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Marine boundary layer drizzle properties and their impact on cloud property retrieval

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Abstract. In this study, we retrieve and document drizzle properties, and investigate the impact of drizzle on cloud property retrieval in Dong et al. (2014a) from ground-based measurements at the ARM Azores facility 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 $\mathrm{LWP_d}$, effective radius r_d, and number concentration N_d for the rain (virga) samples are 4.73 (1.25) $\mathrm{g\,m^{-2}}$, 61.5 (36.4) µm, and 0.38 (0.79) $\mathrm{cm^{-3}}$. The seasonal mean $\mathrm{LWP_d}$ values are less than 3 % of the LWP values retrieved by the microwave radiometer (MWR). The annual mean differences in cloud-droplet effective radius with and without drizzle are 0.75 and 2.35 %, respectively, for the virga and rain samples. Therefore, we conclude that the impact of drizzle below the cloud base on cloud property retrieval is insignificant for a solar-transmission-based method, but significant for any retrievals using radar reflectivity.

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 the North Atlantic. Using aircraft data, Fox and Illingworth (1997) found that drizzle exists ubiquitously in all marine stratocumulus clouds for cloud thicknesses ≥ 200 m. Mace and Sassen (2000) found that cloud layers with maximum reflectivity ≥ −20 dBZ nearly always contain drizzle for continental clouds over the ARM Southern Great Plains (SGP) site. Wang and Geerts (2003) demonstrated that the thresholds varied from −19 to −16 dBZ for three different cases of maritime clouds. Kollias et al. (2011) and others suggested that the radar reflectivity threshold should be −30 dBZ or even lower. As will be discussed later in this paper, however, none of the thresholds stated above are actually suitable for diagnosing the presence or absence of drizzle in MBL stratocumulus.

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

When drizzle drops fall out of the cloud base, they either evaporate before reaching the surface, which is defined as virga (AMS, 2015), or reach the surface in the form of rain. Rémillard et al. (2012) identified the virga and rain samples based on whether the lowest range gate of radar echoes reach near the surface (200 m). Assuming that the drizzle evaporation rate below the cloud base is the same for both forms of drizzle, the evaporation cools the sub-cloud layer and generates turbulence between the sub-cloud layer and the surface.

This turbulence can transport moisture from the surface up to the cloud layer to sustain and enhance the development of cloud. Wood (2005) found that the sub-cloud layer with drizzle is generally wetter and cooler than the drizzle-free region, which is a result of drizzle evaporation and evaporative cooling. On the other hand, the two forms of drizzle have different effects on cloud life cycle and boundary layer liquid water budget. Virga drizzle fluxes evaporate completely at a height before reaching the surface, while rain drizzle fluxes are low enough to reach the surface. In both forms, drizzle depletes liquid water from the cloud layer but enhances liquid water in the sub-cloud layer with different net effects. During the rain period, drizzle drops fall out of the cloud base and reach the surface, which results in a net decrease of liquid water in the atmospheric column, shortens cloud lifetime, and consequently changes cloud microphysical properties. During the virga period, however, all drizzle drops falling out of the cloud base evaporate, which provides additional water vapor to sustain cloud development. This has also been discussed in Dong et al. (2015) in which a conceptual model (their Fig. 7) was developed to demonstrate the differences in total water mixing ratio for both rain and virga periods. The boundary layer total water mixing ratio tends to remain constant for virga drizzle while it decreases with height for rain drizzle. In this study, we refer to "virga" as drizzle fluxes which evaporate before reaching the surface and "rain" as drizzle fluxes which reach the surface.

In this study, we will first separate all drizzle samples into forms of virga or rain, and simply analyze drizzle (either virga or rain) underneath the MBL cloud base over the Azores. We will describe the method of retrieving both virga and rain microphysical properties in Sect. 2, and present the seasonal means of drizzle properties and investigate to what extent drizzle can impact cloud property retrievals given in Dong et al. (2014a) in Sect. 3. Finally, a brief summary and conclusions are given in Sect. 4.

2 Data and methodology

The data sets used in this study were collected by the Atmospheric Radiation Program Mobile Facility (AMF), which was deployed on the northern coast of Graciosa Island (39.09° N, 28.03° W) from June 2009 to December 2010 (for more details, please refer to Wood et al., 2015; Rémillard et al., 2012; Dong et al., 2014a). The detailed operational statuses 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 reflectivity measured by the W-band Doppler radar (WACR) and the cloud-base height detected by the Vaisala laser ceilometer (VCEIL). 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 drizzle. When drizzle drops fall out of the cloud base and the radar echoes at the lowest range gate ($\sim$ 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 drizzle, we adopt the method of O'Connor et al. (2005) to retrieve the drizzle microphysical properties using both radar reflectivity and laser-ceilometer-attenuated backscatter coefficient. The cloud base heights used in this study were determined using a threshold of $10^{-4}\,\mathrm{Sr^{-1}\,m^{-1}}$ in attenuated backscatter coefficient (similar to O'Connor et al., 2004 and Fielding et al., 2015). 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 to be adequately represented by a normalized gamma distribution. The ratio of radar reflectivity (Z) to the calibrated-ceilometer-attenuated backscatter coefficient (β) is proportional to the fourth power of drizzle size and can be written as

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

where 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 the measured radar spectral width. Once D_0 and μ values are determined, normalized concentration can be calculated from radar reflectivity. Thus three drizzle parameters – drizzle liquid water content ($\mathrm{LWC_d}$), number concentration (N_d), and effective radius (r_d) – can be calculated. Note that D_0 was provided in O'Connor et al. (2005), and drizzle particle effective radius r_d in this study is calculated using the following equation:

$$r_e = \frac{1}{2}\frac{\int_0^\infty D^3 n(D)\,\mathrm{d}D}{\int_0^\infty D^2 n(D)\,\mathrm{d}D} = \frac{1}{2}\frac{\Gamma(4+\mu)}{\Gamma(3+\mu)}\frac{D_0}{3.67+\mu}. \tag{2}$$

ARM WACR radar data are well calibrated for the AMF Azores according to the data report in the ARM data archive (http://www.archive.arm.gov/DQR/ALL/D100729.5.html). To assess the impact of ARM WACR reflectivity on drizzle property retrievals, we adopt the conclusion of Hogan et al. (2003) in which they found that the uncertainty of WACR reflectivity measurements during rain drizzle is likely to be around 1.5 dB from the theoretical calculation. To account for the shift of backscatter signal between observation and theoretical value and consider the effect of multiple scattering, the raw Vaisala-ceilometer-attenuated backscatter coefficients were multiplied by a factor of 2.45. The uncertainty of the calibrated β is around 20 % (see O'Connor et al. (2004) and http://cedadocs.badc.rl.ac.uk/77/2/vaisala_ceilometer.html). Following the same error analysis method as O'Connor et al. (2005), the fractional errors in $\mathrm{LWC_d}$, N_d, and r_d can be expressed as

$$\frac{\Delta \mathrm{LWC_d}}{\mathrm{LWC_d}} = \frac{1}{7}\left[\left(\frac{\Delta Z}{Z}\right)^2 + \left(\frac{6\Delta\beta}{\beta}\right)^2\right]^{\frac{1}{2}} \tag{3a}$$

$$\frac{\Delta N_\mathrm{d}}{N_\mathrm{d}} = \frac{1}{7}\left[\left(-\frac{5\Delta Z}{Z}\right)^2 + \left(\frac{12\Delta\beta}{\beta}\right)^2\right]^{\frac{1}{2}} \tag{3b}$$

$$\frac{\Delta r_\mathrm{d}}{r_\mathrm{d}} = \frac{2}{7}\left[\left(\frac{\Delta Z}{Z}\right)^2 + \left(\frac{\Delta\beta}{\beta}\right)^2\right]^{\frac{1}{2}}. \tag{3c}$$

Based on the uncertainties of Z and β, the uncertainties of retrieved $\mathrm{LWC_d}$, N_d, and r_d are estimated as 18, 45, and 13 %, respectively, in this study.

The daytime cloud microphysical properties presented in Dong et al. (2014a) are retrieved from Dong et al. (1998, hereafter D98). The layer-mean cloud-droplet effective radius ($\overline{r}_\mathrm{c}$) during the daytime was parameterized as a function of cloud liquid water path ($\mathrm{LWP_c}$), solar transmission ratio (γ), and cosine of solar zenith angle (μ_0) (D98). This parameterization is given by the following expression:

$$\begin{aligned}\overline{r_\mathrm{c}} = &-2.07 + 2.49\mathrm{LWP_c} + 10.25\gamma \\ &-0.25\mu_0 + 20.28\mathrm{LWP_c}\gamma - 3.14\mathrm{LWP_c}\mu_0,\end{aligned} \tag{4a}$$

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

$$N_\mathrm{c} = \frac{3\mathrm{LWP}_C}{4\pi\rho_\mathrm{w} r_\mathrm{c}^3 \Delta H}\exp(3\sigma_x^2), \tag{4b}$$

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:

$$\tau_\mathrm{c} = \frac{3\mathrm{LWP}_C}{2r_\mathrm{c}\rho_\mathrm{w}}. \tag{4c}$$

Dong et al. (2014a) summarized the uncertainties for the retrieved cloud properties: ∼ 10 % for r_c, ∼ 20–30 % for N_c, and ∼ 10 % for τ_c based on the comparisons with aircraft in situ measurements at midlatitude continental sites (Dong et al., 1998 and 2002; Dong and Mace, 2003). Dong et al. (2014a) also compared the MBL cloud property retrievals with aircraft in situ measurements during ASTEX (field intensive operational period (IOP) during 1992 at Azores) with reasonable agreement. Aircraft in situ data are required to directly validate the MBL cloud microphysical property retrievals in Dong et al. (2014a and b).

The microwave-radiometer-retrieved LWP represents the entire atmospheric column, including both cloud liquid water path ($\mathrm{LWP_c}$) and drizzle liquid water path ($\mathrm{LWP_d}$). Therefore it is necessary to estimate $\mathrm{LWP_c}$ by eliminating $\mathrm{LWP_d}$ from LWP in order to get more accurate cloud property retrievals from Dong et al. (2014a).

3 Results and discussions

Figure 1 demonstrates virga and rain drizzle below the cloud base from two selected cases along with their retrieved microphysical properties. Case I represents a typical virga case which occurred on 22 November 2009, and Case II is a typical rain case that occurred on the late afternoon of 8 November and lasted until the morning of 9 November 2010. Figure 1a and f present WACR reflectivity profiles and cloud-base heights (CBHs), and Fig. 1b and g illustrate the ceilometer-attenuated backscatter coefficients for Cases I and II, respectively. Both cases have significant time periods in which the radar reflectivities are greater than −37 dBZ below the cloud base, but this happened more frequently in Case II than in Case I. Comparing Fig. 1a with Fig. 1f, the radar reflectivities are generally lower in Case I than in Case II, and the cloud layer in Case I is higher (CBH is 1246 m, cloud top height is 1625 m) and thinner (379 m) than that in Case II (CBH is 698 m, cloud top height is 1255 m, cloud thickness is 557 m). The retrieved r_d values (Fig. 1c) are relatively smaller in Case I than in Case II (Fig. 1h), but the N_d values are higher in Case I (Fig. 1d) than in Case II (Fig. 1i).

The mean r_d in Case I is 30.88 µm, with a range of ∼ 20–50 µm, while it is 42.48 µm for Case II, ranging from 20 to 70 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 70 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 and b). However, their mean N_d values of 0.882 and 0.692 cm^{-3} are 2 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 and b). The retrieved r_d and N_d values in both cases are also of the same magnitude as some previous studies (e.g., O'Connor et al., 2005; Frisch et al., 1995; Wang, 2002). The drizzle LWC ($\mathrm{LWC_d}$) below the cloud base is about 1–2 orders of magnitude lower than the cloud LWC ($\mathrm{LWC_c}$) above the 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 1c and d show that the r_d values below the 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

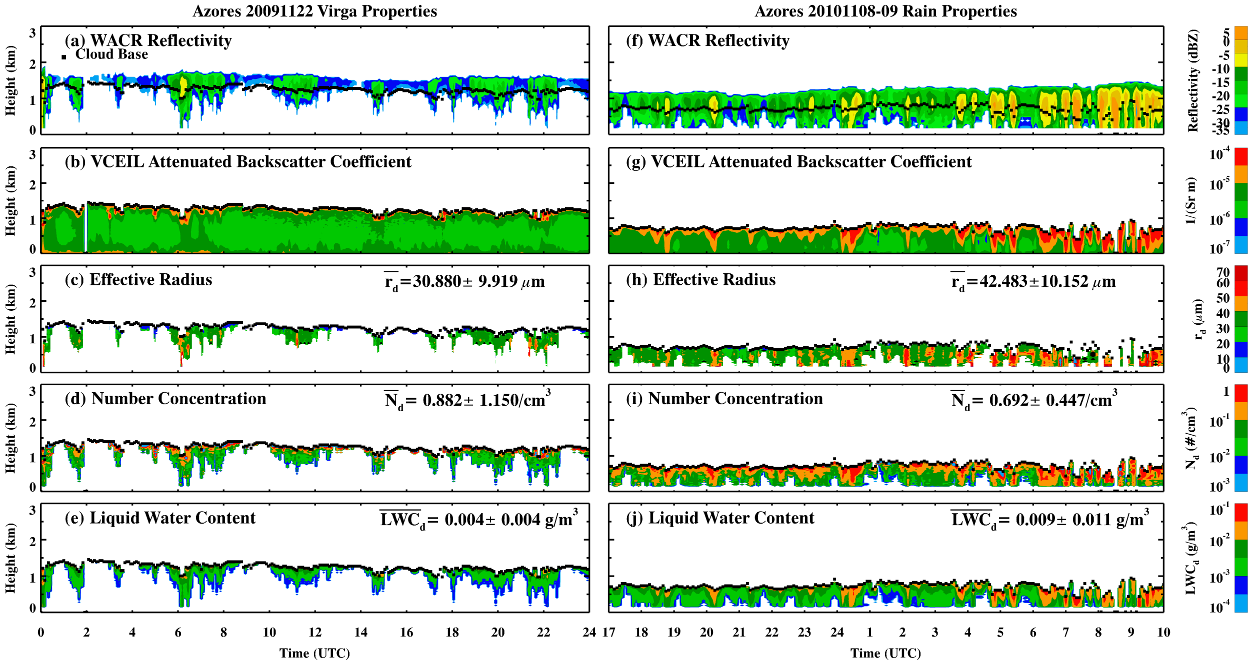

Figure 1. Drizzle properties observed by ARM radar lidar and retrieved from this study at the ARM Azores site. Two cases have been selected: Case I (left panel, 22 November 2009) is a typical virga case, and Case II (right panel, from late afternoon on 8 November 2010 to the morning of 9 November 2010)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

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

	VIRGA					RAIN				
	Year	Winter	Spring	Summer	Autumn	Year	Winter	Spring	Summer	Autumn
Samples (5 min)	4237	464	693	1742	1338	1345	244	225	574	302
LWP (g m^{-2})	107.39	90.48	135.86	108.36	94.84	223.24	197.13	269.35	231.41	195.08
r_c (μm)	12.44	12.13	12.94	12.93	11.77	16.15	15.55	16.54	16.41	16.11
N_c (cm^{-3})	78.96	76.66	75.98	72.20	90.98	34.44	30.23	35.85	36.68	35.01
τ	13.54	11.70	16.55	13.24	12.67	22.00	19.41	27.07	22.62	18.89
LWP$_d$ (g mm^{-2})	1.25	1.76	1.22	0.89	1.14	4.73	5.31	4.46	4.51	4.62
(% of LWP$_d$/LWP)	(1.16)	(1.95)	(0.90)	(0.82)	(1.20)	(2.12)	(2.69)	(1.66)	(1.95)	(2.37)
r_d (μm)	36.45	38.07	37.81	35.67	34.24	61.46	62.32	63.76	57.36	62.41
N_d (cm^{-3})	0.79	0.71	0.83	0.87	0.74	0.38	0.41	0.27	0.46	0.37
LWP$_c$ (g m^{-2})	106.09	88.72	134.58	107.39	93.66	218.52	191.82	264.89	226.90	190.46
r_c' (μm)	12.35	11.98	12.88	12.86	11.68	15.78	15.10	16.18	16.11	15.71
N_c' (cm^{-3})	79.74	78.38	76.72	72.21	91.63	35.61	31.73	36.92	37.47	36.32
τ'	13.52	11.67	16.53	13.23	12.65	21.95	19.33	27.03	22.60	18.85

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 the 19-month period (Dong et al. 2014a).

the 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 be a result of either the evaporation of the drizzle particles or the collision–coalescence process of rain.

To provide statistical results of drizzle microphysical properties and investigate to what extent drizzle impacts cloud property retrievals given in Dong et al. (2014a), 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 mode values of 0 and −20 dBZ, respectively. The mode value (0 dBZ) of rain is consistent with the definition

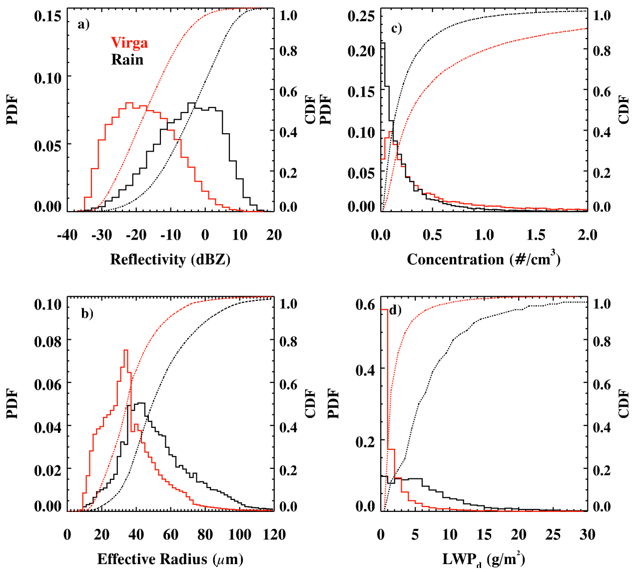

Figure 2. Probability distribution functions (PDFs) and cumulative density functions (CDFs) of daytime drizzle properties at the Azores during the period from June 2009 to December 2010. PDFs and CDFs of **(a)** WACR reflectivities below the cloud base for drizzle from virga and rain in this study, **(b)**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

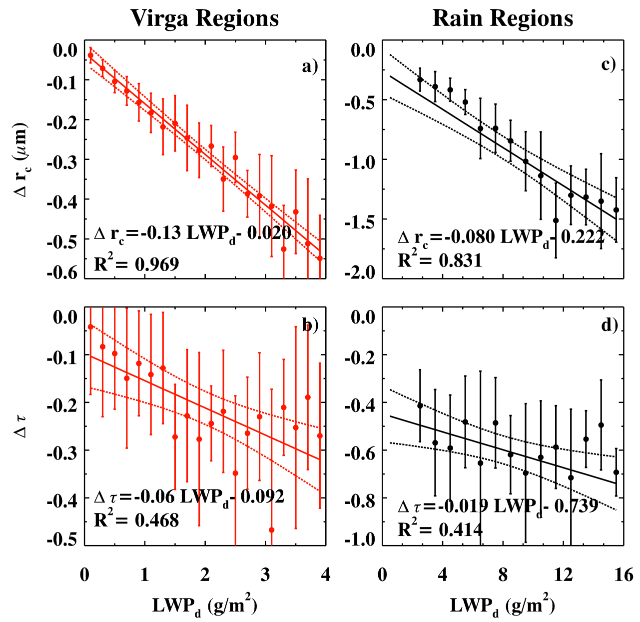

Figure 3. The impact of drizzle on cloud property retrievals (daytime only). The left panel is for the selected virga samples (red line) and the right panel is for the selected rain samples (black line). Solid dots denote the mean values of each bin, and the bottom and top of each whisker represent 1 standard deviation. 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.

of intense precipitation type given in Rémillard et al. (2012). From the CDFs of Fig. 2a, 57 % of the virga and 13 % of rain samples are less than −15 dBZ, and 36 % of the virga and 10 % 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 values of virga and rain samples are ∼ 35 and 44 µm, respectively. Nearly 81 % of the virga samples and 55 % of the rain samples are less than 50 µm, while there are almost no virga samples and only 10 % rain samples left for $r_{\mathrm{d}} > 80$ µm. 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 60 % for virga and 85 % for rain less than 0.5 $\mathrm{cm^{-3}}$ and more virga samples for large values. About 85 % of virga $\mathrm{LWP_d}$ values are less than 4 $\mathrm{g\,m^{-2}}$ and 90 % of the rain samples are less than 16 $\mathrm{g\,m^{-2}}$.

To investigate the impact of drizzle on cloud property retrievals given in Dong et al. (2014a), the cloud liquid water path ($\mathrm{LWP_c}$) is calculated by subtracting $\mathrm{LWP_d}$ from the microwave-radiometer-retrieved LWP, and then using it as an input for (4) to retrieve new MBL cloud microphysical properties, r'_{c}, $\mathrm{N'_c}$, and τ' without drizzle effect. These newly retrieved cloud properties (r'_{c}, $\mathrm{N'_c}$, τ') are then compared with the original retrievals in Dong et al. (2014a) where the LWP was used as $\mathrm{LWP_c}$ in (4). Figure 3 shows the dependence of the differences between originally and newly retrieved r_{c} and τ on $\mathrm{LWP_d}$ where both Δr_{c} and $\Delta\tau$ linearly decrease with increased $\mathrm{LWP_d}$. The slope of the linear regression line (Δr_{c} vs. $\mathrm{LWP_d}$) for the virga samples is 0.13, with a correlation coefficient ($\mathrm{R^2}$) of 0.969 (Fig. 3a), that is, the retrieved r_{c} decreases 0.13 µm at an increase of 1 $\mathrm{g\,m^{-3}}$ in $\mathrm{LWP_d}$. The r_{c} values will decrease by up to 0.55 µm with an increase of 4 $\mathrm{g\,m^{-3}}$ in $\mathrm{LWP_d}$, which is within the uncertainty (∼ 10 %) of originally retrieved $\mathrm{r_c}$ values in Dong et al. (2014a). The impact of drizzle on cloud optical depth retrieval (Fig. 3b) is weak with a slope of −0.06 and $\mathrm{R^2}$ of 0.468. For the rain samples, the slope is −0.08 and the correlation is 0.831. The r_{c} values can be reduced ∼ 1.5 µm, with an increase of 16 $\mathrm{g\,m^{-2}}$ in $\mathrm{LWP_d}$ and relatively larger fluctuation than for the virga samples. The impact of $\mathrm{LWP_d}$ on cloud optical depth retrieval is also weak in rain regions with a R^2 of 0.414.

A 95 % confidence interval for each regression line is computed, indicating that the true best-fit line for the samples has a 95 % probability of falling 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 and c suggest high reliability of the regression, whereas the broad interval in Fig. 3b and d 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 have been selected from the 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. The annual means of LWP_d, r_d, and N_d for the rain (virga) samples are 4.73 ($1.25\,g\,m^{-2}$), 61.46 (36.45 µm), and 0.38 ($0.79\,cm^{-3}$). 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 at a minimum 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 given in Dong et al. (2014a), we also calculate the ratio of LWP_d to LWP and cloud properties (r_c, N_d, τ) using (4) with the MWR-retrieved LWP and newly calculated cloud LWP_c (i.e., $LWP - LWP_d$). Although the annual mean LWP_d from the rain samples is about 4 times as large as that of the virga samples, their seasonal means are less than 3 % of the MWR-retrieved LWP. Therefore, their impact on cloud property retrievals given in Dong et al. (2014a) is insignificant. Notice that the cloud properties in Dong et et al. (2014a) are retrieved from a solar-transmission-based method (Eq. 4), which is nearly independent of drizzle, whereas for other methods using cloud radar reflectivity, their retrievals are heavily affected by any form of drizzle within and below clouds. As listed in Table 1, the annual mean differences of $(r_c - r_c')$ are 0.09 µm (0.75 %) and 0.38 µm (2.35 %) for the virga and rain samples, respectively. These differences fall within the cloud property retrieval uncertainty (∼ 10 %), validated by in situ aircraft measurements at midlatitude continental sites (Dong et al., 1998, 2002; Dong and Mace, 2003).

Regarding to the impact of the uncertainties of cloud LWP (10 %), γ (5%) and σ_x (0.13) on the cloud property retrievals in (4), D98 conducted some sensitivity studies. For example, a 10 % change (increase or decrease) in LWP will result in a parameterized $\bar{r_e}$ change within 10 %, and a 10 % change in γ can vary $\bar{r_e}$ by 12.4 %. Dong et al. (1997) conducted a sensitivity study on the impact of σ_x on the retrieved cloud properties and found that the retrieved $\bar{r_e}$ values are nearly the same, while the cloud-droplet number concentrations change from 15 to 30 % when σ_x varies from 0.2 to 0.5.

From Table 1, the contribution of drizzle LWP_d to total LWP is less than 3 %, thus the impact of drizzle below the cloud base on the cloud property retrievals given in Dong et al. (2014a) can be ignored when compared to the uncertainties from γ, σ_x and LWP values. Therefore, we conclude that the cloud-droplet effective radius retrieved using D98 is biased by the presence of drizzle, but the bias is generally very small. But for some individual cases, the differences can reach as large as ∼ 2 µm, which may cause a large uncertainty, especially in the study of cloud radiative properties using radiative transfer models (D98). The impacts of drizzle on the retrieved cloud-droplet number concentration and optical depth in Dong et al. (2014a) are also relatively small, presumably due to small changes in both LWP_c and r_c. The annual mean differences in cloud-droplet number concentration are -0.78 and $-1.17\,cm^{-3}$, respectively, for the virga and rain samples.

4 Summary and conclusion

In this study, we use a similar method as described in Rémillard et al. (2012) to identify virga and rain drizzle samples below the 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 in Dong et al. (2014a). 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 LWP_d, r_d, and N_d for the rain (virga) samples are 4.73 (1.25) $g\,m^{-2}$, 61.5 (36.4) µm, and 0.38 (0.79) cm^{-3}, respectively. 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. On the other hand, their N_d values are highest but their LWP_d and r_d are at a maximum during summer due to the persistent high pressure and dry conditions over the Azores.

2. To investigate the impact of drizzle on cloud property retrievals given in Dong et al. (2014a), we calculate the ratio of LWP_d to LWP and cloud properties (r_c, N_d, τ) using (4) with the MWR-retrieved LWP and newly calculated cloud LWP_c (i.e., $LWP - LWP_d$). The seasonal mean LWP_d values are less than 3 % of LWP values. The annual mean relative differences $(r_c - r_c')/r_c$ are 0.75 and 2.35 %, respectively, for the virga and rain samples. These differences fall within the cloud

property retrieval uncertainty ($\sim 10\,\%$). 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 for a solar-transmission-based method. For other methods using cloud radar reflectivity, however, their retrievals are heavily affected by any forms of drizzle within and below clouds.

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