

# EVALUATION OF GROUND-BASED REMOTELY SENSED WATER CLOUD PROPERTIES USING RADIATION AND AIRCRAFT IN-SITU MEASUREMENTS

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## 1. INTRODUCTION

High temporal resolution of ground-based remote sensing measurements enables long-term observations of the effect of aerosols on cloud microphysical and optical properties on a regional scale. The greatest challenge of this possibility is to retrieve and to relate the relevant parameters involved in the processes from increased anthropogenic aerosol production to changes of the cloud albedo from the observations. Our work introduces a retrieval technique of microphysical (concentration, effective radius) and optical properties (extinction, optical thickness) of low level water clouds using different ground-based observations to obtain the temporal and spatial variation of water cloud properties. The crucial parameter in this technique is the retrieval of droplet concentration, which is an important indicator related to the physics of the first indirect aerosol effect (Twomey, 1977).

## 2. RETRIEVAL TECHNIQUE

### 2.1 Method

The retrieval technique of droplet concentration combines cloud radar, microwave radiometer, lidar and radio sounding measurements with a microphysical and thermodynamic model (Boers et al., 2006). In this model the cloud is described by a single-mode droplet distribution

$$N = \int_0^{\infty} n(r) dr \quad (\text{EQ 1})$$

$N$  is the droplet concentration with an assumed gamma function for the droplet size distribution  $n(r)$ :

$$n(r) = \frac{D^\nu}{\Gamma(\nu)} r^{\nu-1} e^{-Dr} \quad \text{for } r > 0 \quad (\text{EQ 2})$$

$\Gamma(\nu)$  is the gamma function,  $\nu$  the breadth parameter and  $D$  the size parameter.

The vertical model also includes mixing effects and considers the sub-adiabatic structure of the cloud, which can be expressed by using the following definition of liquid water content (LWC):

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

where  $\langle r^3 \rangle$  is the third moment of the assumed droplet size distribution of  $n(r)$ :

$$\langle r^3 \rangle = \frac{\int_0^{\infty} n(r) r^3 dr}{\int_0^{\infty} n(r) dr} \quad (\text{EQ 4})$$

$h$  is height above cloud base,  $\rho_w$  is density of water,  $\rho_a$  is density of air,  $A_{ad}$  is the adiabatic lapse rate of liquid water content mixing ratio depending on cloud base pressure and temperature. The subscript *ad* refers to the adiabatic value of the variable. The function  $f(h)$  represents the sub-adiabatic fraction of liquid water content and it describes the variation of LWC with height from cloud base (cb) to cloud top (ct). Furthermore it can be attributed to variations in the droplet concentration  $N$  and in the third moment of the assumed droplet size distribution  $\langle r^3 \rangle$ .

The measured radar reflectivity factor from the cloud radar can be expressed by

$$Z = 64N \langle r^6 \rangle \quad (\text{EQ 5})$$

where  $\langle r^6 \rangle$  is the sixth moment of the assumed droplet size distribution of  $n(r)$ :

$$\langle r^6 \rangle = \int_0^\infty n(r)r^6 dr / \int_0^\infty n(r)dr \quad (\text{EQ 6})$$

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

$$\langle r^6 \rangle = k_6 f^2(h) \langle r^3 \rangle^2 \quad (\text{EQ 7})$$

The constant coefficient  $k_6$  depends on the breadth parameter  $\nu$  of the assumed Gamma size distribution

$$k_6 = \frac{(\nu+3)(\nu+4)(\nu+5)}{\nu(\nu+1)(\nu+2)} \quad (\text{EQ 8})$$

It is fixed on the basis of in-situ measurements of droplet size distributions (Miles et al., 2000).

Altogether we derive a functional form of the radar reflectivity factor:

$$Z(h) = k_6 \left( \frac{6 \rho_a}{\pi \rho_w} A_{ad} \right)^2 \frac{1}{N} f^2(h) h^2 \quad (\text{EQ 9})$$

depending on the height  $h$ , the adiabatic lapse rate  $A_{ad}$ , the droplet concentration  $N$  and the sub-adiabatic fraction function  $f(h)$ . In this equation  $f(h)$  is attributed to variations in the third moment of the assumed droplet size distribution  $\langle r^3 \rangle$  and we assume a constant droplet concentration  $N$  with height. This implies a homogenous mixing process, which means that the droplets evaporate to such a degree that the total amount remains the same. The derived vertical profile of the radar reflectivity factor enables an estimation of the droplet concentration  $N$ , where the greatest uncertainty is given in the unknown sub-adiabatic fraction function  $f(h)$ , which is a free parameter to be fixed.

## 2.2 Implementation

The provided method leads to different possibilities to derive the droplet concentration  $N$ . For example a least

square regression of the functional form of reflectivity (EQ 9) and the measured radar reflectivity profile could be used to estimate

$f(h)$  and the droplet concentration  $N$ .

The used implementation in this work involves an integrated approach by estimating the sub-adiabatic fraction function  $f(h)$  under following conditions.

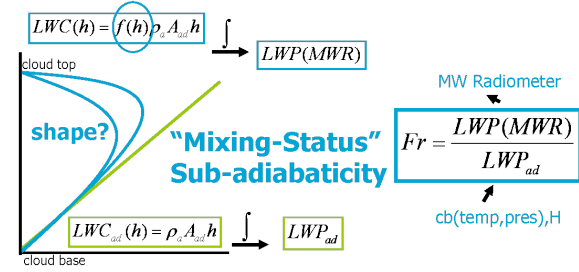


Fig 1: Schematic diagram to illustrate the estimation of the sub-adiabatic fraction function.

The adiabatic liquid water content ( $LWC_{ad}$ ) is related to the maximum amount of water a cloud with a certain geometrical thickness could hold. It is a linear function with height from cloud base to cloud top and it is depending on cloud base pressure and temperature (Fig. 1 green line). But it is well-known that on average clouds are not adiabatic in nature. This can be expressed by our defined sub-adiabatic fraction function  $f(h)$ , which describes the variation of LWC with height and it is an unknown parameter (Fig. 1 light blue). This parameter can be fixed by using the integrated LWC from cloud base to cloud top:

$$LWP(MWR) = \int_{cb}^{ct} \rho_a A_{ad} f(h) h dh = Fr LWP_{ad} \quad (\text{EQ 10})$$

as measured by microwave radiometer (MWR) in combination with the adiabatic LWP (Fig.1). The term  $Fr$  describes the mixing-status or the degree of sub-adiabaticity in the cloud and if  $Fr$  is equal to one the cloud is assumed to be adiabatic. This ratio between the retrieved LWP from microwave radiometer and the adiabatic LWP is used to derive an estimation of the droplet concentration in combination with

the integrated radar reflectivity  $iZ$  of EQ 9. The implementation results in

$$N = k_6 \left( \frac{6\rho_a A_{ad}}{\pi\rho_w} \right)^2 \frac{1}{iZ} Fr^2 \frac{1}{3} H^3 \quad (\text{EQ 11})$$

where  $H$  is the geometrical thickness of the cloud layer. This formulation enables the derivation of the droplet concentration in dependency of an estimation of the sub-adiabatic fraction function  $f(h)$ . The main remote sensing based input parameter are the radar reflectivity, the geometrical thickness derived from lidar and radar, the LWP from microwave radiometer as well as cloud base temperature and pressure from radio soundings in order to calculate the degree of adiabaticity.

### 3. APPLICATION

#### 3.1 Water Cloud Case Study

The application of the retrieval of droplet concentration is restricted to non-precipitating low level water clouds without drizzle formation. The chosen water cloud case in this study on 17 May 2003 at Southern Great Plain (SGP) was presented in Feingold et al. (2006). They 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 in the framework of the Atmospheric Radiation Measurement (ARM) Program, supported by the U.S. Department of Energy. Referring to Feingold et al. (2006) in which a detailed cloud characterization of the 17 May 2003 is described, the following analysis is constrained as well after 17.0 UTC related to drizzle events before. This case study is used to discuss the retrieval of droplet concentration, where the results of effective radii are secondary products.

#### 3.2 Remote sensing based input data

##### 3.2.1 Radar Reflectivity

Fig. 2 shows the millimeter cloud radar (MMCR) reflectivity data of the cloud layer

and cloud base (blue line) and cloud top (black line).

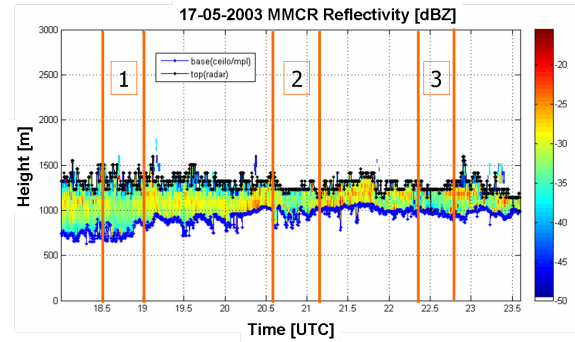


Fig 2: MMCR radar reflectivity [dBZ] 17 May 2003 SGP

The observed cloud layer is characterized by a relatively high variability, which is caused by the incipient day time heating. It became thinner and initiation of mixing processes and turbulence could be expected. There are three parts in the cloud layer (Fig 2) where the values of reflectivity became really low ( $< \sim -35$ dBZ). This could be related to the transition of the cloud layer due to the day time heating. In respect to the data quality these three parts are excluded from the analysis, because the retrieval technique is only applicable for a continuous cloud layer.

##### 3.2.2 Degree of sub-adiabaticity $Fr$

Fig. 3 A illustrates the microwave radiometer retrieval of LWP (black) (Turner et al., 2007) and the calculated adiabatic LWP (dark blue), which is based on the derived cloud geometrical thickness and on cloud base pressure and temperature from radio soundings. Both parameters are also influenced by the incipient day time heating. The adiabatic LWP decreases during the day, because of the influence of the variations in the geometrical thickness. The quadratic dependency on the geometrical thickness leads to a difference from about 600 to  $\sim 200$ g/m<sup>2</sup> (Fig 4) after 21.0 UTC. This has an impact on the quantification of the degree of sub-adiabaticity. Also the LWP from microwave radiometer decreases and it reached values below 100g/m<sup>2</sup> after 20.0 UTC.

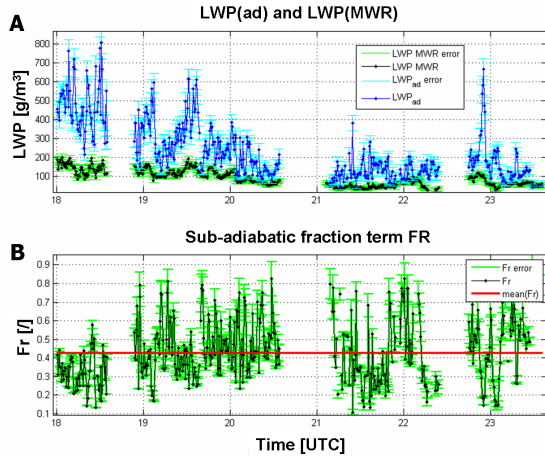


Fig 3: A) LWP retrieved from microwave radiometer (black) and adiabatic LWP [ $\text{g}/\text{m}^2$ ] (blue), B) Sub-adiabatic fraction term  $Fr$ .

The variability of both parameters results in the beginning of the cloud layer in a low value of sub-adiabaticity  $Fr$  (Fig. 3 B), which tend to vary around the mean value of  $\sim 0.4$  in the center of the layer (19.9 to 20.5 UTC). The variation in the end of the cloud layer is quite high, which is caused by the fluctuations of the geometrical thickness and by low values of the LWP from microwave radiometer.

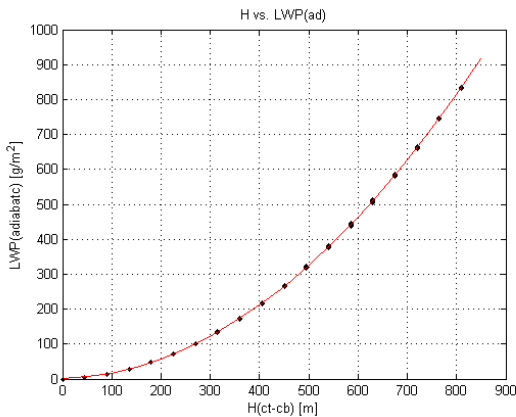


Fig 4: Dependency of geometrical thickness  $H$  on the derived adiabatic LWC.

All these effects in the measurements have a strong influence on the droplet concentration and particle size, which are depending on turbulence and mixing effects. The values of the estimated sub-adiabatic fraction term show that an adiabatic assumption ( $Fr = 1$ ) in this case would lead

to a large error source in the retrieval of droplet concentration.

### 3.3 Estimation of droplet concentration $N$

Fig 5 shows the time series of the estimated droplet concentration based on the remote sensing input data. The concentration  $N$  is varying in the beginning of the cloud layer between 400 and 1500 droplets per cubic centimeter and it decreases between 20.0 to 22.0 UTC. This behavior reflects the fluctuations in the input data, which are demonstrated again in Fig 6 A-C.

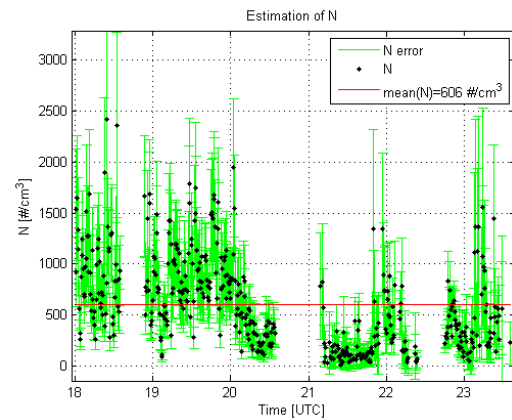


Fig 5: Retrieved droplet concentration [ $\#/\text{cm}^3$ ].

Between 18.0 and 20.0 UTC the integrated reflectivity (Fig 6 A) varies close to the mean value (pink line). The geometrical thickness (Fig 6 C) decreases slightly,  $Fr$  increases (Fig 6 B) and the resulting droplet concentration tend to higher values (Fig 5).

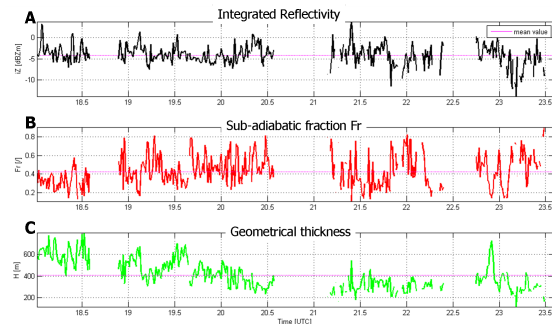


Fig 6: Remote sensing based input data: A) integrated reflectivity  $iZ$  [dBZm], B) Sub-adiabatic fraction  $Fr$ , C) geometrical thickness  $H$  [m].

After 20.0 UTC when the cloud layer became much thinner, the concentration

decreases (Fig 5) and an increase in  $iZ$  is observed (Fig 6 A). The observations related to the degree of adiabaticity and the radar reflectivity show a significant influence on the estimated droplet concentration and therefore a sensitivity analysis has been performed.

### 3.4 Sensitivity analysis of N

This sensitivity analysis is based on the mean values of the input data and the variation of each parameter has been performed in the range of their standard deviation. In Fig 7 the sensitivity of  $N$  referring to variations of the integrated reflectivity  $iZ$  is demonstrated. The geometrical thickness, LWP adiabatic and LWP from microwave radiometer are assumed to be constant.

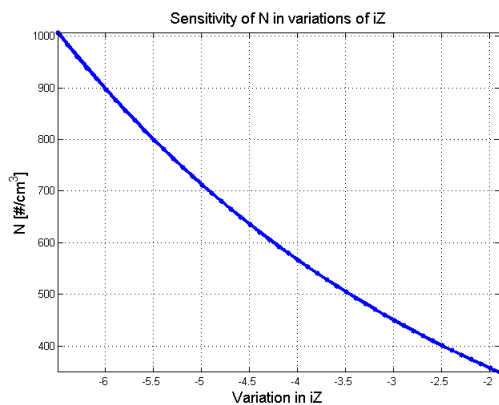


Fig 7: Sensitivity of  $N$  referring to variations of the mean value of  $iZ$  in the range of its standard deviation.  $H$ , LWP(ad), LWP(MWR) are assumed to be constant.

The droplet concentration decreases with an increase of  $iZ$ . This tendency to lower values of  $N$  is limited by the applicability of the technique on pure water clouds. Only cloud layers with reflectivity values below -17 dBZ are used, which is a proper threshold for drizzle formation. Low values in the reflectivity profiles result in a high concentration of droplets. This leads to an uncertainty in the retrieval of droplet concentration, because it is affected by the quality of the cloud radar data. The problem that has recently been identified (Russchenberg et al., 2004) is that the

measured reflectivity factor of non-drizzling stratocumulus clouds can be significantly smaller than expected based on the theory of incoherent scatter, which strongly influence the standard radar reflectivity. The underestimation of the radar reflectivity could be caused by cloud mixing processes at small scales and it has a significant influence on the radar based retrieval techniques of water cloud properties.

The variation of the geometrical thickness has an impact on the sub-adiabatic fraction term  $Fr$ , because it is depending on the adiabatic LWP. An increase of 200 m in the geometrical thickness changes  $Fr$  from 0.8 (close to adiabaticity) to 0.3 (Fig 8) if LWP from MWR is assumed to be constant.

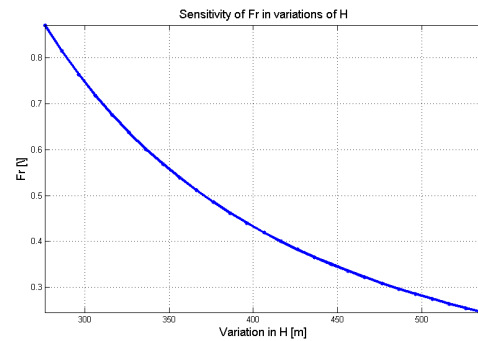


Fig 8: Sensitivity of  $Fr$  referring to variations of the mean value of  $H$  in the range of its standard deviation. LWP(MWR) and  $iZ$  are assumed to be constant.

In terms of droplet concentration it results in a difference of 300 droplets per cubic centimeter (Fig 9), which implies that the maximum amount of droplets is expected under adiabatic conditions.

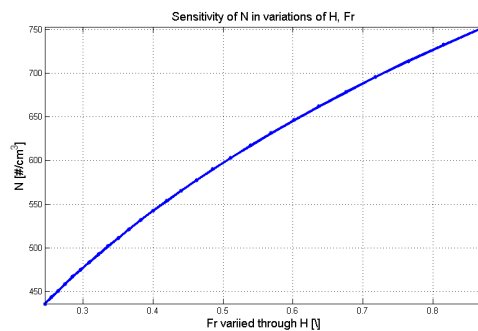


Fig 9: Sensitivity of  $N$  referring to variations of the mean value of  $H$  in the range of its standard deviation. LWP(MWR) and  $iZ$  are assumed to be constant.

The effect on the droplet concentration of assuming an adiabatic cloud layer ( $Fr=1$ ) for this case study is shown in Fig 10. It results in exorbitant amount of droplets (red line), which emphasizes the importance of including the degree of adiabaticity. It also confirms that the greatest uncertainty in the retrieval of droplet concentration is related to the quantification of  $Fr$ . The degree of sub-adiabaticity is depending on the cloud dimension and on LWP retrieved from the microwave radiometer and so far no systematic analysis of  $Fr$  on global water clouds have been applied (Boers et al., 2006).

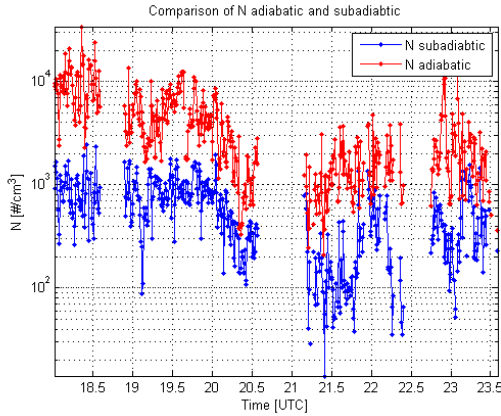


Fig 10: Estimated droplet concentration for  $Fr=1$  (adiabaticity, red) and  $Fr<1$  (sub-adiabaticity, blue).

#### 4. OPTICAL PROPERTIES

The estimated droplet concentration could be used to calculate the optical properties like effective radius, extinction and optical thickness as a secondary retrieval output. These parameters are important for radiation transfer calculations.

##### 4.1 Effective radius

The effective radius is retrieved on the basis of Frisch et al., 2002. They provide two different methods to derive profiles of effective radius using cloud radar and microwave radiometer observations. The droplet concentration in their method is fixed to be constant with height. We can combine this technique by assuming that the sub-adiabatic fraction function  $f(h)$  is depending on the shape of the reflectivity

profile according to the specified Gamma size distribution and breadth parameter. The estimated droplet concentrations and the measured radar profiles are used to derive profiles of effective radius.

$$r_{effective} \propto \left( \frac{Z(h)}{N_{est}} \right)^{\frac{1}{6}} \quad (EQ 12)$$

Fig 11 A represents again the estimated droplet concentration in terms of histogram, which result in effective radii in mean about 5.2 microns (Fig 11 B). These values are in the same range of the derived effective radii in Feingold et al., 2006.

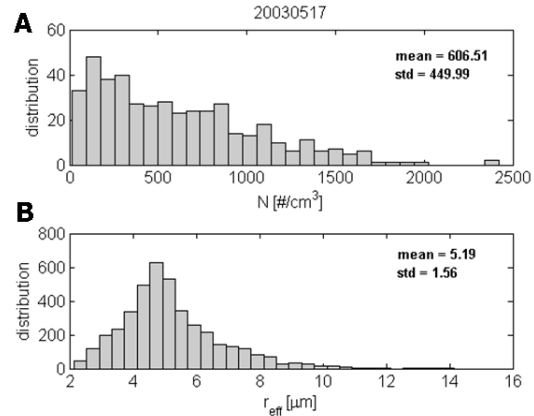


Fig 11: A) Estimated droplet concentration  $N$  [# $cm^{-3}$ ], B) Derived effective radius using the estimated droplet concentration and Frisch et al., 2002 approach.

According to EQ 12 and to Frisch et al., 2002 the droplet concentration is less sensitive to this retrieval method of effective radius. Fig 12 shows the sensitivity of effective radius in variations of droplet concentration using the mean radar profile of the observed cloud layer. The variation from 200 to 1000 droplets results in this case in a difference of only one micron in effective radius and therefore this parameter is inapplicable for evaluation studies of the estimated droplet concentration.

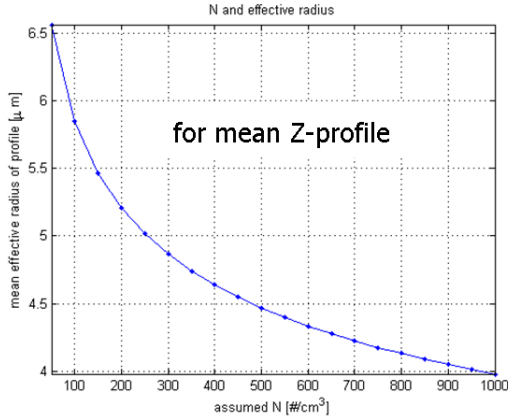


Fig 12: Sensitivity of effective radius in variations to the droplet concentration using the mean radar reflectivity profile of the observed cloud layer.

#### 4.2 Extinction and optical thickness

The optical extinction can be expressed, assuming big particles compared to the wavelength, in the following form:

$$\sigma_{ext} \approx 2\pi N_{est} \langle r^2 \rangle \quad (\text{EQ 13})$$

This relation is used to calculate profiles of the optical extinction coefficient under consideration of the made assumptions in 4.1. and using the estimated droplet concentration. Fig 13 A shows the result of the optical thickness, which is the integrated value of the optical extinction profile (Fig 13 B).

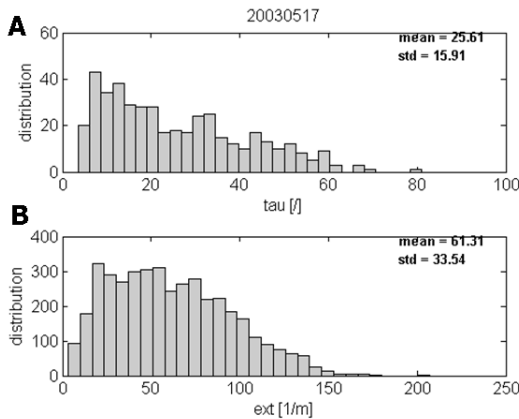


Fig 13: A) Derived optical thickness using the estimated droplet concentration, B) Derived extinction using the estimated droplet concentration.

The derived optical thickness is more sensitive to the estimated droplet concentration, which is demonstrated in Fig 14. Changes in the droplet concentration

from 300 to 400 particles per cubic centimeter lead to a difference of optical thickness about 10. Consequently this parameter is an adequate input parameter for evaluation purposes of the retrieved droplet concentration using radiative transfer calculations for a closure experiment.

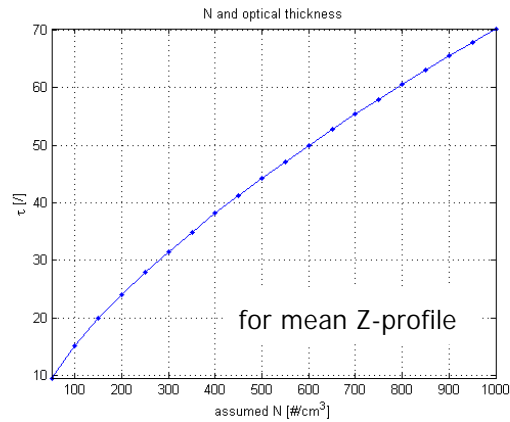


Fig 14: Sensitivity of optical thickness in variations to the droplet concentration using the mean radar reflectivity profile of the observed cloud layer.

### 5. EVALUATION

The quality of the retrieval products is strongly depending on the model assumptions and on the accuracy of the ground-based observations. Therefore evaluation methods are required, which are independent from the remote sensing based input parameter.

#### 5.1 Radiative transfer calculations

In this evaluation study the derived optical thickness has been used as input for radiation transfer model calculations to simulate narrowband fluxes and to compare them with radiation measurements at the ground. The narrowband observations are used from the Multi-Filter Rotating Shadowband Radiometer (MFRSR), which is operational at Southern Great Plains (SGP). It measures global and diffuse irradiances at six wavelengths 415, 500, 615, 673, 870 and 940 nm. The first five channels are outside water vapor absorption regions and they are most suitable for the evaluation process. The simulated narrowband irradiances are

calculated with the Doubling Adding KNMI (DAK) (P. Stammes et al., 2001) radiative transfer model. 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 radiative transfer model based input data are the mean effective radius of the retrieved profile, the assumed Gamma droplet size distribution and the retrieved optical thickness. The model environment is set by the SGP site characteristics. The simulations have been calculated for the wavelengths of 415 nm with a surface albedo of 0.05. Within the comparison of the MFRSR measured irradiances with the simulated ones an assumed Gauss spectral response function of the MFRSR at the nominal wavelength with half power width of 10nm has been considered. Fig 15 shows the comparison of the irradiances of MFRSR (blue line) and the DAK simulations including an aerosol optical thickness (AOT) of 0.3 (red line) and without aerosols (black line).

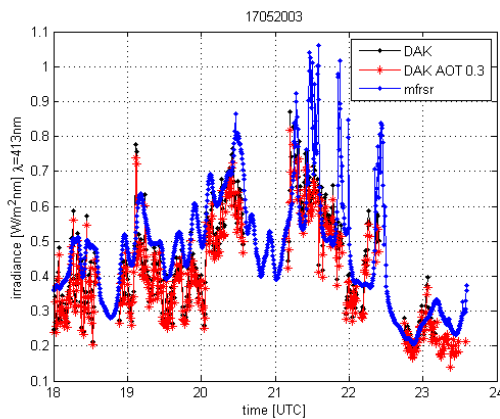


Fig 15 Comparison of MFRSR measurements (not fully calibrated!) (blue) and DAK simulated (using the optical retrievals) irradiances  $[W/m^2 \text{ nm}]$  for different aerosol optical thickness (AOT), AOT=0.3 red line, AOT=0 black line.

So far no detailed evaluation studies have been done yet by using this approach, because the MFRSR data are not fully calibrated. The MFRSR is an adequate instrument to derive accurate values of transmittance without an absolute

calibration and this work is in progress in order to evaluate the retrieved droplet concentration using the optical properties of the cloud layer.

## 5.2 In-situ observations

A more accurate evaluation of the quality of the products, also in consideration of the assumed droplet size distribution, will be analyzed by using aircraft in-situ measurements of water clouds. On the basis of an 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). In four different flight mission simultaneous Raman lidar, cloud radar and microwave radiometer measurements at three different observation sites located in Southern Germany in the period of July 2007 could be coordinated. These data will be used for a detailed intercomparison of the in-situ and ground based measurements in order to validate the observations and to optimize the retrieval technique. Furthermore the validation process will be extended through an aircraft measurement campaign in Cabauw, Netherlands in May 2008 organized within the framework of EUCAARI (European integrated project on aerosol cloud climate air quality interactions).

## 6. CONCLUSIONS AND OUTLOOK

The application of the introduced retrieval technique of droplet concentration showed that an adiabatic assumption for this water cloud case would result in unrealistic, huge values of droplet concentration. The consideration of the sub-adiabatic structure of the cloud, which is closer to reality, is improving the quality of the retrieved cloud microphysical and optical properties. The sensitivity analysis pointed out that especially the degree of sub-adiabaticity (Fr) and the quality of the radar

observations are the main uncertainties in the retrieval technique.

Therefore two evaluation studies are in progress in order to improve the quality of the input data and to enhance the model assumption. The closure experiment on the basis of radiation transfer calculations will be used to draw conclusions from the optical thickness to the retrieved droplet concentration, because of the determined sensitivity. The in-situ data will be analyzed in order to improve the quality of the ground-based remote sensing based input parameter. In-situ measurements of droplet size distributions will approve the model assumptions of the fixed size distribution and breadth parameter.

Altogether the enhanced droplet concentration retrieval product could be related to aerosol, vertical forcing and radiation measurements in order to cover the whole chain of processes related to the first indirect aerosol effect.

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