Intercomparison of various cloud radar-based retrieved water cloud properties

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ABSTRACT

Cloud radar based retrievals of liquid water content (LWC) are mainly based on form in-situ measurements, from which the relationship between radar reflectivity (Z) and LWC is obtained. In this study three different Z-LWC relationships have been applied on a water cloud case to retrieve the LWC. Furthermore the integrated LWC from cloud base to top has been compared with microwave radiometer derived liquid water path (LWP). The comparison results in large underestimations of the measured LWP, which could not be explained by drizzle effects or radar calibration. The underestimation is varying with time, which indicates that the microphysical properties are changing and influencing the Z-LWC relationships. The microphysical properties are varying with cloud dynamics and turbulence, like mixing and entrainment processes. These effects have been analyzed using the vertical variance of mean doppler velocity. The turbulence explains the variability of the underestimation with time, but the great difference between the retrievals and measurements are still under discussion.

1. INTRODUCTION

One of the most basic properties to describe the microphysical status of a water cloud is the LWC. The liquid water or the vertically integrated value LWP of warm boundary layer clouds is one of the most important parameters to quantify the radiative impact, because small changes have a great impact on the radiative fluxes [11]. Therefore an accurate retrieval of cloud liquid water is essential and it requires the improvement of various LWC retrievals.

The LWC can be retrieved directly from aircraft or indirectly from ground-based remote sensing measurements. Observations of millimeter-wave radars have been indispensable for studying microphysical properties of low level water clouds. A number of remote sensing retrieval techniques provide either radar-only retrievals of LWC or combine millimeter-wave radar with microwave radiometer measurements [1], [2], [3], [4] and [5]. Multi-sensor approaches are generally more robust, but radar-only LWC retrievals are important, when microwave radiometer measurements are not available. The greatest uncertainty of radar-based LWC retrievals is the non-unique relationship of radar reflectivity factor and LWC, which is strongly depended on the physical mechanism of cloud evolution [7].

This paper presents the application of various radar based retrieval techniques on a case study in order to evaluate and improve the retrieved LWC and LWP. Furthermore their relation to cloud dynamics is discussed. The intercomparison of the retrieved microphysical properties using various techniques based on cloud radar observations and the additional information of the cloud dynamics could be a further step towards a better understanding of cloud-radiation interaction and elucidate the underlying physical processes behind.

2. RADAR-BASED RETRIEVAL TECHNIQUES

Under Rayleigh scattering conditions, as given for non-precipitating water clouds, the radar reflectivity factor Z is equal to the sixth moment of the droplet size distribution (DSD) and LWC is equal to the third moment of the DSD. To infer LWC from Z, commonly a power law relationship is used:

$$Z = aLWC^{b} \tag{1}$$

where the parameters a and b are constants. These parameters can be derived empirically from in-situ data of DSD. The following empirical Z-LWC relationships are used in the intercomparison analysis:

$$Z = 0.048LWC^{2} \quad \text{[1] } \textit{Atlas} \tag{2}$$

$$Z = 0.012LWC^{1.16} \quad \text{[2] } \textit{Fox and Illingworth} \tag{3}$$

$$Z = 0.03LWC^{1.31} \quad \text{[10] } \textit{Sauvageot and Omar} \tag{4}$$

Furthermore a and b can be also retrieved from a theoretical derived relation of Z-LWC assuming a DSD, whereas the sixth moment of the distribution is proportional to its third moment squared with a vertically constant droplet concentration. This relation is used in combination with microwave radiometer (MWR) observations in the well-known technique from [3] and [4]. The LWP from MWR is used to scale the LWC profile derived from radar reflectivity factor Z:

$$LWC = \frac{LWP(MWR)Z^{0.5}}{\sum_{z_{cb}}^{z_{ct}} Z^{0.5}\Delta z} \quad \text{[3], [4] } \textit{Frisch} \tag{5}$$

where Δz is the cloud depth and the summation of Z is from cloud-base (cb) to cloud-top (ct).

In this study the vertically integrated LWC values retrieved from radar-only observations (Eq. 2-4) have been compared with LWP derived from a microwave radiometer, which is considered as the ground truth in case of single layer clouds. Furthermore the Z-LWC relationships have been compared with the one derived from Frisch [3] and [4] (Eq. 5). Also the relation

© Proceedings of the 8th International Symposium on Tropospheric Profiling, ISBN 978-90-6960-233-2
Delft, The Netherlands, October 2009. Editors, A. Apituley, H.W.J. Russchenberg, W.A.A. Monna

to the cloud turbulent characteristics has been analyzed by using the mean Doppler velocity, which gives information of the cloud internal circulation structure in terms of up-and downdrafts. It can be used to analyze the internal dynamics and the interaction with the environment [8].

3. INSTRUMENTATION AND DATA

In the framework of COPS campaign (Convective and Orographically Induced Precipitation Study) in 2007 the third deployment of the Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) took place in the Murgvalley of the Black Forest region of Germany from March 2007 till January 2008. In this study, reflectivity data from the W-band (95 GHz) ARM Cloud Radar (WCAR) are used to derive LWC based on the different Z-LWC relationships (Eq. 2-5) and the mean doppler velocity to study the turbulent cloud structure.

The microwave radiometer derived LWP have been taken from the instrument HATPRO, which has been collocated with the radar and operated by University of Cologne [9]. The LWP from MWR has an uncertainty of about 20 g/m^2 and therefore it is expected to be the ground truth and used to compare and evaluate the retrievals.

4. CASE STUDY

The WCAR radar reflectivity and HATPRO LWP of the chosen water cloud case on 26th of October 2007 observed in the Murgvally of the COPS area are presented in Fig. 1

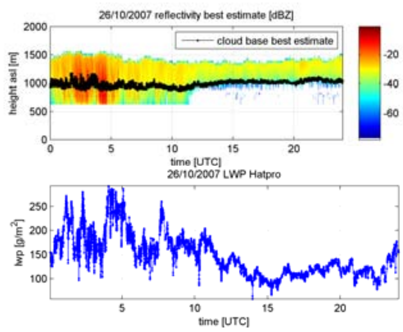

Figure 1 *WCAR Radar reflectivity [dBZ] and LWP [g/m^2] derived from MWR HATPRO.*

The observed cloud layer on this day is characterized by rain and drizzle events in the early morning hours, which lead to an increase of the geometrical thickness with time. The analysis is restricted to 12 UTC and later, because the used Z-LWC relations are only valid for non-drizzling clouds.

4.1 Radar based estimates of LWC and LWP

The LWC values derived from the radar reflectivity factor using Eq. 2-4 have been vertically integrated from cloud base to top and compared with LWP from HATPRO. The difference is shown in Fig. 2 and it can be seen that all used relations to calculate LWP are resulting in an enormous underestimation of LWP measured from MWR. The deviation is varying between -60 to -160 g/m^2 with time and all used relations show the greatest underestimation around 13, 20 and 24 UTC.

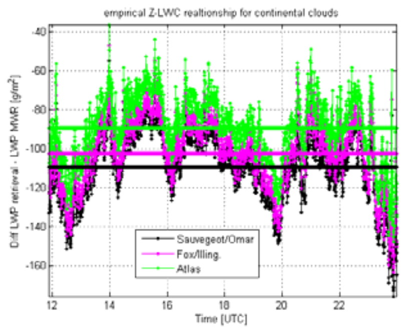

Figure 2 *Difference between retrieved LWP from radar for 3 Z-LWC relations and LWP from MWR. The continuous lines are based on the mean value of the difference.*

An important problem of radar-only retrievals, which could cause such underestimation, is related to drizzle-size droplets. They are affecting the reflectivity factor and it results in error of the radar derived water content. In this study we can exclude the influence of drizzle in the retrievals, because 96% of the radar reflectivity is below -26 dBZ, which fulfils the radar reflectivity based thresholds for drizzle. In [3] and [4] drizzle effects could be neglected when reflectivity is below -17 dBZ. Furthermore the selected cloud layer has been also identified as drizzle free from the CloudNet target classification file (Illingworth et al. 2007), which combines radar and lidar observations in order to classify the atmospheric targets. Another reason for an underestimation could be that there is LWP present below the estimated cloud base from lidar and radar observations. These contributions to HATPRO MWR observations are expected to be small and it would not explain a negative bias greater than 60 g/m^2. An important issue is the radar calibration, which could lead to differences in the Z–LWC relationship. The WCAR radar data have been compared with data from a 35.5 GHz collocated cloud radar (MIRA 36-S), which showed a 3 dB offset in reflectivity [5]. This offset could cause a difference in LWP of about 15 g/m^2, but does not explain the large underestimation of water applying standard Z-LWC relationships from literature. The Z-LWC relationship, which reproduces LWP measured from MWR and is additionally independent from radar calibration, can be derived by applying the *Frisch* method of [3] and [4] (Eq. 5). Fig. 3 shows the scatter plot of Z and LWC retrieved from method [3] and [4] (blue dots) and the used empirical Z-LWC relationships (Eq. 2-4).

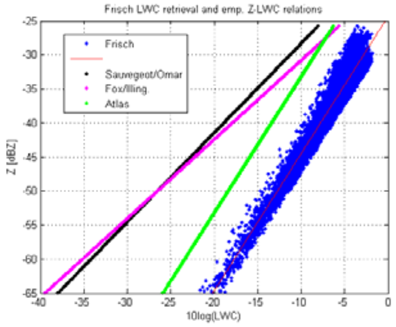

Figure 3 *LWC retrieval from Frisch (blue dots) and the empirical Z-LWC relationships from Eq. 2-4.*

The following Z-LWC relationship applying Eq. 5 has been derived:

$$Z = 0.004 LWC^2 \tag{6}$$

whereas the squared power relation (with *b*=2 in Eq. 1) is due to assumptions of the technique. The second power relation has been derived in the earlier work of Atlas [1] (Eq. 2 green line). The estimated LWP in this case results in an underestimation of around 88 *g*/m^2 in mean. The two other relations with *b*<2 (Eq. 3 and 4, black and magenta lines) are resulting in a greater underestimation of LWP from HATPRO with mean values around -100 and -110 g/m^2. All used Z-LWC relationships show a greater difference in their derived parameter a (Eq. 1), which is depending on the DSD width (σ) and droplet concentration (N):

$$Z = a(\sigma, N) LWC^b \tag{7}$$

There is a difference in factor *a* of one order magnitude between Atlas [1] relation and the one derived from Frisch (Eq. 5) [3] and [4]. In [10] a set of in-situ data of water cloud DSD is summarized and the mean coefficient for parameter *a* (Eq. 1) for continental clouds is around 0.0473, which is consistent to the one from Atlas [1] (Eq.2).

5. ANALYSIS

The statistically derived Z-LWC relations from independent in-situ data sets are not applicable for this water cloud case. The LWP measured from the ground could not be reproduced and the large deviation can not be explained only by the impact of drizzle and the radar calibration. A further link for an explanation is that the difference in LWP from HATPRO varies with time (Fig. 2), which implies that the structure of the cloud layer has been changed (possibly due to the impact of the diurnal cycle). Therefore the cloud structure and dynamics have been analyzed.

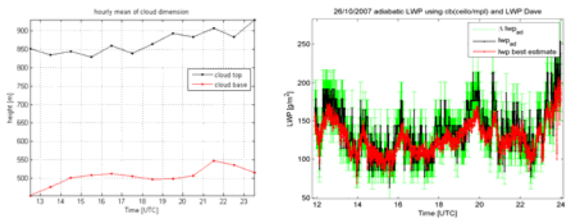

Figure 4 (left) *Averaged (1h) cloud boundaries*, (right) *LWP adiabatic and LWP HATPRO.*

Fig. 4 (left one) shows the 1 h averaged values of the cloud boundaries, which are varying within 100 m. Cloud top is ascending with time and cloud base is rising around noon and late night and relatively uniform from 14 to 20 UTC. The certain geometrical thickness and cloud base temperature and pressure from radiosoundings have been used to calculate the adiabatic LWP, which is shown in Fig. 4 on the right. When compared to LWP from HATPRO, the observed cloud layer seems close to being adiabatic, which implies a second order dependency to the geometrical thickness ($H \propto LWP_{ad}^{0.5}$). This relation has an effect on the derived LWP from the radar-based retrievals of LWC. Fig. 5 (left and right) shows that an increase of the cloud dimension results in a greater deviation between the retrieved LWP from Atlas relation [1] (Eq.2) and LWP HATPRO. The right figure demonstrates the 1h averaged cloud dimension (blue line) and the deviation in LWP (green line). The three main peaks at around 13, 20 and 24 UTC in Fig. 2 are caused by an increase of the geometrical thickness. The average underestimate is 70 (+/- 5 %) and the relative difference does not depend on the cloud thickness.

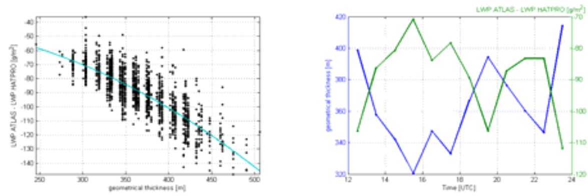

Figure 5 (left) *geometrical thickness vs. LWP Atlas – LWP HATPRO*, (right) *1 h averaged cloud dimension (blue) and 1 h averaged LWP Atlas – LWP HATPRO*.

The variability of the cloud structure can be affected by radiation cooling, cloud-top entrainment and surface fluxes, which are linked to the dynamics.

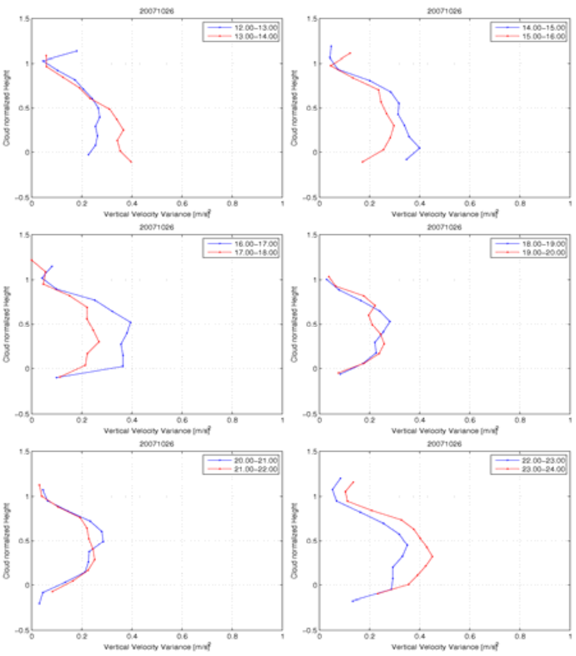

Figure 6 *1 h average of mean Doppler velocity variance in dependency of the normalized cloud height.*

Fig. 6 shows 1 h averaged vertical velocity variances of the WCAR mean doppler velocity in dependency of normalized cloud height of the whole observation period. In the first two hours form 12 to 14 UTC the turbulence activity is surface forced, because it is greater at cloud bottom. In this time window cloud base height increases (Fig. 4 left) and a maximum in LWP from HATPRO has been observed (Fig. 4 right). Afterwards the turbulence intensity develops in a double-peaked structure with a second maximum at the cloud centre. This decoupled system is often caused by solar absorption during the day. From 19 to 20 UTC the second maximum ascends to the upper part of the cloud and cloud top rises (Fig. 4 left). In this period the second peak in LWP is observed (Fig. 4 right). After 20 UTC the maximum of vertical velocity variance resolves at cloud bottom and cloud base height rises (Fig. 4 left). The maximum ascends to the upper part of the cloud, which could be caused by radiative cooling and entrainment at the top. Till midnight the turbulence activity is developing towards the centre of the cloud and it reaches its maximum. In this period LWP reaches its third maximum and the cloud dimension increases (Fig 4 left and right). The evolution of turbulence intensity due to various mechanisms (like radiative cooling, entrainment or solar absorption) dictates the cloud boundaries and persistence. Furthermore it influences the microphysical properties due to the mixing processes with entire air. This is reflected by the variability of the deviation of the retrieved LWP from measured LWP. The retrievals are based on a unique Z-LWC relation, which result, depending on the turbulence activity, in an underestimation between -60 to -160 g/m^2 with time. Although the turbulence activity explains the variability, the question about the enormous underestimation of the retrieved LWP is still open.

6. FUTURE WORK

The characterization of in-cloud turbulences looks promising for a better understanding of radar derived microphysical properties and therefore a more detailed analysis of the turbulence activity is planned (e.g. dissipation rate). Furthermore the effect of the radar calibration will be analyzed by comparing the data with the 35.5 GHz collocated cloud radar (MIRA 36-S) especially for water cloud cases. More water cloud cases will be analyzed in order to analyze the occurrence of the underestimation of LWP using standard Z-LWC relations from literature.

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