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An enhanced algorithm for the retrieval of liquid water cloud properties from simultaneous radar and lidar measurements. Part I: The basic analysis of in situ measured drop size spectra

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

Abstract. The possibilities to detect and characterize the drizzle fraction in water clouds using the ratio between simultaneously measured radar reflectivity and optical extinction profiles is presented. An enhanced algorithm for the retrieval of liquid water cloud properties from simultaneous radar and lidar measurements that is based on features of this parameter is described. The study is based on theoretical calculations of remotely measurable quantities from the particle size spectra that were measured with aircraft-mounted in-situ probes during a few field campaigns, in the different geographical regions, and inside the different types of water clouds.

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. The remote sensing methods are less direct but give much better coverage and are much less expensive.

But as it was marked in many studies, especially in Fox and Illingworth (1997), there are some problems in applicability of the radar measurements alone for the retrieval of the mentioned above parameters. The main of such problems is that small number of big particles (so-called drizzle) can produce the major part of the cloud's reflectivity without strong contribution in the LWC and effective radius. A few Z-LWC relations were published in literature, but all of them are noted as applicable only for the cases of the drizzle absence. From other point of view, in many studies were noted that the presence of the drizzle fraction in water clouds is more usual than its absence (see, for example, Gerber, 1996; Fox and Illingworth, 1997). All these facts give the background for the tries to find the combination of the remotely measurable parameters, which can be used for the detection of drizzle fraction, its parameterization and taking into account in cloud's microphysics retrieval algorithm.

In this paper a retrieval technique based on the possibilities to characterize drizzle fraction in water clouds using the ratio between simultaneously measured radar reflectivity and optical extinction profiles is presented. This study is based on theoretical calculations of remotely measurable quantities from the particle size spectra that were measured with aircraft-mounted in-situ probes.

Correspondence to: O. A. Krasnov (o.krasnov@irctr.tudelft.nl)

2 Datasets and processing details

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 measurement of the drop-size distributions (DSD) (see ESA, 1999 for details).

During CLARE'98 campaign the particle size spectra in clouds were measured from the UK MRF's C-130 aircraft with a Forward Scattering Spectrometer (FSS) and a Two-Dimensional Cloud (2DC) probes in the size ranges between 1 μm and 23.5 μm radius and between 6.25 μm and 406.25 μm radius, respectively. The available data have a 5-sec interval of averaging.

2.1.2 The DYCOMS-II campaign

The DYCOMS-II field campaign took place in July 2001 in Pacific Ocean near California (Stevens et al., 2002). It was directed to collect data to study nocturnal marine stratocumulus. The main measuring part of campaign was made during 10 research flights of the NCAR's RAF EC-130Q. On this aircraft cloud droplet spectrums were measured using a set of probes: the PMS-PCASP 100; the PMS-FSSP-100; the PMS-FSSP-300; the PMS-260X; the PMS-2DC; and the PMS-2DP in the different size ranges between 0.045 and 786 μm radius. 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. The available data have a 1-sec interval of averaging.

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–September 1998. The objective of the field program was data collection for research in tropical cyclone using NASA-funded aircrafts ER-2 and DC-8, and ground-based remote sensing. For this study it was important that all research flights took place in cumulus clouds. For measurement of the cloud drop size distributions were used FSS (the size range between 0.42 μm and 23.67 μm radius) and 2DC (the size range between 17.75 and 762.50 μm radius) probes that were mounted on the DC-8. The available data have a 60-sec interval of averaging.

2.2 In-situ clouds particle spectrum data processing and analysis

The above presented descriptions of field campaigns and their instrumentation show that in order to obtain a complete cloud DSD, the distributions that were measured by a few individual particle probes have to be merged. There are some possible techniques for such merging (e.g. Baedi et al., 1999). For this study the simple method was used: all spectrum probes that had been taking into account for a given platform were analyzed on an equal basis. For every bin of every probe middle size was calculated, counted concentration was normalized by the bin's width. Then all bins for the probes were combined and rearranged in increasing order of their middle size values. The 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 the possibility to include in calculations all available data without any a priori assumptions about shape of DSD. Any moments of the resulting DSD can be calculated as numerical integrals for tabulated functions. Before the start of merging procedure from every probe's data first and last bins were removed as possible sources of error information.

Since this paper only deals with liquid water clouds, it was assumed 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 equations for the spectral moments of 2nd, 3rd, and 6th order.

3 Observational results

3.1 Cloud droplets and drizzle

In cloud physics the total DSD in water clouds usually is divided with size in two parts – small cloud droplets and big drizzle particles. The reason for such division is that their formation processes, behavior, and influence on measurable variables are different. The threshold size for division of DSD into droplets and drizzle fractions is not common and well established – most of researchers are using the values around 50 μm diameter. From other point of view the answer for this question is possible to find from the available in-situ probes datasets for different measurements campaigns.

First, it is necessary to check the existence of the statistical difference between the droplets and drizzle particles. For such study we used data that were measured during the DYCOMS-II campaign with three in-situ probes: the PMS-FSSP-100 (size range 1–47 μm diameter); the PMS-FSSP-300 (size range 0.3–20 μm diameter); the PMS-260X (size range 15–645 μm diameter). The FSSP-100 and 260X probes was mounted on NCAR's RAF EC-130Q aircraft very close one to other, and FSSP-300 was mounted under other wing, about 35 m faraway. For these probes we have analyzed the measured concentration. In despite of different size ranges and big spatial separation between two FSS probes for all available DYCOMS-II data the correlation between counted concentrations is more then 0.9. And vice versa, there is no any correlation between concentrations from FSSP-100 and PMS-260X that are placed onboard at a short distance.

Such statistical independence of the cloud droplets and drizzle particles has as result two important conclusions:

- for analytical representation of the total DSD in water clouds it is necessary to use the mixture of independent DSDs, there is no way to combine characteristics of both fractions in the framework of any united distribution, and

- the statistical independence of the droplets and drizzle gives the possibility to separate and analyze the influence of every fraction on measurable variables.

Let consider now the total DSD in water clouds, which was merged from measured with every available probe spectra using described in Sect. 2.2 procedure. Every spectrum does not give us the information how to divide it in droplets and drizzle fractions. Such information exists only in the set of all or selected with some criterion spectra. It is possible to estimate threshold size for separation of independent fractions of cloud particles using correlation function:

$$C(R_{thres}) = \frac{\left\langle F(0, R_{thres}) \cdot F(R_{thres}, \infty) \right\rangle}{\left\langle F(0, R_{thres})^2 \right\rangle^{1/2} \cdot \left\langle F(R_{thres}, \infty)^2 \right\rangle^{1/2}}, \quad (1)$$

where $F(A, B = \int_A^B Y(r) N(R) dr$, $N(r)$ is the total DSD, and $Y(r) = 1$ is any function of drop radius r. For the correlation between the concentrations in fractions $Y(r) = 1$,

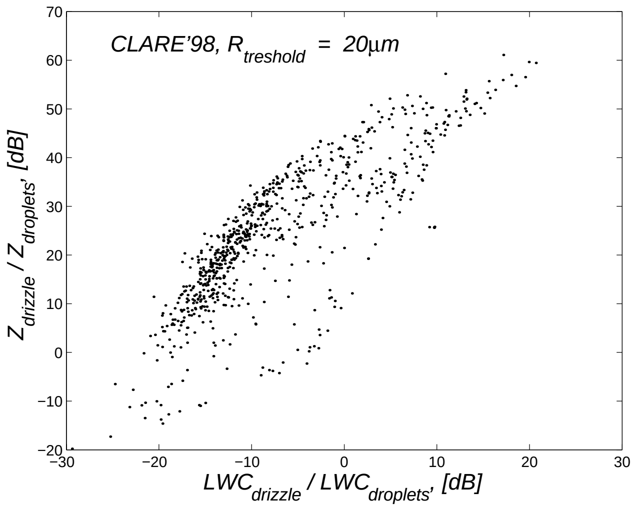

Fig. 1. The dependence between the ratio of drizzle to droplets reflectivities versus the ratio of drizzle to droplets LWCs for CLARE'98 campaign data.

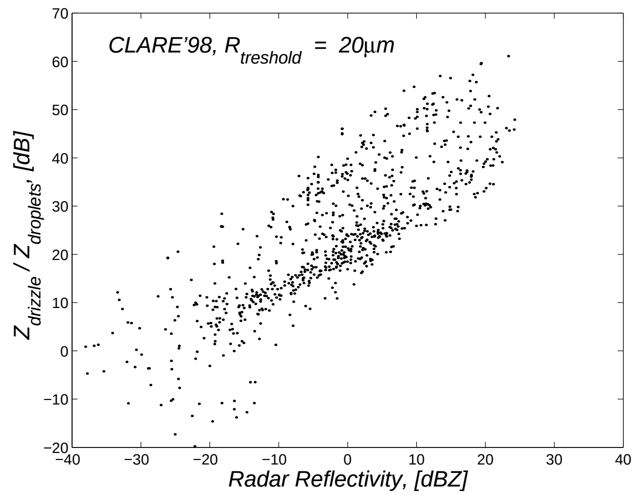

Fig. 2. The dependence of the ratio of drizzle to droplets reflectivities versus total radar reflectivity for CLARE'98 campaign data.

but it also possible to estimate the correlation between the optical extinctions, the liquid water contents, and the radar reflectivities of fractions. By the reason of the statistical independence of cloud droplets and drizzle particles, all correlation functions have additional minimum. Most clear it is visible for concentration – around 17 μm radius. For radar reflectivity such minimum is wider and coincides with radius value 20–25 μm that is most often-used in drizzle studies.

3.2 The estimation of drizzle fraction

The importance of possibilities to detect the presence of the drizzle mode in clouds and to characterize it follows from the strong influence of drizzle particles on the radar measurements. The fact that radar reflectivity is proportional to the sixth moment of DSD leads to the result that small number of drizzle particles can produce the major part of the cloud's reflectivity without strong contribution in the LWC. The illustration of this fact is presented on Fig. 1, where we plotted the ratio of drizzle reflectivity to droplets reflectivity versus the ratio of drizzle LWC to droplets LWC. It was calculated from merged spectra for CLARE'98 campaign data using threshold size 20 μm from previous section. From this graph follows that for most of the spectra the contribution of the drizzle fraction into total LWC becomes compatible with cloud droplets only when drizzle reflectivity exceeds the droplets reflectivity in 30–40 dB.

Because the reflectivity is very sensitive to the presence of big drops, the ratio of drizzle to droplets reflectivities can be selected to characterize the presence of drizzle fraction and to estimate its amount. Which remote sensing measurable quantity can be used for the estimation of such ratio? On Fig. 2 the dependence of reflectivities ratio versus total radar reflectivity is presented, and we can see that this dependence is very widely scattered – for given value of total reflectivity

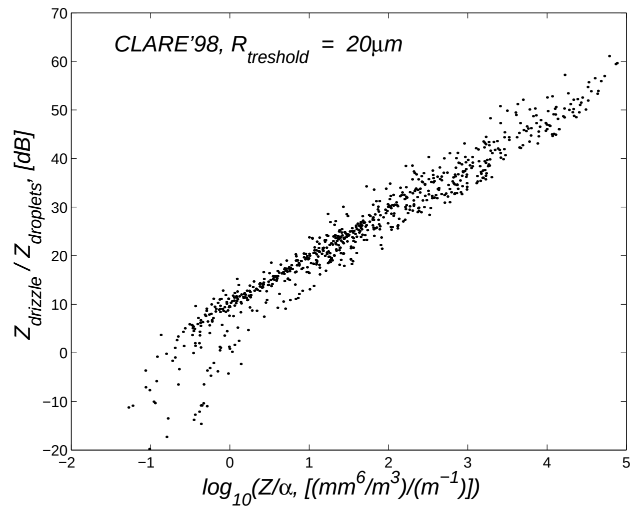

Fig. 3. The dependence of the drizzle to droplets reflectivities ratio versus the ratio of radar reflectivity to optical extinction Z/α for CLARE'98 data.

the variation in drizzle to droplets reflectivities ratio can exceed 20 dB. The conclusion that radar reflectivity alone can not characterize presence and amount of drizzle follows from this figure.

From the simultaneous and collocated radar and lidar measurements it is possible to estimate another parameter – the ratio of radar reflectivity to optical extinction Z/α. The dependence of the drizzle to droplets reflectivities ratio versus this parameter for CLARE'98 data is presented on Fig. 3. This plot shows very strong correlation between analyzed parameters, our estimations for all used in this study datasets show that such values are not less then 0.95. The conclusion is that the Z/α ratio is very sensitive to the presence of drizzle fraction and is directly proportional with strong correlation to this fraction amount.

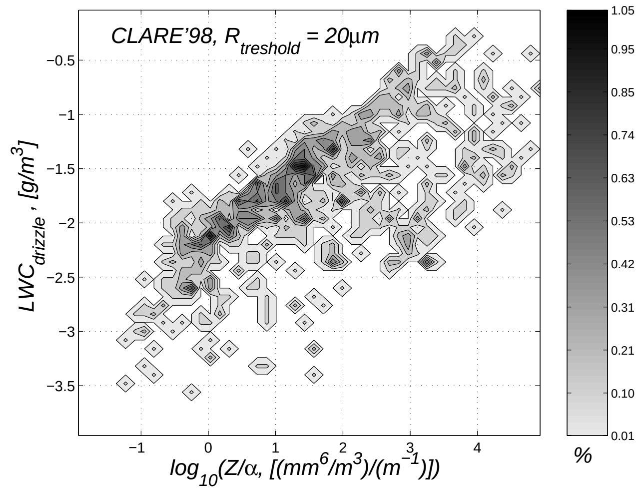

Fig. 4. The dependence of the LWC in drizzle fraction versus the Z/α ratio for CLARE'98 data.

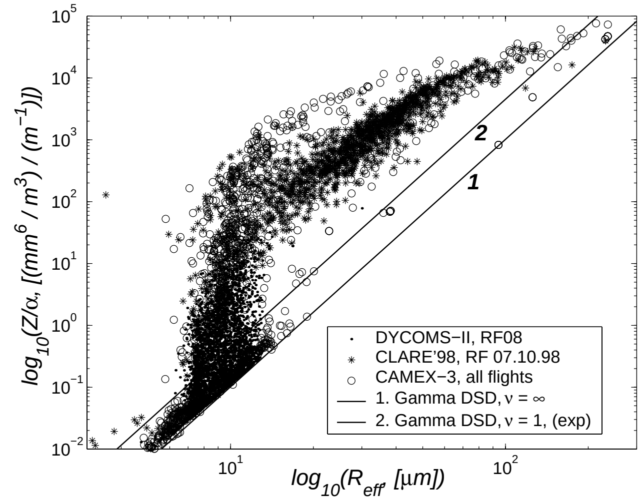

Fig. 5. The Radar to Lidar Ratio versus the Effective Radius for the CLARE'98, DYCOMS-II, and CAMEX - 3 campaigns data

On Fig. 4 the dependence of the LWC in drizzle fraction versus the Z/α ratio for CLARE'98 data is presented. It is relatively wide scattered, but the trend of direct proportionality between these two quantities is visible, especially from the behavior of mean value. Follow Gerber (1996), such representation can be used for the classification cloud with drizzle fraction into two classes – cloud with light drizzle and cloud with heavy drizzle. Because presented dependence shows the linear relationship between drizzle LWC and radar to lidar ratio, it is not clear, which threshold value of the Z/α ratio is necessary to use for such classification. Is it possible to find to find such threshold value that is based on sound arguments? The answer for this question gives the study of the relation between the Z/α ratio and the effective radius in water cloud.

3.3 The radar to lidar ratio versus effective radius

The merged drop size distribution data for all campaigns were depicted on the plane "ratio of radar reflectivity to optical extinction versus the effective radius" ($Z/\alpha - r_{eff}$) (Fig. 5). On the same plot the relationships for three parameters gamma drop size distributions with two extreme values of the shape parameter $\nu(\nu=\infty$, that corresponds to the narrow, δ-function-like gamma distribution, and $\nu=1$, that corresponds to the exponential distribution) are presented. The conclusions that follows from this representation are:

– All data that were measured in the different geographical regions, inside the different types of water clouds, and during the different field campaigns with the different sets of the cloud's particle probes have the similar behavior. It means that the observed dependence has a stable character.

– The observed data show a complicated difference with theoretical relationships for three parameters analytical distributions. Only the part of observed DSD that are characterized by lowest value of the Z/α ratio can be described in terms of the simple statistical distributions.

Detail study (Krasnov and Russchenberg, 2002) shows that the observed $Z/\alpha - r_{eff}$ relationship can be explained and described using a model of the mixture of independent statistical distributions, for example, modified gamma distribution for cloud droplets and exponential distribution for drizzle particles.

The reliable fitting equation for the $r_{eff} = F(Z/\alpha)$ dependency was found as a 4th order polynomial:

$$lg(r_{eff}) = -0.0027(lg(Z/\alpha))^4 + 0.026(lg(Z/\alpha))^3 \\ -0.0094 \cdot (lg(Z/\alpha))^2 + 0.0098 \cdot (lg(Z/\alpha)) + 0.99 \qquad (2)$$

From the analysis of the observed data for all campaigns together and for every campaign separately follows that Eq. (2) has good agreement with the CLARE'98 and the DYCOMS-II data for stratiform clouds. For cumulus clouds, which were observed during the CAMEX-3 campaign, the noticeable difference in the region of maximal variability of the Z/α ratio can be seen – the observed effective radii in that region for a given Z/α ratio are shifted to lowest values. It can be explained as natural difference between stratiform and cumulus clouds in cumulus clouds the drizzle fraction has to be taken into account for drop size distributions that have smallest effective radii.

The analysis of the observed $Z/\alpha - r_{eff}$ relationship shows that its behavior remarkably changes in two points – around $\log_{10} Z/\alpha = -1$, where influence of drizzle fraction becomes visible, and around $\log_{10} Z/\alpha = 1.8$, where very fast growing Z/α as function of the effective radius changes into slow. The last point can be used as threshold value for classification of the drizzle fraction into light and heavy classes. On Fig. 4 we can see that the value $\log_{10} Z/\alpha = 1.8$ corresponds with value 0.03 g/m^3 of mean drizzle LWC that is close to the proposed by Gerber (1996) value 0.01 g/m^3.

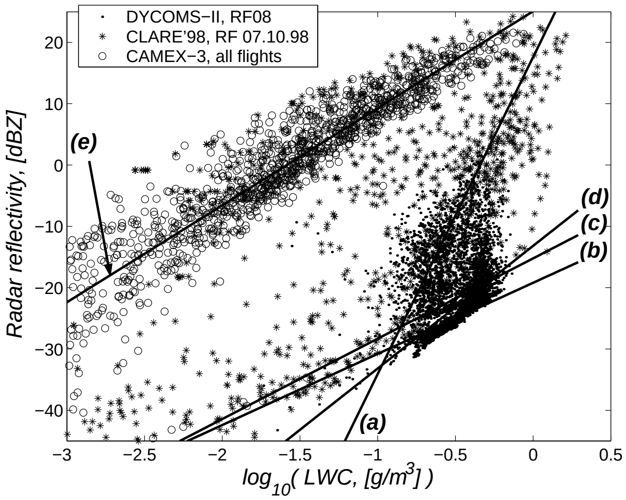

Fig. 6. The relation between Liquid Water Content and Radar Reflectivity for different field campaigns. Lines represent the different linear fittings of this relation.

As result, from our analysis follows the possibility to use the Z/α ratio for classification the clouds into three types:

– "The cloud without drizzle": $\log_{10}(Z/\alpha) < -1$, $Z_{drizzle}/Z_{droplets} < 0$ dB, the contribution drizzle fraction into LWC is negligible, for the DSD description it is possible to use standard three parameters distributions like modified gamma or log-normal;

– "The cloud with light drizzle": $-1 < \log_{10}(Z/\alpha) < 1.8$, $Z_{drizzle}/Z_{droplets} < 30$ dB, the contribution of the drizzle fraction into LWC is less then 0.03 g/m^3. This class can be characterized with very fast growing of the Z/α ratio as the effective radius increases;

– "The cloud with heavy drizzle": $\log_{10}(Z/\alpha) > 1.8$, $Z_{drizzle}/Z_{droplets} > 30$ dB, the contribution of the drizzle fraction into LWC is essential, slow growing of the Z/α ratio as function of the effective radius, for the description of the DSD it is necessary to use the model of the mixture of independent DSD.

3.4 Application of the features of the radar to lidar ratio for the retrieval of the LWC in water clouds

Consider now the application of described above cloud type classification technique for the parameterization of the Z-LWC relation in water clouds. On Fig. 6 in-situ data for three campaigns on the Z-LWC plane are presented. On the same plot a few known approximations for this relationship are also presented:

(a) Baedi et al. (2000): $Z = 57.54 \cdot LWC^{5.17}$
(b) Fox and Illingworth (1997): $Z = 0.012 \cdot LWC^{1.16}$
(c) Sauvageot and Omar (1987): $Z = 0.03 \cdot LWC^{1.31}$
(d) Atlas (1954): $Z = 0.048 \cdot LWC^{2.0}$
(e) Best fit of all data for the CAMEX-3 campaign and the CLARE'98's data for the drizzle clouds:
$Z = 323.59 \cdot LWC^{1.58}$

It is clear from this representation that the Z-LWC relation is very scattered and not one of known analytical relationships can be used alone. From other point of view, the positions of presented data on the Z-LWC plane show some tendency to concentrate around every lines (a)–(e). It gives the background for the search of the algorithm for the classification of cloud DSD into a few classes, which can be parameterized with the different Z-LWC relationships. On Fig. 7 two-dimensional distributions of in-situ observed DSDs on the separate for every class Z-LWC plane and related analytical relationships (a)–(e) are presented. For such classification we used two methods. Both of them use cloud types classification with the value of Z/α ratio technique that was described in previous section. The difference are only in same additional criteria, which for the first method require the knowledge about in-situ measured parameters – r_{eff} and LWC and for the second method – only the results of radar and lidar measurements of Z/α and Z. The used criteria for classification of the cloud type and selection of the Z-LWC relationship also are presented on the Fig. 7. As result from Fig. 7 it can be seen that equations (b), (c), and (d) can parameterize the relationship in the clouds without drizzle, Eq. (a) can be applied for the clouds with light drizzle, and (d) – for the clouds with heavy drizzle. The second important conclusion, which follows from the comparison of images in columns on Fig. 7, is that the method based only on remote sensing measurables gives practically the same classification result as the use of the complete DSD information.

4 Conclusions

Using set of in-situ data that were measured during different field campaigns in different geographical regions inside different types of water clouds was shown:

– Very good characteristics for the detection and parameterization of the drizzle fraction in water clouds has the ratio between radar reflectivity and optical extinction;

– The presence of stable $Z/\alpha - r_{eff}$ relationship for the different geographical locations, different field campaigns and different cloud types. It is possible to use for all analyzed campaigns and cloud types a unified 4th order polynomial fitting of this relationship;

– The possibility to classify water clouds into three types – the cloud without drizzle, the cloud with light drizzle, and the cloud with heavy drizzle, using the ratio Z/α of radar reflectivity to optical extinction;

– The possibility to retrieve LWC from radar reflectivity using different types of the Z-LWC relationships for the cloud without drizzle, for the cloud with light drizzle, and for the cloud with heavy drizzle. For the classification of the cloud cell into such three types is possible to

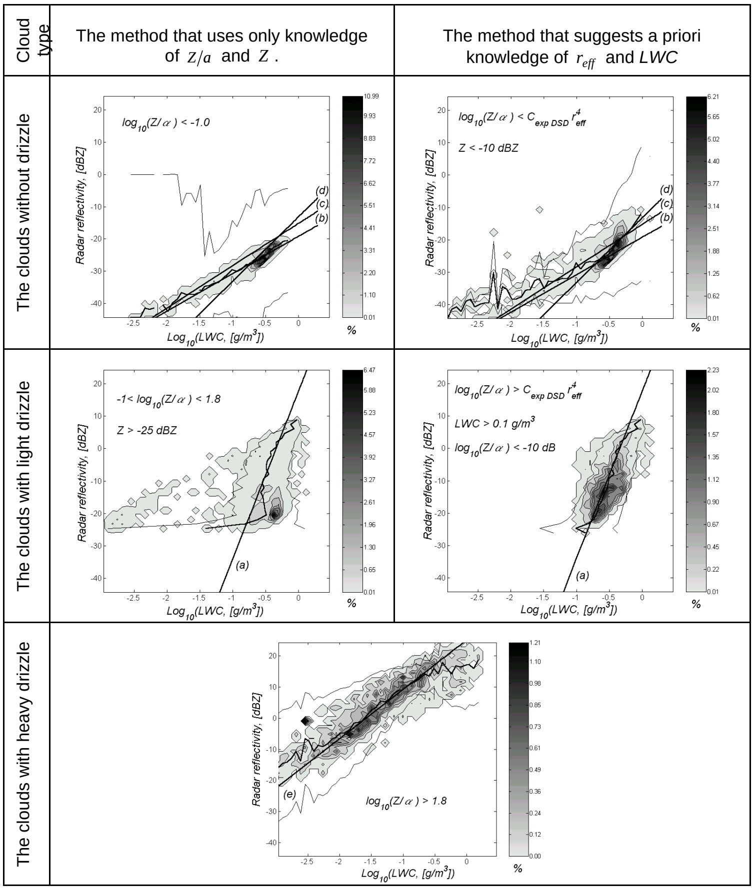

Fig. 7. Two-dimensional histograms for the Z-LWC relation (with mean, standard deviations, and linear fittings) for different criteria and methods of cloud's type classification.

use only parameters that are available for measurements with radar and lidar.

The described results can be used as background for the development of new enhanced algorithm for the retrieval of liquid water cloud properties from simultaneous radar and lidar measurements.

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