The comparative study of the relation between clouds microphysics and radar-to-lidar ratio for the different geographical regions and field campaigns

O. A. Krasnov and H. W. J. Russchenberg

International Research Centre for Telecommunications-transmission and Radar,
Faculty of Information Technology and Systems, Delft University of Technology,
Mekelweg 4, 2628 CD Delft, The Netherlands.
Ph. +31 15 2787544, Fax: +31 15 2784046 E-mail: o.krasnov@its.tudelft.nl

1. Introduction

The parameterization of the microphysical characteristics for low-level stratiform water clouds can be developed in terms, among others, of the effective radius of droplets and the liquid water content (*LWC*). These parameters can be directly measured using aircraft mounted in-situ probes observations. The instruments used to perform these measurements, however, have an extremely small sample volume. Consequently, a large number of expensive and labour intensive flights are necessary to acquire statistically reliable profiles. The remote sensing methods are less direct but give much better coverage and are much less expensive.

For the estimation of the *effective radius* of droplets r_{eff} and the *LWC*, the two properties that determine radiation transfer characteristics of water cloud, with remote sensing instruments the following procedure was proposed in (Baedi et al., 2000). The retrieval of the *effective radius* of droplets can be made with combining radar and lidar observations using a relation between *effective radius* and *radar reflectivity* Z *- to - lidar extinction* a *ratio*. This complicated dependence was derived from the drop size distributions measured with aircraft mounted in-situ probes during the CLARE'98 campaign (near Chilbolton, UK, October 1998) and fitted using piecewise-linear equation. The retrieval of the LWC was done on the basis of radar observations using *LWC-Z (LWC - Radar Reflectivity)* diagram calculated from in-situ drop size distributions. Usually such diagram shows a lot of scatter, preventing a direct derivation of the *LWC-Z* relationship. Such scatter was significantly reduced using information about effective radius of drops for filtering out distributions that have rather large values of it, and the new empirical *LWC-Z* relation was derived. For co-located and quasi-simultaneous aircraft, radar, lidar, and radiometer measurements during the CLARE'98 campaign these methods of cloud microphysics retrieval have shown reasonably good agreement between measured and retrieved cloud parameters.

The key question for the practical use of such retrieval technique is the stability of the relationship between the *effective radius* of cloud drops and the *radar reflectivity-to-lidar extinction ratio* for different geographical regions, for different cloud types, and under different meteorological conditions. In this paper the results of comparative study of such relationship using in-situ aircraft data for a few field campaigns are presented. Data for the CLARE'98 (October 1998, Chilbolton, UK, stratiform clouds), the DYCOMS-II (July 2001, Pacific Ocean near California coastal zone, stratiform clouds), the CAMEX-3 (August - September 1998, Florida, clouds in tropical storm) campaigns were analyzed. For all these field campaigns the unified procedure for calculation of the drop size distributions (DSD) from the measured with different probes data was used. Resulting merged distributions were used for the calculation of the "*effective radius* - to - *radar reflectivity-to-lidar extinction ratio*" scattering diagrams and two-dimensional histograms. The analysis of data for different campaigns shows a good agreement between their behavior on such plane and the possibility to use a joint distribution over all field campaigns for estimation of the mean $Z/a - r_{eff}$ relationship. The difficulties of the parameter estimation for piecewise-linear fitting of the mean $Z/a - r_{eff}$ relationship were shown and the possibility to use unified for all analyzed campaigns and cloud types a 4th order polynomial fitting was demonstrated. The theoretical analysis of the statistical models for the observed DSDs shown that the information about DSD position on the $Z/a - r_{eff}$ plane can be used for cloud type classification into three classes: the clouds without drizzle, the clouds with drizzle, and the drizzle clouds. The application of the developed classification technique to the representation of observed data on the *LWC-Z* plane allowed us to use different *LWC-Z* relationships for different cloud types. The previously published by (Fox and Illingworth, 1997), (Sassen and Liao, 1996), (Sauvageot and Omar, 1987), and (Atlas, 1954) relationships for the clouds without drizzle; by (Baedi et al., 2000) for the cloud with drizzle; and the new relationship for the drizzle clouds show reasonable agreement with observed data. The applicability of the remote sensing technique based on simultaneously measured radar and lidar data for the cloud's type classification and selection of the *LWC-Z* relationship was demonstrated.

2. Experimental details and instrumentation

2.1. Observational data used

2.1.1. The CLARE'98 campaign

The Cloud Lidar and Radar Experiment (CLARE) took place near Chilbolton (United Kingdom) in October 1998. This extensive cloud campaign included airborne and ground-based radar and lidar observations as well as in-situ aircraft measurements of the drop-size distributions. A C-130 aircraft 'Hercules' of the UK Meteorological Research Flight (MRF) flew through the clouds and carried particle size probes to count the cloud droplet concentrations. The instruments on board another aircraft, the Fokker 27 'Arat' owned by the IPSL (France), included a 94 GHz radar 'Kestrel', and a 532 nm lidar 'Leandre'. The aircraft flew legs towards and away from the Chilbolton site and, although they had slightly different velocities, the idea was that they should pass overhead Chilbolton at the same time for the benefit of simultaneous ground-based measurements. The duration of each leg was about 10 minutes, which corresponds to approximately 60 km. The ground-based instruments at the measuring site consisted of, among others, a 95 GHz vertically pointing radar 'Miracle' of the GKSS (Germany) and the 93 GHz radiometer, which was operated by the Rutherford Appleton Laboratory in England. A detailed description of CLARE98 can be found in (Wursteisen and Illingworth, 1999) and (Illingworth et al. 1999).

During CLARE98 the particle size spectra were measured with a Forward Scattering Spectrometer Probe (FSSP) and a Two-Dimensional Cloud probe (2DC). A Johnson-Williams (J/W) sensor measured the cloud liquid water content. The FSSP measured the cloud droplets in the size range of 1 μm to 23.5 μm radius. The particles were sized in 15 radius bins of 1.5 μm each. The 2DC-probe imaged cloud particles in the size range of 6.25 μm to 406.25 μm radius, which were sized in 32 radius bins of 12.5 μm each. Both probes produced a particle size distribution every 5 seconds.

2.1.2. The DYCOMS-II campaign

The DYCOMS-II field campaign (Stevens et al., 2002) took place in July 2001 in Pacific Ocean near California coastal zone around the point with geographical coordinates (122° W, 31° N). It was directed to collect data to study nocturnal marine stratocumulus and to test large-eddy simulations of theirs. The main measuring part of campaign was made during 10 research flights (RF) of the National Center for Atmospheric Research (NCAR) Research Aviation Facility (RAF) aircraft EC-130Q. On this aircraft are installed instrumentation for acquiring data in support of various facets of atmospheric research. Cloud droplet spectrums were measured using a big set of probes: the PMS - PCASP 100 (counting particles with diameters 0.09 - 3 μm in 31 bins with sizes from 0.01 up to 0.4 μm); the PMS-FSSP-100 (counting particles with diameters between 1 to 47 μm in 41 bins with equal sizes 1.153 μm); the PMS-FSSP-300 (counting particles with diameters between 0.3 to 20 μm in 31 bins with sizes from 0,05 up to 3 μm); the PMS-260X (counting particles with diameters between 15 to 645 μm in 64 bins with sizes 10 μm); the PMS-2DC (counting particles with diameters between 17 to 792 μm in 32 bins with sizes 25 μm); and the PMS-2DP (counting particles with diameters between 17 to 1592 μm in 64 bins with sizes 25 μm). For this study data from the PMS-2DC and the PMS-2DP were not available yet. For in-situ measurements of LWC on aircraft two King hot-wire probes, that were installed on different wings, and the Gerber's Particulate Volume Monitor PVM-100A were used. All available data are presented as time series with 1 sec. interval of averaging.

For this study we used preliminary data for some research flights that were selected after analyzing of flight descriptions and data quality reports for each probes. Only working legs were used, and filtration out of all samples with altitudes outside clouds was made using the LWC profiles from the Gerber PVM-100A.

2.1.3. The CAMEX-3 campaign

The third field campaign in the Convection And Moisture Experiment series (CAMEX – 3) took place in Florida coastal zone in August 6 - September 23, 1998. The objective of the field program was the data collection for research in tropical cyclone development, tracking, intensification, and landfalling impacts using NASA-funded aircrafts ER-2 and DC-8 and ground-based remote sensing. During campaign were successfully studied Hurricanes Bonnie, Danielle, Earl and Georges. For this study it was important that all research flights took place in strong cumulus clouds that were the part of topical storms. For the measurement of the cloud drop size distributions were used FSS (counter drops with diameters between 0.42 and 23.67 μm in 13 bins) and 2DC (counter drops with diameters between 17.75 and 762.50 μm in 10 bins) probes that were mounted on the DC-8 aircraft. The spectrums in available datasets (http://ghrc.msfc.nasa.gov/camex3/) are represented as time-series with 60 sec. averaging. For this study were used data for research flights that took place August 15, 20, 21,23, 24, 26, 29, and 30, 1998.

2.2. In-situ clouds particle spectrums data processing and analysis

The presented above descriptions of field campaigns and their instrumentation show that in order to obtain a complete cloud drop sizes spectrum, the measured by a few individual particle probes distributions have to be merged. There are some possible techniques for such merging (see, for example, (Baedi, de Wit and Baptista, 1999)). For this study the simplest technique was used: all spectrum probes that have been taking into account for a given platform were assumed on an equality with others. For every bin of every probe was calculated its middle size and counted concentration was normalized by the bin's width. Then all bins for all probes were combined together and rearranged in increasing order of their middle size values. Resulting grid of middle sizes was used for estimation of the values for new borders of bins - as half distance between neighbor bin's centers. Such approach gives possibility to include in calculations all available data without any a priori assumption about shape of drop size distribution. Any moments of the resulting drop size distribution can be calculated as numerical integrals for tabulated function. It is necessary to note that before merging from every probe for every platform/campaign were removed first and last bins as possible sources of error information (Francis, 1999).

Since this paper only deals with liquid water clouds, it is possible to assume that for radar observations the spherical drops act as Rayleigh scatterers, while for lidar observations they approximately act as optical scatterers. In that case, various cloud parameters can be computed from the particle size spectra using the following equations:

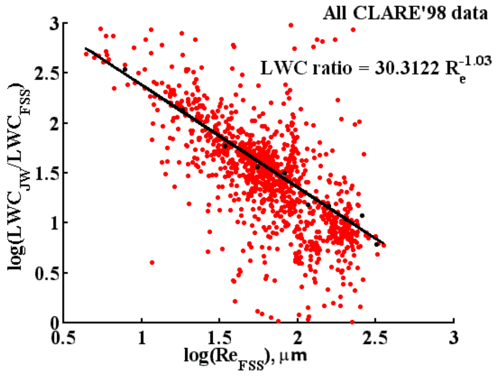

Fig. 1. The ratio of LWC measured with Johnson-Williams probe to LWC calculated from merged DSD versus the DSD's effective radiuses.
The Correlation Coefficient = - 0.68

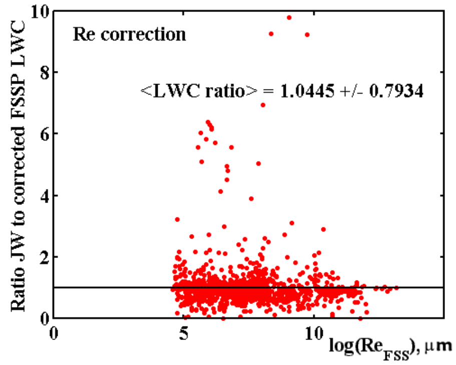

Fig. 2. The ratio of LWCs measured with Johnson-Williams probe to calculated from merged DSD versus the DSD's effective radius after correction of FSSP bin sizes.

Radar reflectivity:

$$z = 64 \cdot \sum_i N_i \cdot r_i^6 \cdot \Delta r_i\,, \qquad [mm^6 \cdot m^{-3}] \qquad (1)$$

Lidar extinction cross-section:

$$a = 2 \cdot p \cdot \sum_i N_i \cdot r_i^2 \cdot \Delta r_i \cdot 10^{-6}\,,\ [m^{-1}] \qquad (2)$$

Liquid water content:

$$LWC = \frac{4 p r_w}{3} \cdot \sum_i N_i \cdot r_i^3 \cdot \Delta r_i \cdot 10^{-6}, [g \cdot m^{-3}] \ (3)$$

Effective radius:

$$r_e = \frac{\sum_i N_i \cdot r_i^3 \cdot \Delta r_i}{\sum_i N_i \cdot r_i^2 \cdot \Delta r_i} \cdot 10^3,\ [mm] \qquad (4)$$

where r_w is the density of water in $[kg \cdot m^{-3}]$, N_i is the normalized by bin width number of particles measured in i[th] bin $[m^{-3} \cdot mm^{-1}]$, r_i and Δr_i are the mid-radius and width of i[th] bin $[mm]$.

It is known fact that liquid water content estimated from the size spectrum probes is significantly different from the LWC measured with the Johnson-Williams, King and Gerber PVM sensors. At the present it is not clear what exactly caused this difference. However, it is suggested usually that the sampling volume of the FSSP may depend on the size of the cloud droplets (Dye and Baumgardner, 1984); (Brenguier et al. 1998). One possible method for the correction of the FSSP concentrations was developed in (Baedi et al. 1999) and was used in (Baedi et al., 2000). This method uses for the estimation of sample volumes for the different FSSP bins the assumption about possibility to represent observed DSD as gamma distribution with a priori known shape parameter. Such assumption are questionable after (Krasnov and Russchenberg, 2001) where the limitations of the simple statistical models like gamma or log-normal distributions for the representation of cloud's DSD were shown. These simple models can be used for representation of cloud DSD whenever its radar reflectivity is less then some threshold value (-30 dB for the CLARE'98 campaign). Otherwise, the mixture of distributions as the model for DSD representation has to be used.

The analysis of the CLARE'98 in-situ data shows a strong functional dependence between the ratio of LWC that was measured with Johnson-Williams probe to LWC that was calculated from merged droplet spectrums, and effective radii of merged spectra (see Fig.1). This dependence can be written as

$$LWC\ ratio = \frac{LWC_{Johnson-Williams}}{LWC_{DSD}} = a \cdot r_{eff}^b\,, \ (5)$$

For the estimation of unknown parameters a least-squares criterion for best fit of logarithmic representation of observed data to a linear relation was used. The results of estimation show that the exponent parameter b has quite close to -1 values for all the CLARE'98 research flights in the water clouds.

Some methods that use this dependence for the correction of measured drop size distribution were analyzed. For the assumption that analyzed relationship is the result of the size dependence of bin's sample volumes it follows that the biggest correction coefficients have smallest bins. But in these bins biggest concentrations were observed. As result, after correction of DSD the total concentration is increased in some times and reaches the unreasonable high values. The total concentrations that were measured with FSSP and 2DC probes during the CLARE'98 campaign have reasonable values for stratocumulus clouds. Based on this information we decided to use for the CLARE'98 data the correction algorithm that conserves the total measured concentration. Such correction algorithm is based on the assumption that observed dependence between effective radius of cloud drops and ratio of Johnson-Williams to DSD's LWCs is formed by difference in true and measured (tabulated) the mid-radius and width of FSSP's bins, i.e.,

$$R_{FSSP} = f(R)\ ,\ \ N_{FSSP}(R) = N_{true}(R)\,. \qquad (6)$$

From this assumption that measured with the FSSP concentration is correct, it follows

$$LWC\ ratio(R) = \frac{R^3 N(R)}{[f(R)]^3 N(R)} = \frac{R^3}{[f(R)]^3} \quad (7)$$

and

$$R_{FSSP} = f(R) = R \cdot [LWC\ ratio(R)]^{-1/3}. \quad (8)$$

The resulting correction method can be written as

$$R_{true} = R_{FSSP} \cdot \sqrt[3]{LWC\ ratio(R_{FSSP})}\ ,$$
$$N_{true}(R) = N_{FSSP}(R_{true}) \quad (9)$$

The application of this method for the DSD correction was realized as follows. The parameters of relationship (5) for the complete CLARE'98 data set for water clouds were estimated. A least-squares criterion for best fit of logarithmic representation of the observed data to a linear relationship was used. The estimated parameters were used in (9) for calculation of the new sizes for lower and upper bounds of every FSSP's bin. From these new values of boundary sizes the new mid-radius and width of every bin were calculated. This values we used for normalization of drop concentration in every bin, merging DSDs from the FSSP and 2D-C, and calculations of moments.

The resulting dependence of LWCs ratio versus effective radius of cloud drops after such correction is presented on Fig. 2. The mean value of the resulting ratio of LWC is quite close to the unity and there is no dependence between this parameter and effective radius of cloud drops.

This developed method for the correction of DSD is empirical, based on the analysis of specific measured data set. It is necessary to be wary with it application to data set from other campaigns, platforms, and in-situ probes. In this work we used this method only for correction of the cloud drops spectrums that were measured during CLARE'98 campaign.

2.3. The cloud microphysics retrieval method

The method for cloud microphysics retrieval that was used for this study, was described in (Baedi et al., 2000). In that work, based on CLARE'98 campaign dataset, the piecewise-linear (in logarithmic scale) relation between *effective radius* r_{eff} and the *ratio* Z/a *of radar reflectivity* Z *- to - lidar extinction* a were investigated and fitted. This relationship was calculated from the in-situ observed with aircraft's probes drop size distributions for water clouds. The *ratio* Z/a *of radar reflectivity* Z *- to - lidar extinction* a can be written in form

$$\frac{Z}{a} = \frac{64}{2p} \cdot \frac{\langle r^6 \rangle}{\langle r^2 \rangle} \quad (10)$$

The estimated piecewise-linear relationship was used for the retrieval of the effective radius of drops in water clouds. The possibility to use this information for estimation of linear fitting for the $Z - LWC$ relation in water cloud was shown. For such estimation the procedure of filtering out drop size distributions with effective radius that is bigger than experimentally estimated pre-determined value (in that work was used 10 μm) was used.

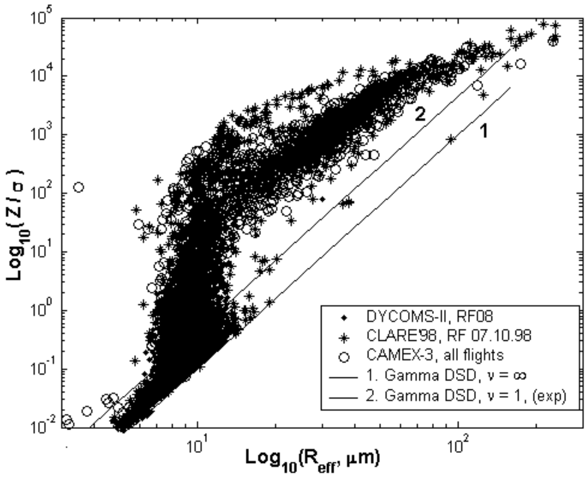

Fig. 3. The Radar to Lidar Ratio versus the Effective Radius for the CLARE'98, DYCOMS-II, and CAMEX - 3 campaigns data

This procedure has physical meaning as filtering out all drop size distributions with significant drizzle fraction. As result, such procedure significantly reduces the scattering in the empirical $Z - LWC$ relationship. The remaining after such filtration drop size distributions were used for the estimation of the coefficients for linear fitting of the $Z - LWC$ dependency.

3. Observational results

Following (Baedi et al., 2000), for all three campaigns the merged drop size distribution data were investigated using scatter plots on the "Ratio of Radar Reflectivity - to - Optical Extinction versus the Effective Radius" ($Z/a - r_{eff}$) plane. The resulting graph is presented on Fig. 3. The important conclusion that follows from this representation is: all data that were measured in different geographical regions, inside different types of water clouds, and during different field campaigns with different sets of the cloud's particle probes have the similar behavior. It means that observed dependence has stable character and can be used as background for the development of cloud microphysics retrieval algorithm.

For better understanding and interpretation of this plot it is necessary to make some remarks. Usually for the representation of the cloud drop size distributions the standard statistical probability functions with similar shapes is used. In many publications the different modifications of gamma probability density functions were applied. Such representation of DSD can be written in form:

$$N(D) = \frac{N_0}{D_{m,gam}^n \cdot \Gamma(n)} \cdot D^{n-1} \cdot e^{-\frac{D}{D_{m,gam}}},\ D \geq 0 \quad , (11)$$

where $\Gamma(n)$ - the gamma function, n and $D_{m,\ gam}$ - shape and scale parameters of gamma distribution. Using equations for the moments of this distribution (see, for example, (Krasnov and Russchenberg, 2000)), the relation

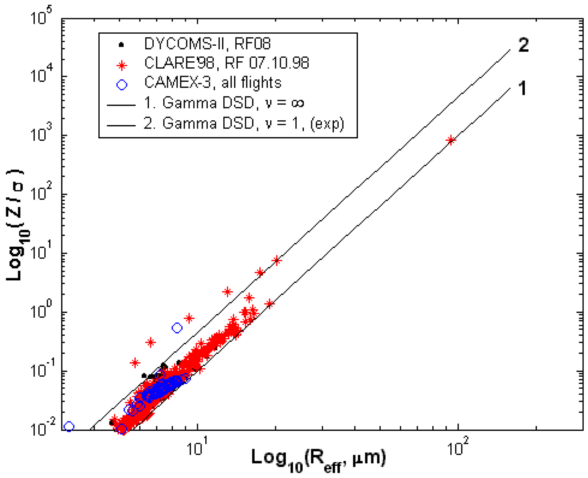

Fig. 4. The Radar to Lidar Ratio versus the Effective Radius for the CLARE'98, the DYCOMS-II, and the CAMEX - 3 campaigns after filtering out sample with reflectivities that exceed threshold values:
for the CLARE'98 campaign data - $Z \le -30\ dB$,
for the CAMEX-3 campaign - $Z \le -60\ dB$, and
for the DYCOMS-II campaign $Z \le -25\ dB$.
The best fit equation:

$$\log_{10}(Z/a) = 4.6363 + 3.842 \cdot \log_{10} r_{eff}\ .$$

1 – the relation for gamma-distribution with $n \to \infty$

$$\log_{10}(Z/a) = 4.992 + 4.0 \cdot \log_{10} r_{eff}\ ;$$

2 – the relation for exponential distribution

$$\log_{10}(Z/a) = 4.3442 + 4.0 \cdot \log_{10} r_{eff}\ .$$

between radar-to-lidar ratio and effective radius of drops can be expressed as:

$$\frac{Z}{a} = \frac{64}{2p} \cdot \left[\prod_{i=2}^{5} \left(1 + \frac{i}{n}\right)\right] \cdot r_m^{\ 4} = \\ = \frac{64}{2p} \cdot \frac{(n+3)\cdot(n+4)\cdot(n+5)}{(n+2)^3} \cdot r_{eff}^4 \qquad (12)$$

For $n = 1$ equation (11) describes the exponential model for the drop size distribution. For the other type of the model drop size distribution – log-normal, that is also widely used in the publications for the representation of water clouds DSD:

$$N(D) = \frac{N_0}{D \cdot s_{\log} \cdot \sqrt{2 \cdot p}} \cdot e^{-\frac{[\ln(D/D_{m,log})]^2}{2 \cdot s_{\log}^2}}, \qquad (13)$$

$$D \ge 0$$

where $s_{\log}$ and $D_{m,\log}$ - shape and scale parameters of the log-normal distribution, the $Z/a - r_{eff}$ relationship can be written as:

$$\frac{Z}{a} = \frac{64}{2p} \cdot \exp\left(14 \cdot s_{\log}^{\ 2}\right) \cdot r_m^{\ 4} = \\ = \frac{64}{2p} \cdot \exp\left(6 \cdot s_{\log}^{\ 2}\right) \cdot r_{eff}^4 \qquad (14)$$

It can be seen that for these model distributions exist the 4th power relationship between the Z/a ratio and effective radius r_{eff}. Two of such relationships that were calculated for extreme values of the gamma distribution's shape parameter n ($n = \infty$, that correspond to d - function-like gamma distribution, and $n = 1$, that correspond to exponential distribution) are also shown on the Fig. 3.

The comparison of observed data with theoretical lines shows that the behavior of the $Z/a - r_{eff}$ relationship for observed data has a complicated difference with theoretical power relationship of 4th order. Only the part of presented scatter plot with lowest value of the Z/a ratio can be described in terms of the simple statistical distributions. This result has good agreement with (Baedi et al., 2000) and (Krasnov and Russchenberg, 2001), where were demonstrated that representation of the drop size distribution as gamma probability density function is possible only for distributions that have radar reflectivity less then some threshold level. For data that were measured during the CLARE'98 campaign this threshold level estimated as -30 dB. The scatter plot of the $Z/a - r_{eff}$ relations for the distributions from which was filtered out samples that described reflectivity more then specified threshold value Z_0 is represented on Fig. 4. For the CLARE'98 data set Z_0 is equal -30 dB, for the CAMEX-3 data Z_0 = -60 dB, and for the DYCOMS-II campaign's research flight RF08 Z_0 = -25 dB. It can be seen that all presented points are placed inside the region of the applicability of gamma drop size distribution. Difference between threshold values for the different campaigns can be explained with assumption of different nature of observed clouds. For the DYCOMS-II campaign's research flight RF08 there were stratiform clouds without drizzle mode, for the CLARE'98 there were stratiform clouds with drizzle, and for the CAMEX-3 there were strongly convective clouds with prevalent drizzle mode. Such dependence can be the subject for the detail investigations in future - there is possibility to use threshold value of radar reflectivity Z_0 that describes upper limit of the applicability of the gamma distribution for representation of complete DSD in water cloud as parameter for cloud type classification.

For the explanation and theoretical representation the complicated behavior of the observed DSD on the $Z/a - r_{eff}$ plane in (Baedi et al., 2000) the model drop size distribution as mixture of gamma and exponential distributions was used. Such mixed DSD demonstrates the $Z/a - r_{eff}$ relationship that is similar to observed data.

There was not found the analytical representation of the $Z/a - r_{eff}$ relationship for mixed distribution. For parameterization of such dependence the piecewise-linear fitting of observed during the CLARE'98 campaign data was used:

$$\log_{10}\left(\frac{Z}{a}\right)=\begin{cases} -4.60+4.06\cdot\log_{10}\left(r_{eff}\right), & Z<-35dB \\ -34.93+40.20\cdot\log_{10}\left(r_{eff}\right), & \log_{10}(Z/a)<1.7 \\ -0.49+2.40\cdot\log_{10}\left(r_{eff}\right), & \log_{10}(Z/a)\geq 1.7 \end{cases} \qquad (15)$$

For this study a different methods for merging and calibration of measured during the CLARE’98 campaign drop size distributions were used and for all three campaigns data was made the try to estimate values of the coefficients for best piecewise-linear fitting of observed data. It was found that such estimations are very strongly depending on the method for the $Z/a - r_{eff}$ plane division for separate regional linear fitting. For example, for the separation of linear-like relation with the very strong $Z/a - r_{eff}$ dependence around $r_{eff} = 10\,mm$ from more horizontal-like tail area were used a few equations for the linear boundaries of regions and the followed estimations of the linear fitting $\log_{10}(Z/a) = a\cdot\log_{10}\left(r_{eff}\right)+b$ were calculated: $a = 18\ldots71$ and $b = -18\ldots-68$. These very broad distributions of the results and absence of the theoretical basis for the $Z/a - r_{eff}$ plane division means that such piecewise-linear fitting is relatively voluntary.

As the alternative of such approach was made the try to estimate possibility to find high order polynomial fitting that is stable for all campaigns in whole area of interest on the plane $Z/a - r_{eff}$ ($-2 \leq \log_{10}(Z/a) \leq 5$, $-0.5 \leq \log_{10}\left(r_{eff}\right) \leq 2.5$). Using MATLAB function for polynomial fitting the reliable solution for the $r_{eff} = F(Z/a)$ dependency was found as a 4th order polynomial:

$$\begin{aligned}\log_{10}\left(\mathrm{r_{eff}}\right) = &-0.0027\cdot\left(\log_{10}(\mathrm{Z}/a)\right)^4 + \\ &+0.026\cdot\left(\log_{10}(\mathrm{Z}/a)\right)^3 - \\ &-0.0094\cdot\left(\log_{10}(\mathrm{Z}/a)\right)^2 + \\ &+0.0098\cdot\left(\log_{10}(\mathrm{Z}/a)\right)+0.99\end{aligned} \qquad (16)$$

The point of curve inflection is $\log_{10}(\mathrm{Z}/a) = 0.124$, $\log_{10}\left(r_{eff}\right) = 0.991$. For $\log_{10}\left(r_{eff}\right) > 1.1$ this curve can be fitted by linear function, that are practically equal to third equation in (15). For $\log_{10}\left(r_{eff}\right) < 0.95$ the same procedure gives the best linear fitting that was determined from observed data with $Z \leq -35$ dB:

$$\log_{10}(Z/a) = 4.6363 + 3.842\cdot\log_{10} r_{eff} \qquad (17)$$

According to our analysis, the best procedure for filtering out of the observed DSDs that described the clouds without drizzle is the estimation of their position on $Z/a - r_{eff}$ plane relatively the theoretical line for exponential DSD. The points that represent gamma-like drop size distributions are placed beyond this linear dependence, but above such line for the d -function-like distribution. This criterion has clear theoretical explanation and shows much better stability then criterion that uses the comparison of observed radar reflectivity with some threshold value, that can vary from campaign to campaign and/or between cloud types, as it was shown above.

The equation (16) is presented on Fig. 5 where it is depicted with two-dimensional histograms of observed data for all campaigns together (Fig. 5a) and for every campaign separately (Fig. 5b, c, d). From these representations it can be seen that the estimated using joint two-dimensional histogram for all campaigns data equation (16) has reasonable good agreement with the CLARE’98 and the DYCOMS-II data for stratiform clouds. For cumulus clouds that were observed during the CAMEX-3 campaign the noticeable difference in the region of maximal variability of the Z/a ratio can be seen. For this campaign observed values of effective radius of cloud drops in this region for a given Z/a ratio are sifted to lowest values. This fact can be explain as natural difference of the stratiform and cumulus clouds – in cumulus clouds the drizzle mode has biggest concentration and has to be taken into account for drop size distributions that have smallest effective radiuses.

As result can be made the conclusion that the investigated in (Baedi et al., 2000) behavior of the observed DSD on the $Z/a - r_{eff}$ plane is relatively stable. The variations in empirically estimated parameters for different geographical regions, field campaigns, and different types of cloud are reasonable small. For the description of this dependence can be used a 4th order polynomial or piecewise-linear relationships. For lowest region that describes the particles distributions for the cloud without drizzle, and for region with highest values of the Z/a ratio that describes the drizzle clouds, both of these approaches give the similar results. There are difference in the linear and nonlinear equations in the region of biggest variability of the Z/a ratio – from –1.0 up to 1.5..2, but for both of these approaches this region is characterized by small variability of effective radius of cloud drops – from 8.9 to 12.5 mm. The second important result that follows from our analysis is the possibility to classify the clouds into three types – the cloud without drizzle, the cloud with drizzle, and the drizzle cloud, using the ratio of radar reflectivity to optical extinction.

Let consider now the possible application of described above results for the parameterization of the $Z-LWC$ relation in water clouds. On Fig.6 are presented in-situ data for all three campaigns on the $Z-LWC$ plane. On the

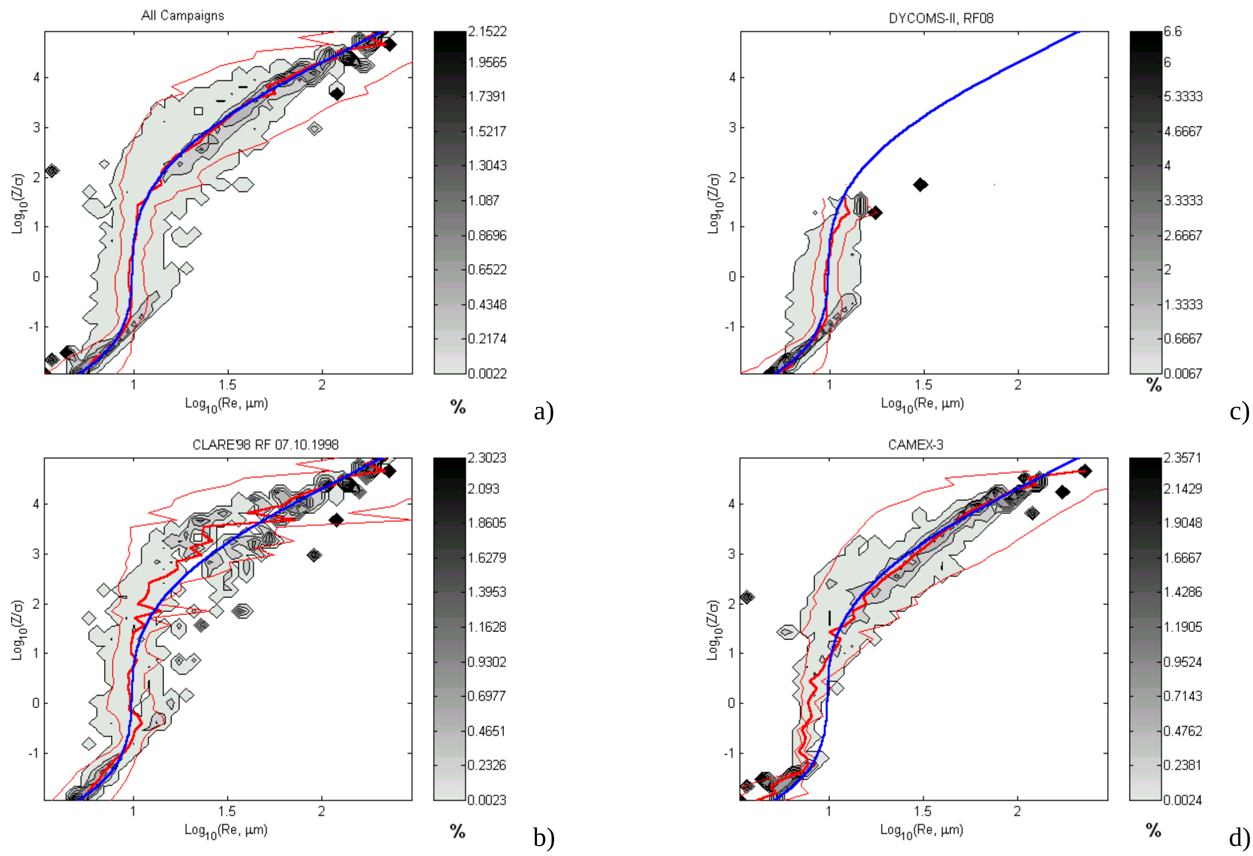

Fig. 5. Two-dimensional histograms for the observed $Z/a - r_{eff}$ relations with mean and standard deviations and their fitting using the 4th order polynomial (19): for all campaigns data (a), for the CLARE'98 RF 07.10.1998 data (b), for the DYCOMS-II RF08 data (c), and for the CAMEX-3 data (d).

same figure are presented a few known approximations for this relationship:

1. (Baedi et al., 2000):

$$\log_{10}\left(Z_{merged}\right) = 1.76 + 5.17 \cdot \log_{10}\left(LWC_{merged}\right) \quad (18)$$

2. (Fox and Illingworth, 1997):

$$\log_{10}\left(Z_{merged}\right) = \log_{10}(0.012) + 1.16 \cdot \log_{10}\left(LWC_{merged}\right) \quad (19)$$

3. (Sauvageot and Omar, 1987):

$$\log_{10}\left(Z_{merged}\right) = \log_{10}(0.03) + 1.31 \cdot \log_{10}\left(LWC_{merged}\right) \quad (20)$$

4. (Atlas, 1954):

$$\log_{10}\left(Z_{merged}\right) = \log_{10}(0.048) + 2.00 \cdot \log_{10}\left(LWC_{merged}\right) \quad (21)$$

5. Best fit of all data for the CAMEX-3 campaign and the CLARE'98's data for the drizzle clouds:

$$\log_{10}\left(Z_{merged}\right) = 2.51 + 1.58 \cdot \log_{10}\left(LWC_{merged}\right) \quad (22)$$

It can be seen from Fig. 6 that equations (19) - (21) describe only the clouds without drizzle, the equation (18) can be applied for the clouds with drizzle, and the equation (22) – for the drizzle clouds. The precision of these

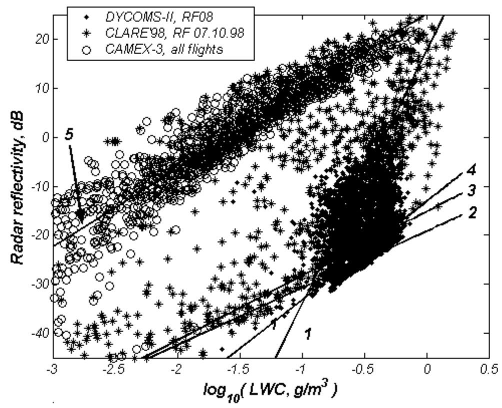

Fig.6. The relation between measured Liquid Water Content and Radar Reflectivity for different field campaigns. Lines represent the different linear fittings of this relation (see text).

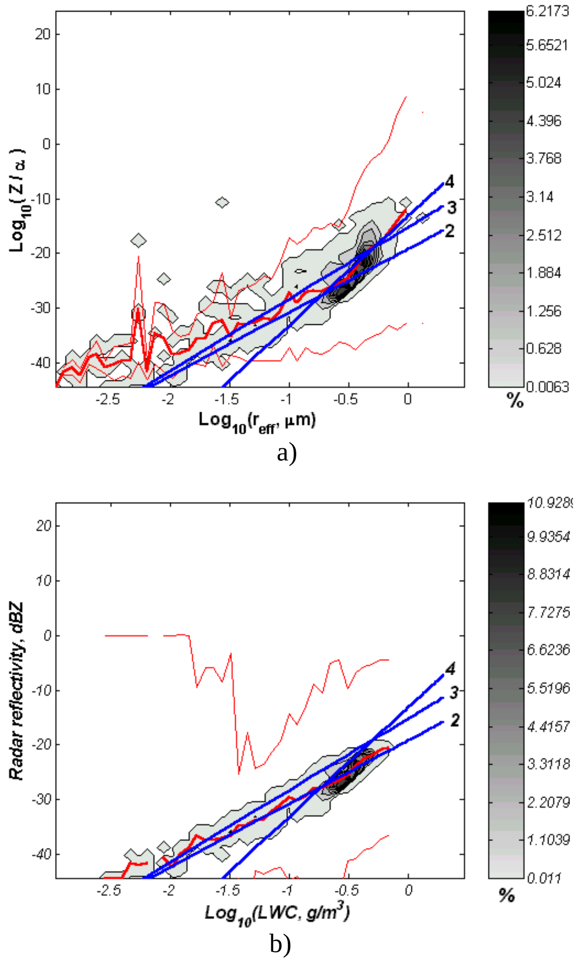

Fig. 7. Two-dimensional histograms for the $Z-LWC$ relation (with mean and standard deviations and proposed linear fittings) for the clouds without drizzle that were filtered using criterion: (a) the method that suggests a priori knowledge of r_{eff} : Z/a is less then value for exponential distribution with same r_{eff} and Z < -10 dB; and (b) the method that uses only knowledge about the Z/a ratio and behavior of curve (16): $Z/a < -1$;

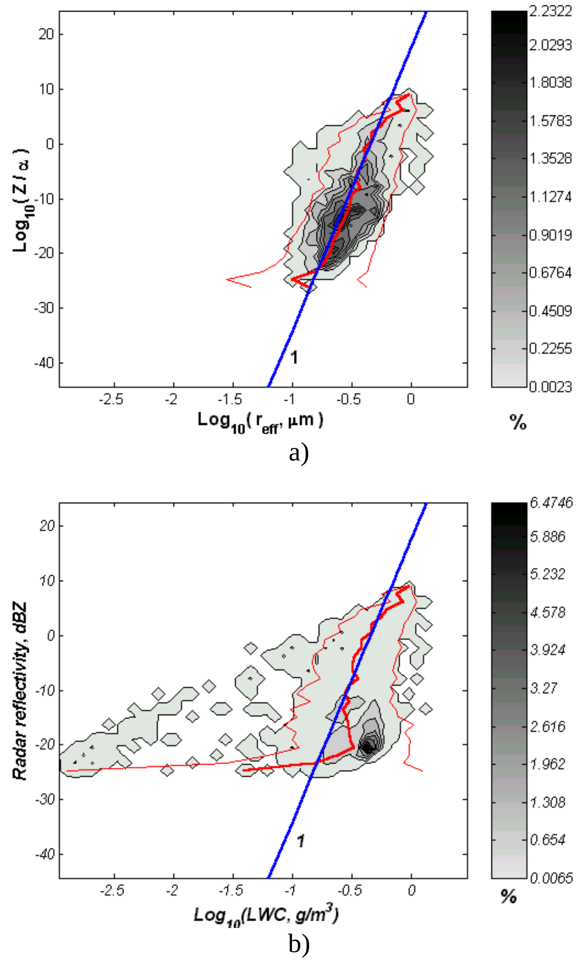

Fig. 8. Two-dimensional histograms for the $Z-LWC$ relation (with mean and standard deviations and proposed linear fitting) for the clouds with drizzle that were filtered using criterion: (a) the method that suggests a priori knowledge of r_{eff} : Z/a is more then value for exponential distribution with same r_{eff} , Z/a < 1.8, and LWC > 0.1 g/m^3, and (b) the method that uses only knowledge about the Z/a ratio and behavior of curve (16): $-1 < Z/a < 1.8$ and $Z > -25\ dB$.

approximations is not discussed here – the dependencies are clearly visible and can be fitted using different methods. The main problem that follows from the Fig 6 is how to separate these cloud types with remote sensing equipment for selection of the specific dependency (18)-(22) for every observed Z . The possibility to use for such classification the information about the $Z/a - r_{eff}$ relation for water cloud can be seen from Fig. 7, 8, and 9. On these figures two-dimensional distributions of in-situ observed DSDs that are placed on the $Z-LWC$ plane after their filtration are presented. For such classification two methods were used. The first method requires the knowledge about in-situ measured parameters - effective radius of clod drops and LWC. The second method is based on the results of radar and lidar measurements of Z/a and Z only. These methods uses follow criteria for the classification of the cloud types and the $Z-LWC$ relationships:

1. Fig. 7 represent the results of the clouds without drizzle classification:
   (a) The method that suggests a priori knowledge of r_{eff} . It uses for the classification the criterion: the ratio Z/a is less then value for exponential distribution with the same r_{eff} and Z < -10 dB.
   (b) The method that uses only knowledge about the ratio Z/a ratio and behavior of the relationship

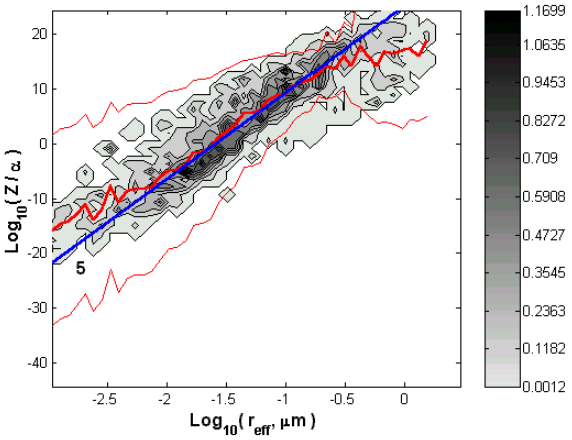

Fig. 9. Two-dimensional histograms for the $Z - LWC$ relation (with mean and standard deviations and it's proposed linear fitting) for the drizzle clouds that were filtered using criterion: Z/a > 1.8.

(16). It uses for the classification the criterion: $Z/a < -1$;

2. Fig. 8 represent the results for the clouds with drizzle classification:
   (a) The method that suggests a priori knowledge of r_{eff}. It uses for classification the criterion: the ratio Z/a is more then value for exponential distribution with the same r_{eff}, Z/a < 1.8, and LWC > 0.1 g/m^3;
   (b) The method that uses only knowledge about the Z/a ratio and the behavior of relationship (16). It uses for the classification the criterion:
   $$-1 < Z/a < 1.8, \text{ and } Z > -25\ dB.$$
3. Fig. 9 represent the results for the drizzle clouds classification. For this type of clouds the classification criterion Z/a > 1.8 for both methods is applicable.

The condition LWC > 0.1 g/m^3 in the 2a criterion for the clouds with drizzle (see Fig. 8(a)) is difficult to check using remote sensing methods, but it is not really important, because only 8.73% of distributions that are selected using the Z/a ratio values do not satisfy it. For decreasing of the influence of such distributions the additional condition $Z > -25\ dB$ was used for the remote sensing criterion 2b.

On the same figures are placed linear approximations, applicable for specific situations and it can be seen that for such methods of the clusterization the known linear approximations of the $Z - LWC$ relation are not far from reality.

From the Fig. 7, 8, and 9 follows the conclusion about the possibility to use the Z/a ratio for clusterization of $Z - LWC$ plane into sub-regions that describe the clouds with different nature and can be parameterized by different equations. Such method can be used for cloud classification and improvement of cloud microphysics retrieval technique.

4.Conclusions

Our investigation confirmed the presence of the $Z/a - r_{eff}$ complicate relationship that is stable for the different geographical locations, different field campaigns and different cloud types. Two approaches for analytical representation of such relation - using piecewise linear fitting and using 4th order polynomial fitting were discussed. It was shown that both of them have as result the similar dependencies for the clouds without drizzle and for the drizzle clouds, the main difference in fitted characteristics for the cloud with drizzle is observed - for area of biggest variation of the Z/a ratio. But for both of these approaches this region is characterized by small variability of effective radius – from 8.9 to 12.5 mm. The possibility to classify clouds into three types – the cloud without drizzle, the cloud with drizzle, and the drizzle cloud, using the Z/a ratio of radar reflectivity to optical extinction is confirmed.

The algorithms for the classification of drop size distribution and cloud's type using the measured by radar and lidar the Z/a ratio for the clusterization of the $Z - LWC$ plane were applied. It was shown that for every resulting cluster of cloud's type is possible to use specified type of the linear $Z - LWC$ relation. For the clouds without drizzle the relationships that were published in (Fox and Illingworth, 1997), (Sauvageot and Omar, 1987), and (Atlas, 1954) is applicable. For the cloud with drizzle the relationship from (Baedi et al., 2000) can be used. The drizzle clouds can be parameterized using the $Z - LWC$ dependence that was estimated in this work using the observations in convective clouds during the CAMEX-3 campaign and the CLARE'98 data for clouds with strong drizzle mode.

The results can be used for the quality improvement of the retrieval algorithms of microphysical cloud parameters that use data from ground-based or space-based remote sensing instruments, like radar and lidar.

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