\nu + 4)(\nu + 5)}{\nu(\nu + 1)(\nu + 2)} \quad (19)$$

The parameter  $k_2$  (Eq. (11)) results in:

$$k_2 = \frac{1}{\nu^{\frac{1}{3}}(\nu + 1)^{\frac{1}{3}}} \frac{1}{(\nu + 2)^{\frac{1}{3}}} \quad (20)$$

Fig. 1 shows the dependency of the correlation factors  $k_2$  and  $k_6$  in relation to changes of the shape parameter. The droplet concentration is a function of  $k_6$ , which shows an exponential dependency on the shape parameter. This will significantly influence the calculated droplet concentration and it is important for the retrieval product to assume an appropriate value of the shape parameter  $\nu$ . In Miles et al. (2000) a database of droplet distributions has been analyzed and the mean value of the shape parameter for a gamma distribution and a continental cloud is 8.7, which is in qualitative agreement with the observations of Levin (1958). The standard deviation of the obtained climatological value of the shape parameter is about 6.8, which provides a wide range of possible assumptions of  $\nu$ . If the assumed  $\nu$  is not close to the actual one, there will be a significant error in the droplet concentration. The products of  $k_6$  and  $k_2$ , which are related to the optical properties of  $\tau$  and  $r_{\text{eff}}$ , are more robust to changes in the shape parameter (Fig. 1). The sensitivity of changes in  $\nu$  within the climatological range and the impact on  $N$ ,  $r_{\text{eff}}$  and  $\tau$  are discussed in Section 4.

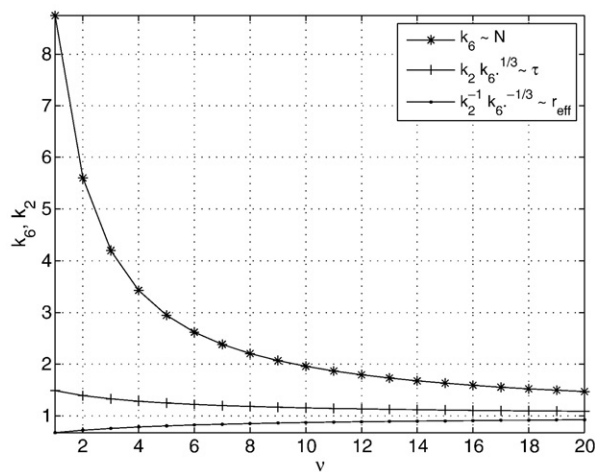


Fig. 1. Dependency of the correlation factors  $k_6$  and  $k_2$  on the shape parameter  $\nu$  of the assumed gamma distribution.

### 3. Ground-based remote sensing input data

The application of the retrieval algorithm is restricted to non-precipitating water clouds without drizzle formation. The chosen water cloud case for 17 May 2003 presented in this study was observed at the Southern Great Plain (SGP) measurement site of the Atmospheric Radiation Measurement (ARM) Program. The following observations of ground-based remote sensing instruments are used in this study: (1) radar reflectivity factor from ground-based Millimeter Cloud Radar (MMCR), where the cloud model height resolution is related to the radar-measured gates; (2) liquid water path retrieval from Microwave Radiometer (MWR) (Turner, 2007); (3) cloud boundaries from ceilometer and cloud radar and (4) pressure and temperature profiles of radio soundings. This case has been already presented in Feingold et al. (2006); where the authors analyzed in detail different effective radii retrieval techniques using surface remote sensing, satellite and airborne observations in relation to changes in aerosol. During this month there was an Intensive Operations Period (IOP) to study the indirect aerosol effect within the framework of the ARM Program, supported by the U.S. Department of Energy. In Feingold et al. (2006) a detailed cloud characterization of 17 May 2003 is described and the following analysis is also constrained after 17.0 UTC, because of drizzle events before.

#### 3.1. Radar reflectivity

Fig. 2A shows the Millimeter Cloud Radar (MMCR) reflectivity data of the cloud layer and cloud base and cloud top. The observed cloud layer is characterized by a relatively high variability, which might be caused by the incipient day time heating. The layer becomes thinner and initiation of mixing processes and turbulence could be expected. The radar reflectivities over this period are smaller than  $-20$  dBZ, which is a criterion, that drizzle effects could be neglected. Frisch et al. (1995) considered reflectivity thresholds of about  $-15$  to  $-17$  dBZ for clouds, which are unlikely affected by drizzle drops.

#### 3.2. Degree of sub-adiabaticity

Fig. 2B illustrates the LWP from MWR measurements and its error, which is based on the retrieval from Turner (2007). The uncertainty in LWP ranges between 5 and 25  $\text{g}/\text{m}^2$ . The adiabatic LWP is derived from adiabatic LWC, which represents the maximum amount of water, a cloud with a certain geometrical thickness, could contain. It is a linear function with height from cloud base to cloud top. The lapse rate ( $A_{ad}$ ) is calculated from Albrecht et al. (1990) and Rogers and Yau (1989) using cloud base pressure and temperature from available soundings.  $LWP_{ad}$  is strongly depending on the cloud geometrical thickness ( $H \propto LWP_{ad}^{0.5}$ ), which is retrieved from combined radar and ceilometer measurements. The uncertainty in the adiabatic LWP is estimated by addressing the uncertainty in the cloud geometrical thickness. The assumed error in the depth ( $\Delta H$ ) is in the range of the radar resolution of 45 m. Both parameters are also influenced by the incipient day time heating. The adiabatic LWP decreases during the day, because of the influence of the decreasing geometrical thickness. The quadratic dependency on the geometrical thickness leads to a difference from about 600 to

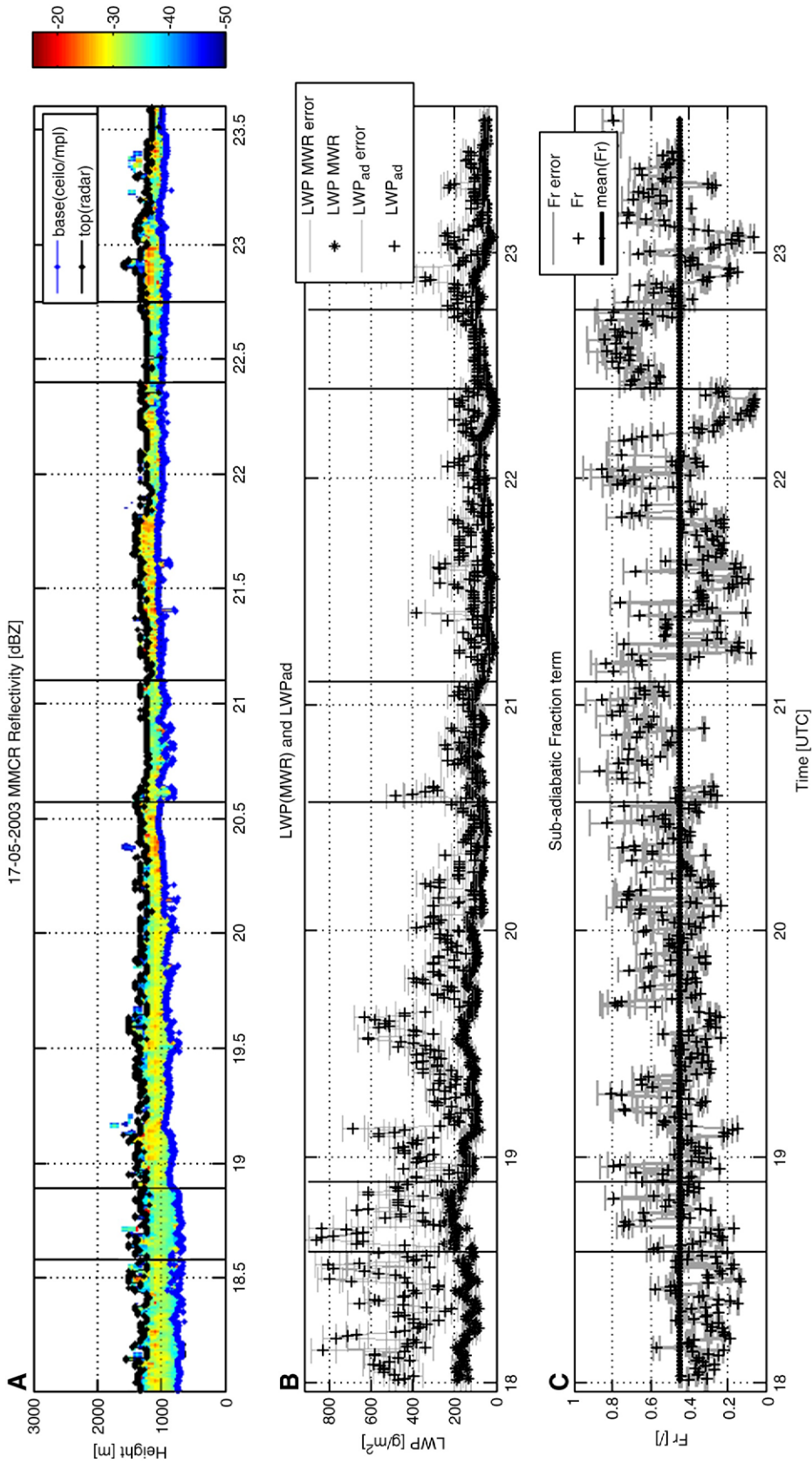


Fig. 2. A: MMCR reflectivity image [dBZ] depending on height and time on May 17 2003. B: LWP derived from MWR and adiabatic LWP in [g/m<sup>2</sup>]. C: sub-adiabatic fraction term  $F_c$ .

200 g/m<sup>2</sup> after 21.0 UTC in  $LWP_{ad}$ . Also the LWP from microwave radiometer decreases and it reaches values below 100 g/m<sup>2</sup> after 20.0 UTC. The variability of both parameters has an impact on the quantification of the degree of sub-adiabaticity  $F_c$ . The sub-adiabatic fraction term  $F_c$  (Fig. 2C) is in the beginning of the cloud layer quite low and it increases to the mean value of 0.4 till 20.5 UTC. The variation of  $F_c$  after that time is quite high, which is caused by the fluctuations of the geometrical thickness and by low values of the LWP from microwave radiometer.

All these effects observed in the measurements have a strong influence on the cloud microphysical properties, because they depend on turbulence and mixing processes, which might be induced through the incipient day time heating. The values of the estimated sub-adiabatic fraction term  $F_c$  show that an adiabatic assumption in this case would lead to an error source in the retrieval products.

### 3.3. Experimental uncertainties

Addressed here are the issues related to the uncertainties in the observations of liquid water clouds using various ground-based remote sensing instruments, which impact the microphysical and optical products of the introduced retrieval technique. The retrievals of droplet concentration ( $N$ ), effective radius ( $r_{eff}$ ) and optical thickness ( $\tau$ ) are mainly dependent on the radar reflectivity  $Z$ , LWP and the geometrical thickness  $H$ . Assuming typical errors in  $Z$  of 1 dBZ, LWP of 25 g/m<sup>2</sup> and  $H$  of 45 m, we estimate an uncertainty in  $N$  of 35–40%, in  $\tau$  of 15–20% and in  $r_{eff}$  of 10–15%. The assumed error in LWP and  $H$  is less significant in the first hours of the observed cloud layer (till 20.5 UTC), but it represents a large uncertainty when the cloud is becoming thinner and LWP decreases to values below 100 g/m<sup>2</sup>. Therefore the relative uncertainties in the retrievals are increasing to more than 100% for the retrieved droplet concentration and to approximately 80% for the optical thickness in most parts of the thin cloud layer. This implies that the retrieval results for thin water cloud layers with low LWP (less than 100 g/m<sup>2</sup>) are hardly reliable and it emphasizes the difficulty to address these clouds with surface remote sensing observations (Turner et al., 2007).

Further uncertainties based on the measurements are indicated in the three marked parts in Fig. 2A–C. In this three sections the radar reflectivity became really low ( $<-35$  dBZ) when LWP is slightly increasing or constant and the transmission of the cloud layer is decreasing (Section 5, Fig. 5). This could be related to the problem that the radar reflectivity tends to be smaller than expected based on the theory of incoherent scatter, which has recently been identified by Russchenberg and Krasnov (2004) and Russchenberg et al. (2009). The possible large uncertainty in the radar reflectivity and in addition the low values of LWP in parts 2 and 3 would lead to a non-appreciable error in the retrievals so that these three parts are excluded from the analysis.

## 4. Application and sensitivity analysis

The introduced retrieval technique is applied to the water cloud case (Section 3) by assuming the climatological value for the shape parameter form (Miles et al., 2000) with  $\nu=9$ . In the following section two main aspects are considered in the discussion of the retrieved droplet concentration, optical

thickness and effective radius: (1) the remote sensing input data of reflectivity, geometrical thickness and LWP are characterized by a relatively high variability; and (2) the impact of the assumed shape parameter (Section 2.4). The evaluation of both effects on the retrieval results is analyzed by a sensitivity study based on the mean values of the input data and the variation of each parameter is performed in the range of their standard deviation.

Fig. 3A,B shows the time series of the estimated droplet concentration and the optical thickness. The error bars indicate the uncertainty in the remote sensing input data with  $\Delta Z=1$  dBZ,  $\Delta H=45$  m and  $\Delta LWP$  in the range of 5 to 25 g/m<sup>2</sup> based on the retrieval algorithm from Turner (2007). The concentration  $N$  varies in the thicker part of the cloud layer between 400 and 1500 droplets/cm<sup>3</sup> and it decreases to half between 20.0 and 22.0 UTC with values of optical thickness between 80 and 18. This behavior reflects the fluctuations in the remote sensing observations and the impact of changes in the cloud structure on the retrievals. The profiles of the effective radius are presented in terms of the histogram in Fig. 4. The mean value of effective radius is about 5  $\mu$ m, which is in the same range of the derived effective radii presented by Feingold et al. (2006).

Table 1 shows the sensitivity of  $N$ ,  $\tau$  and  $r_{eff}$  referring to the variations of the input data with  $iZ=-3.92\pm 2.35$  dBZ m,  $LWP=87.17\pm 41$  g/m<sup>2</sup> and  $H=411.97\pm 136$  m. The mean values exemplify a relatively thick cloud with low LWP. The droplet concentration and optical thickness decrease with increasing  $iZ$  while the mean effective radius of the profile is decreasing. The droplet concentration is strongly affected by the reflectivity and changes of about  $\pm 2.5$  dB result in a difference of 750 droplets. The tendency to the lower values of  $N$  caused by high reflectivity values is limited by the applicability of the technique to pure water clouds without drizzle formation. The presence of drizzle leads to a high uncertainty in the retrievals, because the increase of the reflectivity has a strong effect on the sixth moment of the DSD ( $Z\propto r^6$ ). The assumed DSD with the shape parameter from Miles et al. (2000) is not a representative for drizzle. In this case the reflectivity values are below  $-17$  dBZ, which is a proper threshold for drizzle formation (Frisch et al., 1995). Low values in the reflectivity profiles result in a high concentration of droplets. This leads to an uncertainty in the retrievals, because it is affected by the sensitivity of the cloud radar and furthermore to the possible expected underestimation of  $Z$  in the observations (Russchenberg and Krasnov, 2004; Russchenberg et al., 2009; Brandau et al., 2009).

The sub-adiabatic fraction term  $F_c$  depends on the cloud dimension and on LWP retrieved from the microwave radiometer. An increase of the geometrical thickness of about 270 m changes  $F_c$  from adiabaticity to 0.3 if LWP from MWR is assumed to be constant. In terms of droplet concentration it results in a difference of around 500 droplets/cm<sup>3</sup>. The small value of  $F_c$  implies a lower value of the saturation mixing ratio, which can be caused by an exchange with air dryer. In this approach evaporation affects the particle size and the mean  $r_{eff}$  of the profile decreases to 4  $\mu$ m while the optical thickness increases. Adding more liquid water (up to 80 g/m<sup>2</sup>) to the cloud column results in a quasi-adiabatic degree and the retrievals increase. This emphasizes the important role of the degree of sub-adiabaticity in the retrieval technique and the great uncertainty on its quantification, which is mainly given by the uncertainty in LWP (Section 3.3).

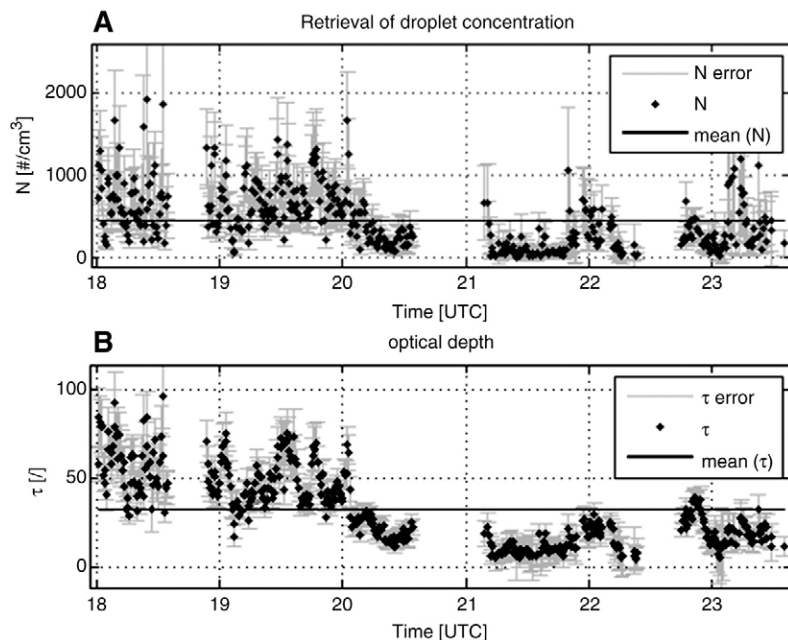


Fig. 3. A: droplet concentration retrieval for  $\nu=9$  and  $F_c$  in [# / cm<sup>3</sup>]. B: time series of retrieved optical thickness [ / ].

The assumed constant shape parameter of  $\nu=9$  with a standard deviation of around 7 from Miles et al. (2000) affects the correlation factors ( $k_2$  and  $k_6$ ) of the DSD moments (Section 2.5 and Fig. 1). This results in a large uncertainty of the retrieved droplet concentration especially for  $\nu < 9$ .  $N$  shrinks to more than half of it changing  $\nu$  from 2 to 9. The optical retrievals are more robust to changes in  $\nu$ . The difference in the optical thickness is about 10 and in  $r_{\text{eff}} = 1 \mu\text{m}$ .

The retrieved droplet concentration is only qualitatively correct. The achievement of a quantitative value for droplet concentration requires an evaluation method, which is independent from the model assumptions and remote sensing based input parameter. Ideally the retrieval of the droplet concentration is validated with simultaneous ground-

based and aircraft in-situ observations, which have been performed during the selected day. But the microphysical measurements of droplet concentration, distribution, size and LWC of the flight mission on this day are not suitable for the validation process, because the cloud cover has been penetrated 30 km far away from the SGP-site, where the cloud structure may have been changed (Feingold et al., 2006). The assumption of observing similar cloud volumes by combing ground-based and in-situ probes leads to problems with the interpretation.

The retrieved optical properties can be evaluated using an alternative approach to in-situ data, because the optical thickness and effective radius are important input parameters for radiative transfer calculations (RTC). The radiative closure experiment presented in the next section is based on comparison of transmission values with the aim of drawing conclusions on the quality of the retrieved optical properties.

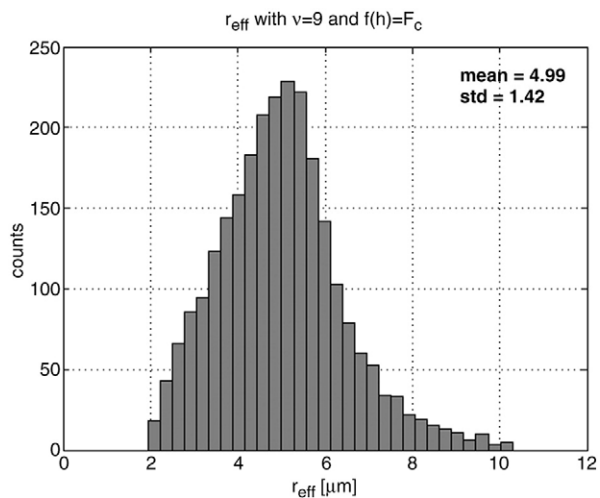
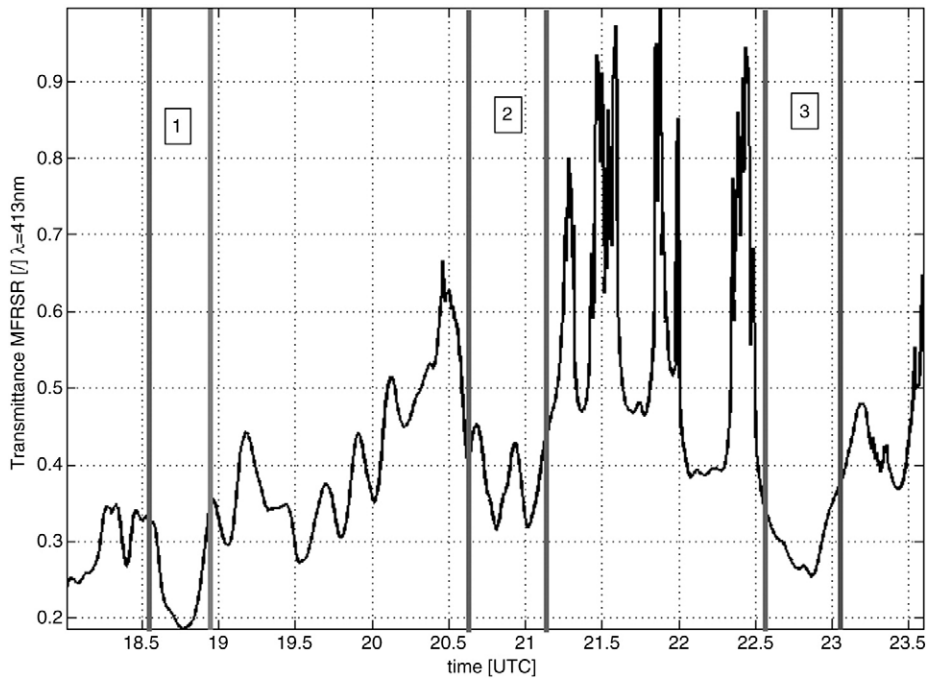


Fig. 4. Histogram of retrieved effective radius [ $\mu\text{m}$ ] for  $\nu=9$  and  $F_c = \text{const}$ .

Table 1  
Sensitivity study to variations in the observations and to retrieval assumptions.

Input data	$F_c$	$N$ [cm <sup>3</sup> ]	$r$ [ / ]	Mean $r_{\text{eff}}$ [ $\mu\text{m}$ ]
$iZ = -3.92$ , LWP = 87.17 $H = 41$ 1.97, $\nu = 9$	0.52	658.76	44.41	4.8944
-2 dBZ	0.52	1130.80	53.17	4.0876
+2 dBZ	0.52	383.75	37.09	5.8604
-136 m	1	983.03	38.86	6.3913
+136 m	0.29	495.36	48.83	4.0473
-41 [g/m <sup>3</sup> ]	0.27	185.30	29.10	3.9618
+41 [g/m <sup>3</sup> ]	0.76	1422.8	57.40	5.5646
$\nu = 2$	0.52	1783.70	53.01	4.0998
$\nu = 16$	0.52	506.23	42.12	5.1614



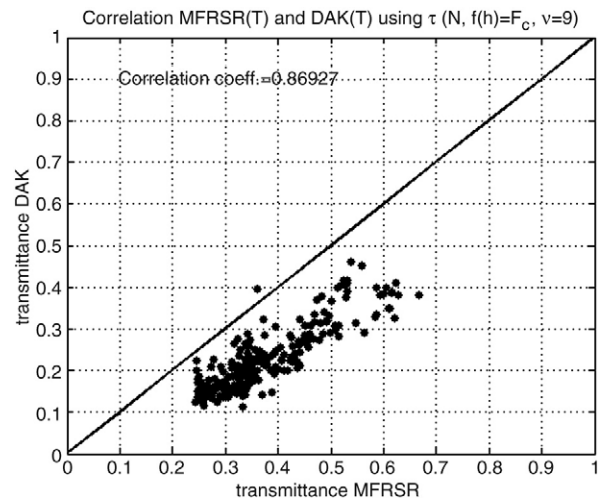
**Fig. 5.** Transmittance from MFRSR observations, which is a value added product of ARM and requested from G. Hodges (PI of MFRSR at SGP). The three bounded parts are excluded from the application, because they are related to low values of reflectivity (Fig. 1), which could be caused by the cloud transition.

## 5. Evaluation of cloud optical properties

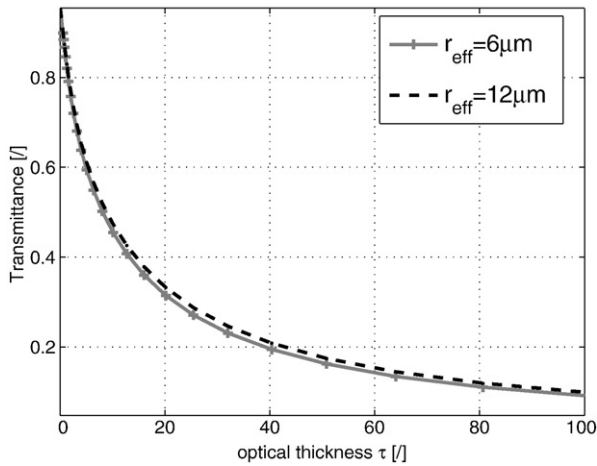
The uncertainties in the retrieval of optical thickness and effective radii are evaluated by means of a radiative closure experiment. The retrieved optical parameters of  $\tau$  and  $r_{\text{eff}}$  for  $\nu=9$  and  $F_c$  are used as input for RTCs to simulate transmittances and to compare them with observed ones at the ground. These data are taken from Multi-Filter Rotating Shadowband Radiometer (MFRSR) observations. The MFRSR is operational at SGP and it measures global and diffuse irradiances at six wavelengths 413, 500, 615, 673, 870 and 940 nm, whereas the first five channels are outside water vapor absorption regions and they are most suitable for the evaluation process. Fig. 5 shows the temporal variation of transmittance at 413 nm. The cloud layer became optically thinner during the day, which shows an increase of the transmittance values. The peaks after 20.5 UTC are caused by holes in the cloud layer, which are detected from images of the total sky imager (TSI). These holes are not observed by the cloud radar (Fig. 2A), which can be understood from the different sampling characteristics of the instruments (Section 5.3). Therefore the comparison of the simulations with the MFRSR observations is restricted to the closed cloud layer before 20.5 UTC. The influence of the broken cloud layer cannot be considered in our RTCs and furthermore the large uncertainty in the retrievals due to low values of LWP and H (Section 3.3) after 21 UTC would strongly affect the evaluation study and lead to misinterpretations. The simulated transmittances are calculated with the Doubling Adding KNMI (DAK) (Stammes, 2000) and radiative transfer model (RTM), which have proven accuracy for the simulations of cloudy atmosphere by means of an inter-comparison of different RTMs (Roebeling, 2007). The monochromatic model

allows for the construction of model atmospheres with plane-parallel clouds consisting of water droplets with specific particle size, size distribution and optical thickness. The main model input data are the column-averaged effective radius, the assumed gamma droplet size distribution, retrieved optical thickness and the solar zenith angle. The simulations are performed for an aerosol optical thickness of 0.3 and a wavelength of 413 nm, because the surface albedo in this channel is small (0.05) and stable.

Fig. 6 shows the correlation between MFRSR transmittances and the DAK simulations based on the retrieved optical depth and effective radius (Section 4). The correlation of



**Fig. 6.** Correlation between measured (MFRSR) and simulated (DAK) transmittances using as inputs  $\tau$  and  $r_{\text{eff}}$  retrieved for  $\nu=9$  and  $F_c = \text{const.}$



**Fig. 7.** Transmittance in dependency of optical thickness for two different effective radii,  $r_{\text{eff}} = 12 \mu\text{m}$  dotted,  $r_{\text{eff}} = 6 \mu\text{m}$  dashed.

around 0.8 shows a good agreement, but the DAK simulations clearly underestimate the transmittance by about 15%. This means that the cloud is assumed to be optically thicker in the simulations than shown in the measurements. There are different possibilities related to our assumptions and errors in the measurements, which could cause the underestimation of the simulated transmittance.

### 5.1. Impact of effective radius and optical thickness in the DAK simulations

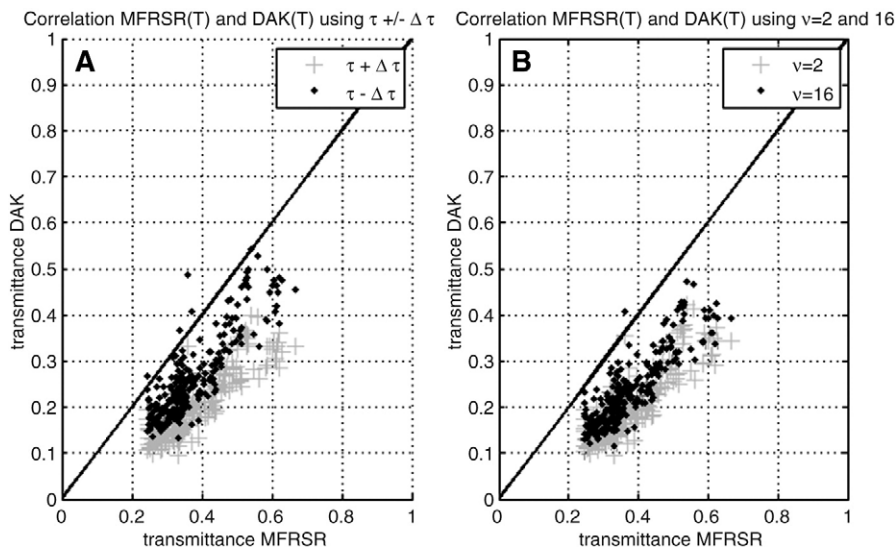
The simulated transmittances mainly depend on the input parameter of effective radius and optical thickness. Fig. 7 shows the dependency of transmittance at 413 nm on the optical thickness for two different effective radii, representing sizes for continental ( $6 \mu\text{m}$ ) and maritime ( $12 \mu\text{m}$ ) clouds. The non-absorbing wavelength has a small effect on the particle size, so

that the differences in transmission in relation to effective radii are too small to explain the underestimation of around 15% in the simulations. Therefore the following discussion is focused on the evaluation of the retrieved optical thickness.

### 5.2. Impact of the measurements and model assumptions

The overestimation of the optical thickness could be related to the quality of the remote sensing measurements. The strongest effect is expected from the quantification of the degree of sub-adiabaticity (Chin et al., 2000), which is mainly caused by the uncertainty in the determination of LWP (Section 4). The radiative fluxes are very sensitive to changes in LWP for clouds with low LWP values (Turner et al., 2007; Sengupta et al., 2003). To minimize this impact the evaluation is focused on that part of the cloud layer where LWP is greater than  $100 \text{ g/m}^2$ . The estimated relative error in the optical thickness for this part of the cloud layer is 15–20% based on the uncertainties in reflectivity, LWP and geometrical thickness (Section 3.3). Considering the range of the uncertainty ( $\tau \pm \Delta\tau$ ) in our RT simulations the underestimation in transmission is still between 10 and 18% (Fig. 8A).

The assumed constant shape parameter  $\nu$  has a great influence on the retrieved droplet concentration, but it is less sensitive to the optical thickness (Table 1). The optical thickness changes from 53 to 42 if  $\nu$  varies from 2 to 16. This means that the effect on the simulated transmittance is expected to be small, because in this range of optical thicknesses the transmittance is between 0.18 and 0.2. Fig. 8B shows the correlation for the two assumed shape parameters, which reflects the uncertainty in the obtained values from Miles et al. (2000). It results in a range of underestimation of 14 to 18% and it is concluded that the uncertainty in the assumed shape parameter does not improve the underestimation of transmission in the simulations. It is important to mention that in this retrieval technique the mixing process is simply constricted to be homogeneous, where the reduction of LWC is affecting the profile of effective. This variation with height is parameterized with our assumption



**Fig. 8.** A: correlation between measured (MFRSR) and simulated (DAK) transmittances using as input  $\tau + \Delta\tau$  and  $\tau - \Delta\tau$  with  $r_{\text{eff}}$  retrieved for  $\nu = 9$ . B: correlation between measured (MFRSR) and simulated (DAK) transmittances using as inputs  $\tau$  and  $r_{\text{eff}}$  retrieved for  $\nu = 2$  and 16.

about the sub-adiabatic fraction function  $f(h)$ , where  $f(h) = \max(f(h)) = F_c = \text{const}$ . As discussed in Section 2.4 this parameterization leads to uncertainties in the retrieval of droplet concentration, effective radius, extinction and optical thickness. This may result in an overestimation of the products, because the dilution from adiabaticity is assumed to be constant and small. Further investigations in relation to this parameterization are necessary, but it is not expected to be the main reason of the underestimation.

### 5.3. Plane-parallel bias

This section addresses the uncertainty in the retrieval results comparing simulations and observations based on different sampling characteristics. There is an acceptable level of agreement (correlation of 0.8) existing between the MFRSR observations and the DAK modeled transmittance based on the retrievals, but with a bias of 15% in the simulations. This could be explained by the influence of the combination of different methodologies for the retrievals, the RTC and the radiation measurements. The retrieval technique is based on a vertical column approximation using vertically pointed cloud radar measurements. The radiative transfer calculations are performed for the optical thickness of each column assuming horizontal homogeneity. The cloud layer is observed at around 1200 m height at which the footprint of the radar is 4 m, which corresponds to 0.16% of radius of the MFRSR at the same height. The MFRSR is performing hemispherical measurements with a footprint of 1 km radius, which contain information about a certain area of radiation properties of the cloud layer and includes the horizontal inhomogeneity of optical thickness. This leads to the fact that the comparison of the transmission properties in the closure experiment is influenced by the so-called plane-parallel (PPH) bias (Cahalan et al., 1994), which implies that inhomogeneous clouds are brighter in transmission and darker in reflection than clouds which are homogeneous and plane parallel, for the same mean cloud optical thickness (Stammes, 1995). This effect can be determined in the radiative transfer calculations of transmission by assuming a distribution function of optical thickness, which

represents the horizontal inhomogeneity. It can be expressed with

$$\overline{T(\tau, \mu_0, r_{\text{eff}})} = \int_0^\infty T(\tau, \mu_0, r_{\text{eff}}) Pdf(\tau) d\tau \quad (21)$$

where the horizontally averaged transmission  $T$  depends on  $\tau$ , the solar zenith angle  $\mu_0$  and  $r_{\text{eff}}$  of a certain domain is the integral over the transmission function  $T$  multiplied by the probability density distribution function ( $Pdf$ ) of optical thickness. The cloud optical thickness distribution of a certain domain is difficult to determine and there is a number of studies presenting different approximations of the  $Pdf$  based on bounded cascade models, satellite or in-situ measurements (e.g. Cahalan et al., 1994; Pincus et al., 1999; Los and Duynkerke, 2001). In this study simplified assumptions are made to estimate the effect of the horizontal inhomogeneity on the transmittance of the simulations. The different footprints of the radar and the MFRSR are considered to derive the horizontal inhomogeneity of the optical thickness. A completely closed cloud layer, which is most suitable for the comparison, was observed from 19 till 20.5 UTC. This time window is used to derive the  $Pdf$  of optical thickness referring to the radar based retrievals. Fig. 9A shows the distribution of the retrieved optical thickness during this time period, which is fitted to a triangular distribution function (black line). The derived  $Pdf$  represents roughly the features of the retrieved distribution of optical thickness and its size distribution parameters (mode and width) have a simple meaning (Stammes, 1995). The mode optical thickness ( $\tau_{\text{mode}}$ ) and width ( $\tau_{\text{width}}$ ) of the fitted  $Pdf$  around 45 were used to calculate the horizontally averaged transmission  $eT$  (Eq. (21)) for the same mean optical thickness. The mean optical thickness of each time step is supposed to be the retrieved one, because the optical thickness distribution of the radar based column approximation can be regarded as a delta function around this value (Stammes, 1995). It is important to mention that the impact of the PPH bias depends on the assumption of the shape of the distribution and in several studies it is modeled either as log-normal or gamma (Pincus et al., 1999). The used  $Pdf$  in this

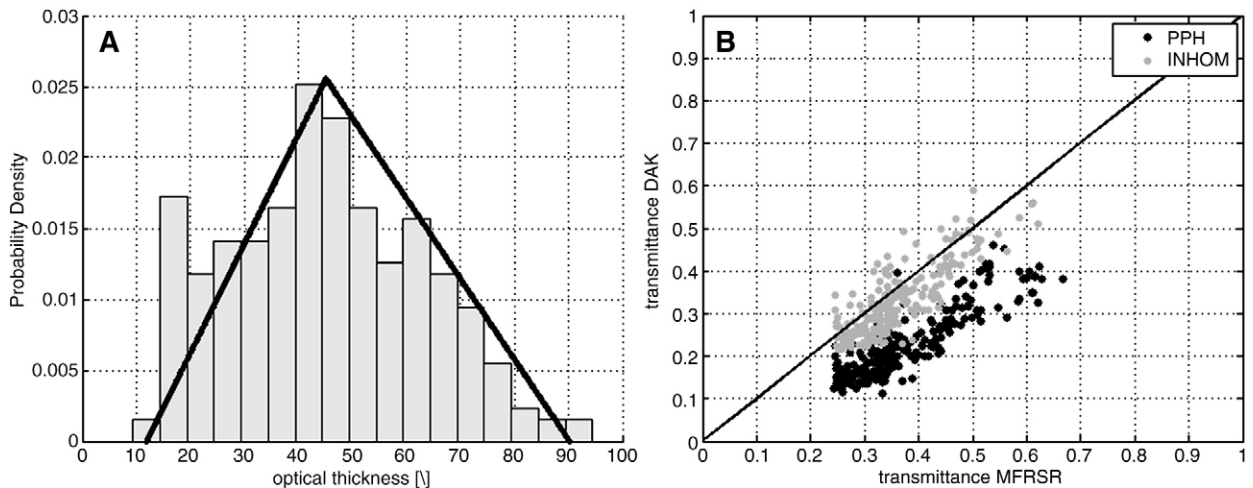


Fig. 9. A: histogram of optical thickness retrieved for  $\nu=9$  and  $F_c = \text{const}$  and a fitted triangle probability density function. B: correlation between measured (MFRSR) and simulated (DAK) transmittances for horizontal inhomogeneity of optical thickness represented by triangular  $Pdf$  and for horizontal homogeneity using as inputs  $\tau$  and  $r_{\text{eff}}$  retrieved for  $\nu=9$  and  $F_c = \text{const}$ .

study is quite broad with a relatively a high mode value in comparison to the distributions based on in-situ measurements (Cahalan et al., 1994; Los and Duynkerke, 2001). But so far there is also no information on how the distribution changes from cloud region to region, which is especially in this cloud case quite important, because the cloud structure changes due to the day time heating. The impact of the PPH bias is represented in Fig. 9B, where the correlation between the measured and simulated transmittances for horizontal homogeneity (PPH) and inhomogeneity (INHOM) is shown. The transmission of the assumed inhomogeneous cloud is higher and in much better agreement with the transmittance measured by the MFRSR. It shows that the consideration of the cloud inhomogeneity is a great improvement and it significantly reduces the bias to around 5%. The plane-parallel assumption in the DAK model in contrast to the hemispherical MFRSR observations caused the largest part of the underestimation in the simulations for this particular chosen *Pdf* of optical thickness. This means that the retrieved optical thickness with the assumption of  $f=F_c$  and the fixed shape parameter of  $\nu=9$  used in this simulations are in a realistic range and therefore the introduced technique might be a new approach to retrieve quantitative values of optical thickness. This requires a more proper study of the impact of the parameters of the *Pdf* on the closure. For example the average transmission may increase with an increase of the width of the assumed distribution of the optical thickness, which influences the degree of the discrepancy between simulations and measurements.

## 6. Summary and conclusions

This paper introduces a retrieval technique of liquid water cloud properties based on ground-based remote sensing measurements and a vertical cloud model, where three main assumptions are made to determine the microphysical and optical characteristics. First the droplet size distribution is assumed to be constant with a fixed shape parameter; second the inner cloud mixing processes are restricted to be homogeneous, where the reduction of LWC with height is affecting the effective radius. Third the vertical profile of LWC is parameterized by the sub-adiabatic fraction function  $F_c$ , which is the ratio of LWP measured from microwave radiometer and the adiabatic one. The retrieval products of droplet concentration, effective radius and optical thickness have been examined for a water cloud case observed on ARM SGP-site.

The retrievals are affected by the measurement uncertainties, in particular by the uncertainty of the radar reflectivity and the observations to derive the sub-adiabatic fraction  $F_c$ . This can be improved by means of reducing the uncertainty in LWP estimates, in particular for LWP. Refinements in relation to the radar data can be obtained by using the Doppler capability to estimate possible drizzle components instead of the reflectivity threshold method. Improvements for a better understanding of the uncertainty for low reflectivity values are under progress by characterizing the in-cloud turbulences. The quality of the retrievals also depends on the model assumptions of the linear LWC profile ( $F_c = \text{const.}$ ) and the fixed shape parameter of the droplet size distribution. The parameterization of LWC could cause an overestimation and other functions of  $f(h)$  could be used to describe the variation of LWC with height. The assumption of an appropriate gamma shape parameter using the information of a reviewed in-situ data set is critical, because it

resulted in a large variation in  $\nu$  and the exponential dependency on  $N$  can result in an uncertainty greater than 100%. Future work on improving the assumptions in the algorithm will be the next step.

The retrieved droplet concentration is only qualitatively correct and it has to be validated by using aircraft in-situ measurements of water clouds. On the basis of a EUFAR (European Fleet for Airborne Research) proposal aircraft measurements of water cloud microphysics (liquid water content, droplet size distribution and concentration) have been performed during the measurement campaign COPS (Convective and Orographically-induced Precipitation Study). Furthermore the validation process will be extended through an aircraft measurement campaign, that was held in Cabauw, Netherlands in May 2008 organized within the framework of EUCAARI (European integrated project on aerosol cloud climate air quality interactions).

The retrieved cloud optical properties are evaluated in this paper by means of a radiative closure experiment, where the droplet effective radius and cloud optical thickness are used as input parameter for a plane-parallel RTM. The simulations are compared with transmittance observations from the ground of an MFRSR and the influence of the retrievals related to the uncertainties of the technique on the transmissivity of the cloud layer is analyzed. The comparison between the measurements and simulations shows that the simulated transmittances are underestimated by about 15%. The main impact on the DAK simulations is related to the input parameter of the retrieved optical thickness, which is influenced by the uncertainties in the measurements and the assumptions in the vertical cloud model. These uncertainties could not explain the underestimation. For example an increase of the fixed shape parameter has a small affect on the retrieved optical thickness and on the simulations of transmittance.

The underestimation of the simulated transmittances could be partly explained by the horizontal cloud inhomogeneity. The simulations are performed with the plane-parallel radiative transfer model DAK. By contrast the hemispherical radiation observations include information about the horizontal cloud inhomogeneity, because of the field of view of the MFRSR. The consideration of this effect by determining the horizontally averaged transmission reduces significantly the underestimation to 5%. The impact of the PPH bias strongly depends on the assumed distribution of the cloud optical thickness, where the average transmission increases with an increase of the width of the assumed distribution. This effect influences the degree of the closure and it has to be taken into account when judging about the quality of the remotely sensed retrievals.

Nevertheless it is remarkable that, despite of the model assumptions and measurement errors, the retrieved optical thickness could be used to reproduce the measured radiation on the surface (albeit not perfect) and that the PPH bias is improving the result. It is concluded that the introduced radar based retrieval technique could be a good opportunity of deriving reliable optical thickness values. The retrieved optical thickness is a function of the integrated reflectivity. The advantage of using radar reflectivity instead of lidar extinction is that there is no need to extrapolate information at cloud base into the cloud due to the fast attenuation of the lidar signal. Of course the single case study presented here has to extend to a better evaluation and more statistical intercomparisons are needed to generalize the results.

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