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MBL drizzle properties and their impact on cloud property retrievals

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Abstract

In this study, we retrieve and document drizzle properties, and investigate the impact of drizzle on cloud property retrievals from ground-based measurements at the ARM Azores site from June 2009 to December 2010. For the selected cloud and drizzle samples, the drizzle occurrence is 42.6 % with a maximum of 55.8 % in winter and a minimum of 35.6 % in summer. The annual means of drizzle liquid water path LWP_d, effective radius r_d, and number concentration N_d for the rain (virga) samples are 5.48 (1.29) $g\,m^{-2}$, 68.7 (39.5) µm, and 0.14 (0.38) cm^{-3}. The seasonal mean LWP_d values are less than 4 % of the MWR-retrieved LWP values. The annual mean differences in cloud-droplet effective radius with and without drizzle are 0.12 and 0.38 µm, respectively, for the virga and rain samples. Therefore, we conclude that the impact of drizzle on cloud property retrievals is insignificant at the ARM Azores site.

1 Introduction

Marine boundary layer (MBL) clouds frequently produce light precipitation, mostly in the form of drizzle (Austin et al., 1995; Wood, 2005, 2012; Leon et al., 2008). Radar reflectivity thresholds have been widely used to distinguish between non-precipitating and precipitating clouds. For example, Sauvageot and Omar (1987) and Chin et al. (2000) proposed a threshold of −15 dBZ for continental stratocumulus clouds, and Frisch et al. (1995) used −17 dBZ as a threshold to distinguish non-precipitating and precipitating clouds over North Atlantic. Mace and Sassen (2000) found that cloud layers with maximum reflectivity ≥ −20 dBZ nearly always contain drizzle for continental clouds over the ARM SGP site. Wang and Geerts (2003) demonstrated that the thresholds varied from −19 to −16 dBZ for three different cases of marine time clouds.

The drizzle effect on stratocumulus-topped boundary layer is complex (Wood, 2012) because it involves the cloud lifetime and evolution (Albrecht, 1993; Wood, 2000). Zhao et al. (2012) summarized current ARM cloud retrievals. For the treatment of drizzle,

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some retrieval methods (e.g., COMBRET) classify drizzle from clouds while others just flag the presence of drizzle (e.g., MICROBASE). However, even in COMBRET, they only classify drizzle and do not investigate the impact of drizzle on cloud property retrievals. So far, none of the studies have quantitatively investigated the extent will drizzle impact cloud property retrievals.

When drizzle occur and fall out of the cloud base, they are either evaporated before reaching the surface, which is defined as virga (AMS, 2014), or reach the surface in the form of rain. Rémillard et al. (2012) identified the virga and rain samples based on whether the radar reflectivity exists below cloud base and whether the lowest range gate of radar echoes reach near the surface (200 m). Different physical and feedback processes can be induced by virga and rain periods. The evaporation of virga cools the sub-cloud layer and generates turbulence between sub-cloud layer and surface. This turbulence can transport moisture from the surface to the cloud layer to enhance the development of cloud. Wood (2005) found that the sub-cloud layer with drizzle is generally cooler and wetter than drizzle-free region, which is a result of evaporation cooling. On the other hand, rain depletes water from the cloud layer to the surface. Note that the Azores is surrounded by ocean, so drizzle or rain drops that reach the surface do not increase water vapor.

In this study, we will follow the AMS definition of virga and rain drizzle, and simply analyze drizzle (either virga or rain) underneath the MBL cloud base over the Azores. We will describe the method to retrieve both virga and rain microphysical properties in Sect. 2, and present the seasonal means of drizzle properties and investigate on what extent drizzle can impact cloud property retrievals in Sect. 3. Finally, a brief summary and conclusions are given in Sect. 4.

2 Data and methodology

The datasets used in this study were collected by the Atmospheric Radiation Program Mobile Facility (AMF), which was deployed on the northern coast of Graciosa Island

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(39.09° N, 28.03° W) from June 2009 to December 2010 (for more details, please refer Wood et al., 2015; Rémillard et al., 2012; Dong et al., 2014a). The detailed operational status of the remote sensing instruments on AMF were summarized in Fig. 1 of Rémillard et al. (2012) and discussed in Wood et al. (2015). The drizzling status is identified through a combination of the W-band Doppler radar (WACR) measured reflectivity and the laser ceilometer (CEIL) detected cloud-base height. Given the absence of disdrometer measurements at the Azores, we use a similar method as described in Rémillard et al. (2012) to identify the virga and rain. When drizzle falls out of the cloud base and the radar echoes at the lowest range gate (~ 200 m above the surface) have reflectivities greater than -37 dBZ, the drizzle is defined as rain, otherwise, it is classified as virga. After identifying the virga and rain, we adopt the method of O'Connor et al. (2005) to retrieve the drizzle microphysical properties using both radar reflectivity and laser ceilometer backscatter coefficient. The liquid water path (LWP) is derived from the microwave radiometer with an uncertainty of $20\,\mathrm{g\,m^{-2}}$ for LWP $< 200\,\mathrm{g\,m^{-2}}$, and 10 % for LWP $> 200\,\mathrm{g\,m^{-2}}$ (Liljegren et al., 2001; Dong et al., 2000).

The method presented by O'Connor et al. (2005) is used to retrieve drizzle particle effective radius, number concentration, and liquid water content. The distribution of drizzle particles can be assumed as a normalized gamma distribution. The ratio of radar reflectivity (Z) to lidar true backscatter coefficient (β) is proportional to the fourth power of drizzle size and can be written as

$$\frac{Z}{\beta} = \frac{2}{\pi}\frac{\Gamma(7+\mu)}{\Gamma(3+\mu)}\frac{S}{(3.67+\mu)^4}D_0^4. \tag{1}$$

D_0 is the median diameter, μ is the shape parameter, and S is the lidar ratio which can be estimated using Mie theory. The retrieval scheme is based on an iterative approach using the radar measured spectral width as a constraint. At first, the initial D_0 can be estimated assuming $\mu = 0$, and then vary D_0 by adjusting μ to calculate the radar spectral width. The final D_0 and μ values can be retrieved until the calculated radar spectral width converges to within 10 % of measured radar spectral width. Once D_0

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and μ values are determined, normalized concentration can be calculated from radar reflectivity. Thus three drizzle parameters: drizzle liquid water content (LWC_d), number concentration (N_d), and effective radius (r_d) can be calculated. The uncertainties of retrieved LWC_d, N_d and r_d are 10, 13, and 14 %, respectively, in this study.

The retrieval method of daytime cloud microphysical properties is from Dong et al. (1998). The layer-mean cloud-droplet effective radius ($\overline{r_c}$) during the daytime was parameterized as a function of cloud liquid water path (LWP_c), solar transmission ratio (γ), and cosine of solar zenith angle (μ_0) (Dong et al., 1998). This parameterization is given by the following expression,

$$\overline{r_c} = -2.07 + 2.49 LWP_c + 10.25\gamma - 0.25\mu_0 + 20.28 LWP_c \gamma - 3.14 LWP_c \mu_0, \tag{2a}$$

where the units of $\overline{r_c}$ and LWP_c are in µm and $100\,\mathrm{g\,m^{-2}}$, respectively. Cloud-droplet number concentration (N_c) is given by:

$$N_c = \frac{3 LWP_c}{4\pi \rho_w r_c^3 \Delta Z} \exp\left(3\sigma_x^2\right), \tag{2b}$$

where ρ_w is water density and σ_x is logarithmic width, which is set to a constant value of 0.38. Cloud optical depth τ can be calculated immediately from the following equation,

$$\tau_c = \frac{3 LWP_c}{2 r_c \rho_w}. \tag{2c}$$

The microwave radiometer retrieved LWP represents entire atmospheric column, including both cloud liquid water path (LWP_c) and drizzle liquid water path (LWP_d). Therefore it is necessary to estimate LWP_c by eliminating LWP_d from LWP in order to get more accurate cloud property retrievals.

3 Results and discussions

Figure 1 demonstrates virga and rain below cloud base from two selected cases along with their retrieved microphysical properties. Case I represents a typical virga case occurring on 22 November 2009, and Case II is a typical rain case that occurred from the late afternoon of 8 November to the morning of 9 November 2010. Figure 1a and e presents the WACR reflectivity profiles and the CEIL measured cloud-base heights for Cases I and II, respectively. Both cases have significant time periods that the radar reflectivities are greater than −37 dBZ below cloud base, but happened more frequently in Case II than in Case I. Compared Fig. 1a with Fig. 1e, the radar reflectivities are generally lower in Case I than in Case II. The retrieved r_d values (Fig. 1b) are relatively smaller in Case I than in Case II (Fig. 1f), but the N_d values are higher in Case I (Fig. 1c) than in Case II (Fig. 1g).

The mean r_d in Case I is 33.73 µm with a range of ∼ 20–50 µm, while it is 48.25 µm for Case II, ranging from 20 to 100 µm. The larger r_d and lower N_d in Case II are anticipated because drizzle particle sizes are larger when relatively intense drizzling occurs. For example, the r_d values range from 50 to 100 µm during the period of 07:00–10:00 UTC in Case II. The mean values of r_d in both Cases are nearly 3–4 times larger than the mean values of MBL cloud-droplet effect radius r_c at the Azores (12.5–12.9 µm, Dong et al., 2014a, b). However, their mean N_d values of 0.885 and 0.535 cm^{-3} are two orders of magnitude lower than the mean values of MBL cloud-droplet number concentration N_c at the Azores (66–82.6 cm^{-3}, Dong et al., 2014a, b). The retrieved r_d and N_d values in both cases are also in the same magnitude as some previous studies (e.g., O'Connor et al., 2005; Frisch et al., 1995; Wang, 2002). The drizzle LWC (LWC$_d$) below cloud base are about 1–2 orders of magnitude lower than the cloud LWC (LWC$_c$) above cloud base (shown in Table 3 of Dong et al., 2014a), and slightly higher in Case II.

High radar reflectivity normally results from large particles because radar reflectivity is proportional to the sixth power of particle size. Figure 1b and c shows that the r_d values below cloud base are vertically invariant, however, the N_d values decrease significantly toward to the surface, indicating that the evaporation of the drizzle particles below cloud base occurs for virga. For Case II, the r_d values increase toward the surface, but the N_d values remain either relatively constant or slightly decrease, which may

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be a result of the collision-coalescence process for rain. It is also notable that a narrow band appears just below the cloud base, called a "transition layer" from cloud to drizzle, which makes the r_d values smaller and the N_d values higher than those at lower levels.

To provide statistical results of drizzle microphysical properties and investigate to what extent drizzle impacts cloud property retrievals, we plot Figs. 2 and 3, and list their seasonal means in Table 1. Figure 2 shows the probability distribution functions (PDFs) and cumulative distribution functions (CDFs) of drizzle properties from a total of 353 h of virga and 112 h of rain samples during the 19 month period. As illustrated in Fig. 2a, the reflectivities of rain are generally higher than those of virga with the mode values of 0 and −20 dBZ, respectively. The mode value (0 dBZ) of rain is consistent with the definition of intense precipitation type in Rémillard et al. (2012). From the CDFs of Fig. 2a, 55 % of the virga and 13 % of rain samples are less than −15 dBZ, and 37 % of the virga and 6 % of the rain samples are less than −20 dBZ. Thus, ∼ 45 % of the drizzle samples would be missed if using a threshold of −15 dBZ, and ∼ 30 % for −20 dBZ. Therefore, we conclude that a significant amount of drizzle samples would be missed if using radar reflectivity as a threshold.

The PDFs and CDFs of drizzle particle effective radius r_d are shown in Fig. 2b. The mode value of virga samples is ∼ 30 µm, whereas it is not so obvious for rain samples with a broad range of 30 ∼ 150 µm. Nearly 66 % of the virga samples are less than 50 µm and 83 % of the rain samples are less than 100 µm, both with long tails towards large values. In contrast to the distributions of r_d, most of the N_d values for both virga and rain samples are located at the tail end with nearly 70–80 % less than 0.2 cm^{-3} and slightly more virga samples for large values. Almost all virga LWP_d values are less than 10 $g\,m^{-2}$ and ∼ 80 % less than 3 $g\,m^{-2}$, while only 18 % of the rain samples are less than 3 $g\,m^{-2}$.

To investigate the impact of drizzle on cloud property retrievals, the cloud liquid water path (LWP_c) is calculated by subtracting LWP_d from the microwave radiometer retrieved LWP, and then used it as an input for (2) to retrieve new MBL cloud microphysical properties, r_c', N_c', and τ' without drizzle effect. These newly retrieved cloud properties

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(r'_c, N'_c, τ') are then compared with the original retrievals in Dong et al. (2014a) where the LWP was used as LWP_c in (2). Figure 3 shows the dependence of the differences between newly and originally retrieved r_c and τ on LWP_d where both Δr_c and $\Delta\tau$ linearly decrease with increased LWP_d. The slope of the linear regression line (Δr_c vs. LWP_d) for the virga samples is 0.1 with a correlation coefficient (R^2) of 0.987 (Fig. 3a), that is, r_c decreases 0.1 µm at an increase of 1 g m^{-2} in LWP_d. The r_c values will decrease by up to 0.3 µm with an increase of 3 g m^{-2} in LWP_d, which is within the uncertainty (∼ 10 %) of originally retrieved r_c values in Dong et al. (2014a). The impact of drizzle on cloud optical depth retrieval (Fig. 3b) is similar to that of r_c with a slope of −0.02 and R^2 of 0.901. For the rain samples, the slope is −0.07 and the correlation is 0.896. The r_c values can be reduced 2 ∼ 3 µm with an increase of 40 g m^{-2} in LWP_d and relatively larger fluctuation than for the virga samples. The impact of LWP_d on cloud optical depth retrieval is weak with a R^2 of 0.568.

A 95 % confidence interval for each regression line is computed, indicating that the true best-fit line for the samples have 95 % probability to fall within the confidence intervals. The two dashed lines in Fig. 3 represent the upper and lower 95 % confidence bounds for each of the regression. The narrow intervals for Fig. 3a–c suggest high reliability of the regression, whereas for the broad interval in Fig. 3d indicates relatively large uncertainty of the regression.

The sample numbers and seasonal means of retrieved cloud and drizzle microphysical properties for the virga and rain periods are listed in Table 1. A total of 1091 h (13 090 samples at 5 min resolution, including 4237 virga samples and 1345 rain samples) daytime single-layered MBL clouds has selected from 19 month period (Dong et al., 2014a). For the cloud and drizzle samples, the overall drizzle occurrence is 42.6 % with a maximum of 55.8 % in winter and a minimum of 35.6 % in summer. For the virga samples, the seasonal mean LWP_d values (winter to autumn) are 1.87, 1.23, 0.90, and 1.16 g m^{-2}, and their corresponding r_d (N_d) values are 42.27 µm (0.36 cm^{-3}), 40.67 µm (0.35 cm^{-3}), 37.25 µm (0.48 cm^{-3}), and 37.68 µm (0.32 cm^{-3}). For the rain samples, the seasonal mean LWP_d values are 6.83, 4.93, 4.98 g m^{-2}, and 5.19 g m^{-2}, and their corresponding r_d (N_d) values are 71.08 µm (0.14 cm^{-3}), 71.97 µm (0.09 cm^{-3}), 63.88 µm (0.21 cm^{-3}), and 67.74 µm (0.13 cm^{-3}). The annual means of LWP$_d$, r_d and N_d for the rain (virga) samples are 5.48 g m^{-2} (1.29 g m^{-2}), 68.7 µm (39.5 µm), and 0.14 cm^{-3} (0.38 cm^{-3}). For both virga and rain samples, their LWP$_d$ and r_d are largest during winter because the dominant low pressure systems and moist air masses during winter result in more deep frontal clouds associated with midlatitude cyclones, which will make the MBL clouds deeper and thicker (Dong et al., 2014a). On the other hand, their N_d values are highest but their LWP$_d$ and r_d are minima during summer due to the persistent high pressure and dry conditions over the Azores (Dong et al., 2014a).

To investigate seasonal variations of the impact of drizzle on cloud property retrievals, we also calculate the ratio of LWP$_d$ to LWP and cloud properties (r_c, N_d, τ) using (2) with the MWR-retrieved LWP and newly calculated cloud LWP$_c$ (= LWP − LWP$_d$). Although the annual mean LWP$_d$ from the rain samples is about four times as large as that from the virga samples, their seasonal means are less than 4 % of the MWR-retrieved LWP. Therefore, their impact on cloud property retrievals is insignificant. As listed in Table 1, the seasonal differences ($r_c - r_c'$) are 0.21 (0.47), 0.11 (0.38), 0.09 (0.32), and 0.12 (0.43) µm for the virga (rain) samples with annual mean differences of 0.12 and 0.38 µm, respectively. These differences fall within the cloud property retrieval uncertainty (∼ 10 %), validated by in situ aircraft measurements at midlatitude continental sites (Dong et al., 1997, 1998, 2002; Dong and Mace, 2003). Therefore, the impact of drizzle on cloud-droplet effective radius, in general, can be negligible. However, for some individual cases, the differences can reach as large as 2 ∼ 3 µm, which may cause a large uncertainty especially in the study of cloud radiative properties using radiative transfer models (Dong et al., 1998). The impacts of drizzle on cloud-droplet number concentration (and optical depth) are also small, presumably due to small changes in both LWP$_c$ and r_c. The annual differences in cloud-droplet number concentration are −0.93 and −1.50 cm^{-3} for the virga and rain samples, respectively.

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4 Summary and conclusion

In this study, we use a similar method as described in Rémillard et al. (2012) to identify virga and rain samples below cloud base using 19 months of ground-based observations at the ARM Azores site. Then we adopt the method of O'Connor et al. (2005) to retrieve drizzle particle effective radius, number concentration and liquid water content. Finally we document the seasonal variations of both drizzle and cloud properties, and investigate the impact of drizzle on cloud property retrievals. From the 19 month record of ground-based observations and retrievals, we report the following findings:

1. For the cloud and drizzle samples, the overall drizzle occurrence is 42.6 % with a maximum of 55.8 % in winter and a minimum of 35.6 % in summer. The annual means of $\mathrm{LWP_d}$, r_d, and N_d for the rain (virga) samples are 5.48 (1.29) $\mathrm{g\,m^{-2}}$, 68.7 (39.5) µm, and 0.14 (0.38) $\mathrm{cm^{-3}}$, respectively. For both virga and rain samples, their $\mathrm{LWP_d}$ and r_d are the largest during winter, whereas their N_d values are at a maximum while their $\mathrm{LWP_d}$ and r_d are at a minimum during summer due to different seasonal synoptic patterns.

2. To investigate the impact of drizzle on cloud property retrievals, we calculate the ratio of $\mathrm{LWP_d}$ to LWP and cloud properties (r_c, N_d, τ) using (2) with the MWR-retrieved LWP and newly calculated cloud $\mathrm{LWP_c}$ (= LWP – $\mathrm{LWP_d}$). The seasonal mean $\mathrm{LWP_d}$ are less than 4 % of LWP values. The annual mean differences ($r_\mathrm{c} - r'_\mathrm{c}$) are 0.12 and 0.38 µm, respectively, for the virga and rain samples. These differences fall within the cloud property retrieval uncertainty (∼ 10 %). The impacts of drizzle on cloud-droplet number concentration (optical depth) are also small, presumably due to small changes in both $\mathrm{LWP_c}$ and r_c. Therefore, we can conclude that the impact of drizzle on cloud property retrievals is insignificant at the ARM Azores site. Results from this study shows the impact of drizzle underneath cloud base to cloud property retrievals in Dong et al. (1998), the investi-

gation of drizzle impact to other cloud property retrieval algorithms are out of the scope of this study because of lacking to access to other algorithms.

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Table 1. Seasonal means of drizzle and cloud properties for virga and rain.

	VIRGA Winter	Spring	Summer	Autumn	RAIN Winter	Spring	Summer	Autumn
Samples (5 min)	464	693	1742	1338	244	225	574	302
LWP ($\mathrm{g\,m^{-2}}$)	90.48	135.86	108.36	94.84	197.13	269.35	231.41	195.08
r_c (µm)	12.13	12.94	12.93	11.77	15.55	16.54	16.41	16.11
N_c ($\mathrm{cm^{-3}}$)	76.66	75.98	72.20	90.98	30.23	35.85	36.68	35.01
τ	11.70	16.55	13.24	12.67	19.41	27.07	22.62	18.89
$\mathrm{LWP_d}$ ($\mathrm{g\,m^{-2}}$) (% of $\mathrm{LWP_d}$/LWP)	1.87 (2.06)	1.23 (0.91)	0.90 (0.83)	1.16 (1.22)	6.83 (3.46)	4.93 (1.83)	4.98 (2.15)	5.19 (2.66)
r_d (µm)	42.27	40.67	37.25	37.68	71.08	71.97	63.88	67.74
N_d ($\mathrm{cm^{-3}}$)	0.36	0.35	0.48	0.32	0.14	0.09	0.21	0.13
$\mathrm{LWP_c}$ ($\mathrm{g\,m^{-2}}$)	88.61	134.63	107.46	93.68	190.30	264.42	226.43	189.89
r'_c (µm)	11.92	12.83	12.84	11.65	15.08	16.16	16.09	15.68
N'_c ($\mathrm{cm^{-3}}$)	78.41	76.75	72.93	91.98	32.62	37.18	37.84	36.54
τ'	11.63	16.53	13.22	12.64	19.31	27.03	22.59	18.83

Note there are a total of 1091 h (13 090 samples at 5 min resolution, including 1270, 1933, 6498, and 3389 5 min samples for Winter, Spring, Summer, and Autumn) daytime single-layered MBL clouds selected from 19 month period (Dong et al., 2014a).

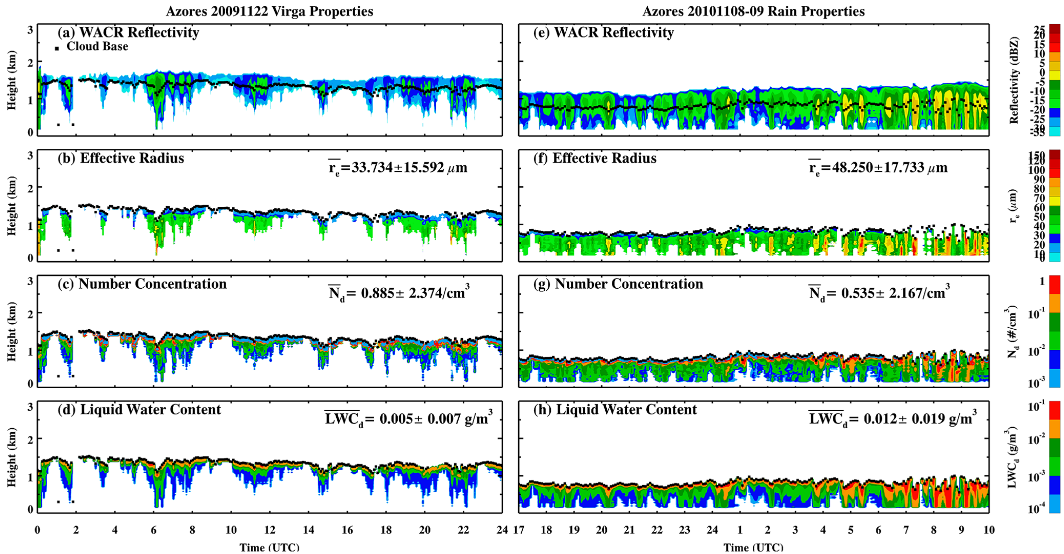

Figure 1. Drizzle properties observed by ARM radar-lidar and retrieved from this study at the ARM Azores site. Two cases have been selected: Case I (left panel, 22 November 2009) is a typical virga case, and Case II (right panel, from late afternoon of 8 November 2010 to the morning of 9 November 2010) is a rain case (drizzle reaches the surface).

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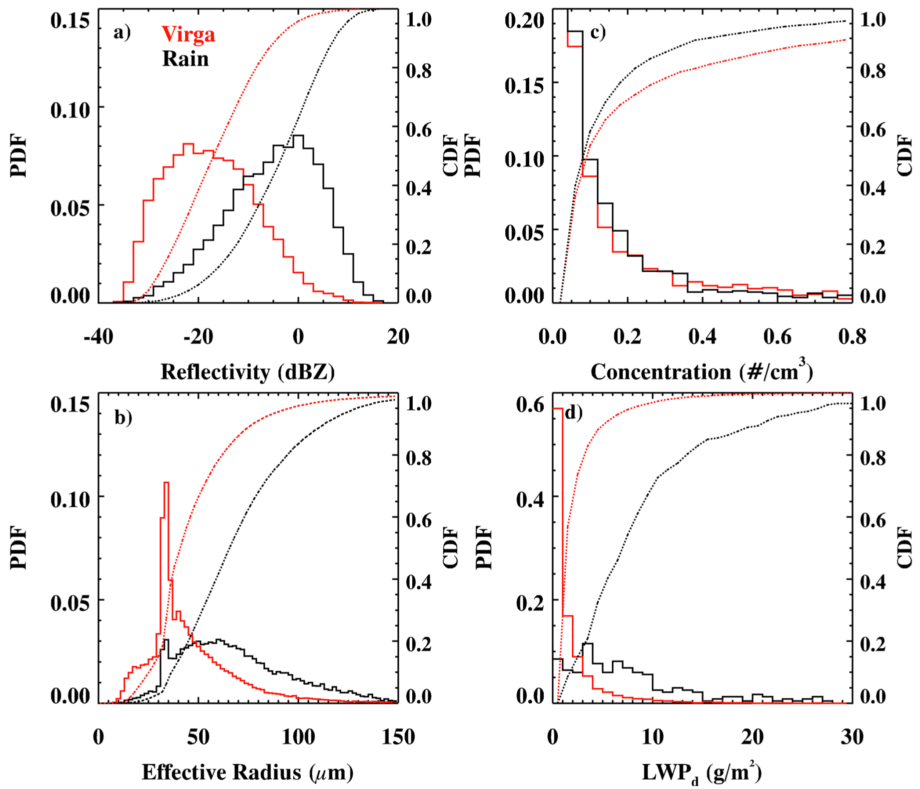

Figure 2. Probability distribution functions (PDFs) and cumulative density functions (CDFs) of daytime drizzle properties at the Azores during the period from June 2009 to December 2010. PDFs and CDFs of **(a)** WACR reflectivities below cloud base for drizzle from virga and rain in this study, **(b)** drizzle particle effective radius r_d, and **(c)** number concentration N_d, and **(d)** liquid water path (LWP$_d$). The red lines and black lines represent the results from the selected virga and rain drizzle episodes, respectively.

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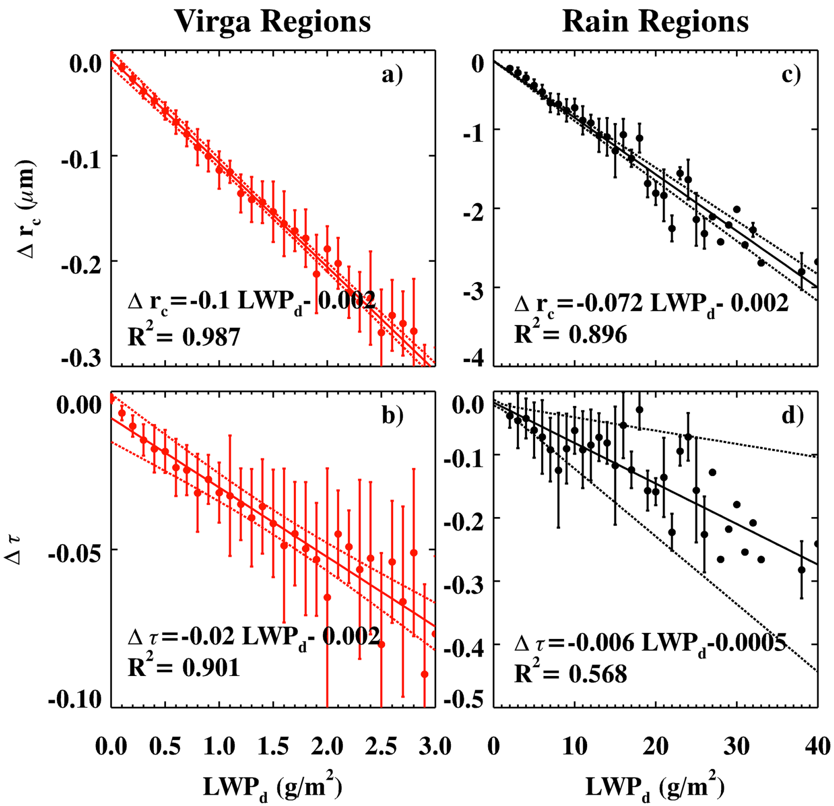

Figure 3. The impact of drizzle on cloud property retrievals (daytime only). Left panel is for the selected virga samples (red line) and right panel is for the selected rain samples (black line). Solid dots denote the mean values of each bin, and the bottom and top of each whisker represent one SD. The solid lines are fitted linear regression lines, the dashed lines indicate upper and lower boundaries of a 95 % confidence interval for the regression. Δr_c and $\Delta\tau$ represent the differences between the originally and newly retrieved values.

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