4-20-2018

Scaling of drizzle virga depth with cloud thickness for marine stratocumulus clouds

Fan Yang
Brookhaven National Laboratory

Edward P. Luke
Brookhaven National Laboratory

Pavlos Kollias
Brookhaven National Laboratory

Alexander Kostinski
Michigan Technological University

Andrew M. Vogelmann
Michigan Technological University

Recommended Citation

Yang, F., Luke, E. P., Kollias, P., Kostinski, A., & Vogelmann, A. M. (2018). Scaling of drizzle virga depth with cloud thickness for marine stratocumulus clouds. *Geophysical Research Letters, 45*(8), 3746-3753. http://dx.doi.org/10.1029/2018GL077145
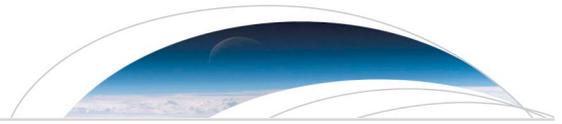Retrieved from: https://digitalcommons.mtu.edu/physics-fp/162

Geophysical Research Letters

Key Points:
- Long-term statistics of marine stratocumulus drizzle virga depth and frequency are analyzed using unique ground-based remote sensing data
- An expression for drizzle virga depth is analytically derived as a function of cloud thickness and subcloud relative humidity
- Derived third-order power law relationship between drizzle virga depth and cloud depth shows good agreement with long-term radar statistics

Scaling of Drizzle Virga Depth With Cloud Thickness for Marine Stratocumulus Clouds

Fan Yang[1] [ID], **Edward P. Luke[1]**, **Pavlos Kollias[1,2]** [ID], **Alex B. Kostinski[3]** [ID], and **Andrew M. Vogelmann[1]** [ID]

[1]Brookhaven National Laboratory, Upton, NY, USA, [2]School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY, USA, [3]Atmospheric Sciences Program, Department of Physics, Michigan Technological University, Houghton, MI, USA

Abstract Drizzle is frequently observed in marine stratocumulus clouds and plays a crucial role in cloud lifetime and the radiation budget. Most drizzling stratocumulus clouds form drizzle virga below cloud base, where subcloud scavenging and evaporative cooling are important. We use unique ground-based cloud radar observations (1) to examine the statistical properties of drizzle frequency and virga depth and (2) to test a simple analytical relationship derived between drizzle virga thickness (H_v) and cloud thickness (H_c). Observations show that 83% of marine stratocumulus clouds are drizzling although only 31% generate surface precipitation. The analytical expression for H_v is derived as a function of H_c and subcloud relative humidity considering in-cloud accretion and subcloud evaporation of drizzle drops. The derived third-order power law relationship, $H_v \sim H_c^3$, shows good agreement with long-term observational data. Our formula provides a simple parameterization for drizzle virga of stratocumulus clouds suitable for use in models.

Plain Language Summary Drizzle plays a crucial role in cloud lifetime and radiation properties of marine stratocumulus clouds. Understanding where drizzle exists in the subcloud layer, which depends on drizzle virga depth, can help us better understand where below-cloud scavenging and evaporative cooling and moisturizing occur. Here we examine the statistical properties of drizzle frequency and virga depth of marine stratocumulus based on unique ground-based remote sensing data. Results show that marine stratocumulus clouds are drizzling nearly all the time. In addition, we derive a simple scaling analysis between drizzle virga thickness and cloud thickness. Our analytical expression agrees with the observational data reasonably well, which suggests that our formula provides a simple parameterization for drizzle virga of stratocumulus clouds suitable for use in other models.

1. Introduction

Stratocumulus clouds cover large areas in subtropical and tropical ocean regions and play an important role in Earth's radiation budget (Lamb & Verlinde, 2011). Drizzle drops, generating light precipitation, are frequently observed below marine stratocumulus clouds (e.g., Glienke et al., 2017; Leon et al., 2008; Rémillard et al., 2012; Wu et al., 2017). The initiation, growth, and depletion of drizzle play crucial roles in the stratocumulus-topped boundary layer and have been studied extensively (Wood, 2012). The definition of drizzle varies depending on the technique and research objective. Based on radar remote sensing, a common criterion for whether drizzle exists is when radar reflectivity exceeds −17 dBz (Frisch et al., 1995). Drizzle can also be observed at significantly lower cloud reflectivities when considering higher-order radar Doppler moments, particularly skewness (Kollias, Rémillard et al., 2011; Kollias, Szyrmer et al., 2011; Luke & Kollias, 2013). Based on in situ measurements or model simulations, drizzle is usually considered to be drops with radii larger than 20 μm, when collision coalescence is efficient, but smaller than rain drops (∼250 μm; Feingold et al., 1999; Glienke et al., 2017).

The growth of drizzle drops in stratocumulus cloud mainly depends on two processes: autoconversion (coalescence between cloud droplets) contributes to drizzle onset, while accretion (coalescence between drizzle and cloud droplets) dominates when drizzle falls through the cloud layer. By assuming vapor diffusional growth of cloud droplets from the bottom up and continuous collection growth of drizzle drops from the top down, Kostinski (2008) predicts that drizzle radius at cloud base (r_{cb}) scales quadratically with cloud thickness (H_c), $r_{cb} \propto H_c^2$. In situ measurements show that the mean volume radii of drizzle drops at cloud base typically range

from 30 μm to 100 μm (Wood, 2005); however, as far as we know, this quadratic relationship between r_{cb} and H_c has not been tested observationally.

Drizzle will evaporate once it falls out of the cloud because of subsaturation in the subcloud region. Those drizzle drops can influence the subcloud layer in several ways. First, drizzle can scavenge aerosols below cloud. This below-cloud scavenging process not only cleans the subcloud layer but it can also process the cloud condensation nuclei spectrum after drizzle totally evaporates (Feingold et al., 1996), and it can even lead to rapid stratocumulus-cumulus transitions (Yamaguchi et al., 2017). Second, evaporative cooling can generate cold pools, which influence subcloud circulation and cloud mesoscale organization (e.g., Feingold et al., 2010; Wang & Feingold, 2009; Zhou et al., 2017). Third, drizzle evaporation will moisten the subcloud layer, thus redistributing water in the boundary layer (Wood, 2005).

Understanding where drizzle exists in the subcloud layer, which depends on drizzle virga depth, can help us better understand where below-cloud scavenging and evaporative cooling and moisturizing occur. Here we use the definition of virga given by Petterssen (1968) where "drizzle virga" is defined as the region where drizzle drops exist below cloud and totally evaporate before reaching the ground. It is known that virga thickness depends on drizzle droplet size at cloud base and the relative humidity profile in the subcloud region (Fraser & Bohren, 1992), while drizzle droplet size at cloud base is related to cloud thickness (Kostinski, 2008). Thus, it is reasonable to conjecture that drizzle virga thickness should depend on both cloud and subcloud properties.

In this study, we investigate how the drizzle virga thickness is related to cloud thickness and subcloud relative humidity. A relationship is derived analytically based on a minimalist cloud model (Kostinski, 2008) and a sedimentation-evaporation drizzle model (Fraser & Bohren, 1992). The resulting analytical expressions, r_{cb} versus H_c and H_v versus H_c, are tested using a unique long-term data set derived from ground-based radar and lidar measurements. Finally, the applications and limitations of this relationship are discussed.

2. Scaling Analysis for Drizzle Virga Thickness

A minimalist cloud model for continuous collision predicts that the size of drizzle drops at cloud base has a quadratic relationship with cloud thickness (equation 5 in Kostinski, 2008):

$$r_{cb} \propto H_c^2. \tag{1}$$

This model assumes adiabatic growth of cloud droplets on the way up, which leads to a linearly increasing liquid water mixing ratio profile. It also assumes that drizzle drops at cloud base result from continuous collision of cloud droplets (accretional growth) starting from cloud top. Equation (1) not only leads to a relationship between drizzle rate and cloud depth (Kostinski, 2008), but it can also connect drizzle virga thickness to cloud thickness because H_v is very sensitive to r_{cb} based on the sedimentation-evaporation drizzle model discussed below.

A drizzle drop of given radius at cloud base, initially $r = r_{cb}$, will fall at its terminal velocity, $v(r)$, in still air. At the same time, the drizzle drop will evaporate following the linear rate dr/dt, which is linearly proportional to the local subsaturation ratio $s(z)$ and inversely proportional to its radius (Lamb & Verlinde, 2011). The collision coalescence and breakup of drizzle drops are ignored because of their relatively smaller size compared with raindrops (Feingold, 1993). The sedimentation-evaporation drizzle model was used to study the evaporation of drizzle/rain below cloud base (Best, 1952; Fraser & Bohren, 1992). It has also been applied to study relationships between radar reflectivity and rain rate below cloud base (Comstock et al., 2004). In this study, we are interested in how drizzle virga thickness depends on drizzle drop size at cloud base and subcloud relative humidity.

The basic equation for drizzle evaporation below cloud base is $r\frac{dr}{dt} = Gs(z)$. In this equation, $s(z) = RH(z) - 1$ is the subsaturation ratio at height z, where $RH(z)$ is the relative humidity at that level. The prefactor G is usually assumed to be almost constant with a weak dependence on temperature and pressure. Using the chain rule, we can get

$$r\frac{dr}{dz}v(r) = Gs(z), \tag{2}$$

where $v(r) = \frac{dz}{dt}$ is the terminal velocity of a drizzle drop. With two sets of assumptions we can get a simple relationship between r_{cb} and H_v. First, the fractional relative humidity is assumed to be unity at cloud base and to have a linearly decreasing profile below. A similar assumption is used in Comstock et al. (2004). The slope

of the $RH(z)$ profile below cloud base ($k = \mathrm{d}RH(z)/\mathrm{d}z$) is then a constant. Because s has a linear relationship with RH ($s(z) = RH(z) - 1$), a linearly decreasing profile of RH below cloud base leads to a linearly decreasing profile of $s = kz$ with 0 at cloud base. Second, the terminal velocity is assumed to be linear with drop size, $v(r) \sim r$. This is a reasonable assumption for drizzle drops (Kostinski, 2008), but it is not good for small cloud droplets because $v(r) \sim r^2$ in laminar flow. However, if the time period for which large drizzle exists (i.e., when $v(r) \sim r$ holds) is much longer than the time period for which small droplets exist (when $v(r) \sim r$ does not hold), we anticipate that this assumption would have little effect on our calculations of drizzle virga depth. This is probably the case because the evaporation rate of small droplets is faster than large drizzle drops. Additionally, those small droplets usually exist far below cloud base where relative humidity is low and evaporation is thus enhanced.

With these two assumptions, the integral of equation (2) from cloud base to the level where drizzle totally evaporates yields,

$$\int_0^{r_{cb}} r^2 \mathrm{d}r \propto \int_0^{H_v} kz\, \mathrm{d}z \tag{3}$$

and thus,

$$r_{cb}^3 \propto H_v^2 k. \tag{4}$$

Based on equations (1) and (4), we can get

$$H_v \propto H_c^3. \tag{5}$$

Equation (5) predicts that drizzle virga thickness has a third power law relationship with cloud thickness. The prefactor for equation (5) is $\sqrt{2a^3 b/3Gk}$, where a is the prefactor for r_{cb} versus H_c^2, b is from the v-r relationship ($v = br$), G is the condensational growth parameter, and k is the slope of relative humidity profile below cloud base. It is interesting to note that drizzle rate at cloud base also has a third power law relationship with the cloud thickness, as discussed in Kostinski (2008). The power law relationships of r_{cb} versus H_c (equation (1)) and H_v versus H_c (equation (5)) will be tested using long-term remote sensing data.

3. Data and Methods

Data were collected between 6 October 2015 and 23 November 2016 at the Eastern North Atlantic Atmospheric Radiation Measurement Climate Research Facility observation site located on Graciosa Island in the Azores archipelago. Ka-band cloud radar and lidar (ceilometer) were used to derive the information on cloud thickness, drizzle virga thickness, and median volume drizzle diameter near cloud base. The vertical resolutions of the radar and lidar are, respectively, 30 m (one range gate) and 15 m, and the temporal resolutions are 2 s and 16 s. The radar and lidar beams are, respectively, about 3 and 0.1 m wide for our observations. The subcloud relative humidity profiles were interpolated from the twice daily radiosonde data to the radar time-height grid.

Single-layer stratocumulus clouds are manually chosen from days having boundary layer clouds with preferably long duration and minimal variation of cloud base height (hereafter, CBH). The statistical properties for each day with selected stratocumulus clouds are listed in the supporting information. This results in a 42-day data set of stratocumulus clouds containing 1.2 million cloud profiles. For each profile, CBH is first obtained from the ceilometer and then mapped to the corresponding range gate in the nearest time-height radar profile; this is defined as the cloud base in this study. Cloud top is the highest range gate in a continuous column of signal detections above cloud base, and cloud thickness is the distance between cloud top and cloud base. A cloud is defined as drizzling when the lowest radar range gate with detected signal is at least three range gates below cloud base. This three-gate "safe zone" prevents excessively noisy drizzle detections and assurance that cloud droplets do not contaminate the drizzle size retrievals, as discussed later. The height of the lowest range gate is termed the drizzle virga base, and the drizzle virga thickness is the distance between cloud base and the drizzle virga base. We remove the data if drizzle reaches the ground, as drizzle thickness is then limited by the depth of the subcloud layer and violates our definition of virga from Petterssen (1968).

4. Results

Results show that marine stratocumulus clouds are frequently drizzling below cloud base even when they do not generate surface precipitation. Specifically, based on our definition, 83% of our cloud profiles are drizzling,
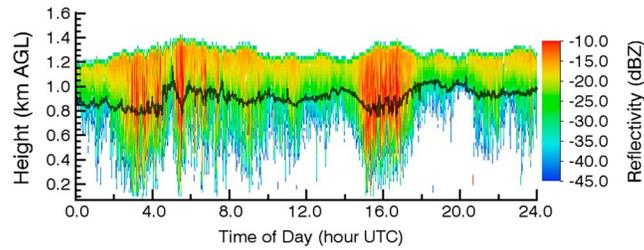
Figure 1. Time series of radar reflectivity of a marine stratocumulus cloud at the Eastern North Atlantic site on 4 March 2016. The black line is the cloud base as detected by the laser ceilometer. The drizzle criterion of three range gates is 0.09 km below cloud base, which would identify almost all of the drizzle in this plot as virga.

but only 31% of those drizzling profiles reach the ground. We note that requiring drizzle to exist 90 m (three radar range gates) below cloud base, although a very sensitive definition, will still underestimate the true fraction of drizzling clouds by excluding those that are drizzling only one or two range gates below cloud base. It also should be mentioned that the drizzling fraction decreases as the minimum radar reflectivity threshold increases (see Figure S1 in the supporting information). In this study, our radar reflectivity threshold is around -55 dBz corresponding to the mean rain rate of about 10^{-5} mm/hr. If we choose a threshold of -37 dBz, the drizzling fraction would be about 70%, which is consistent with Dong et al. (2014). An example of a drizzling cloud is shown in Figure 1. It can be seen that the cloud is drizzling nearly all the time for that particular day and that both H_v and H_c change with time. In addition, H_v and H_c tend to be positively correlated and that the variation of H_v is greater than that for H_c. These properties are qualitatively consistent with the nonlinear relationship between H_v and H_c predicted by equation (5).

The relative occurrence of CBH for all data is shown in Figure 2a. It can be seen that CBH can range from a few hundred meters to more than 2 km, with the maximum occurrence frequency around 852 m. To prevent variations in CBH from controlling the available range of virga thicknesses, we subset the data to confine CBH to be within a narrow range of 852 ± 75 m (total of five radar range gates), which brackets the modal value. This range is chosen to provide a sufficient population of data, and it also provides enough subcloud layer depth for the virga development to span our values of interest. A narrow range of CBH also simplifies the calculation of mean subcloud relative humidity profile. More importantly, it ensures that radar sensitivity, which depends on the distance between the radar and the target, is consistent at three range gates below cloud base for this subset, as our retrieved drizzle size depends on the radar sensitivity. For this subset of stratocumulus cloud, the drizzling cloud fraction is 84%, which is similar to the full data set, 40% of which generates surface precipitation, which is 9% higher than the full data set. The relative occurrences of cloud thickness (solid line) and drizzle virga thickness (dashed line) for the subset are shown in Figure 2b. It can be seen that although the CBH is constrained to be around 852 m, the cloud thickness and drizzle virga thickness can still vary from less than 100 m to 500 m. The maximum occurrence of cloud thickness is around 240 m, and the relative occurrence of drizzle virga depth decreases with its thickness.
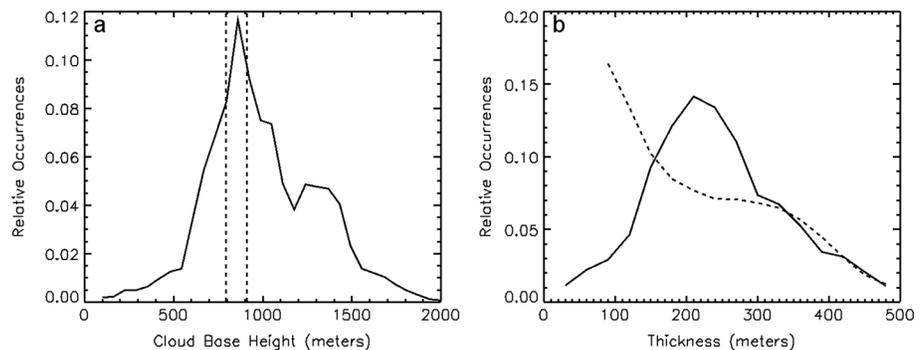
Figure 2. (a) Relative occurrence of cloud base height for all the selected stratocumulus clouds in this study at the Eastern North Atlantic site. The subset bounded by vertical dashed lines centered at the maximum relative occurrence of cloud base height, consisting of five radar range gates (852 ± 75 m), is used for our statistical analysis. (b) The relative occurrences of cloud thickness (solid line) and drizzle virga thickness (dashed line) for the subset data in (a).
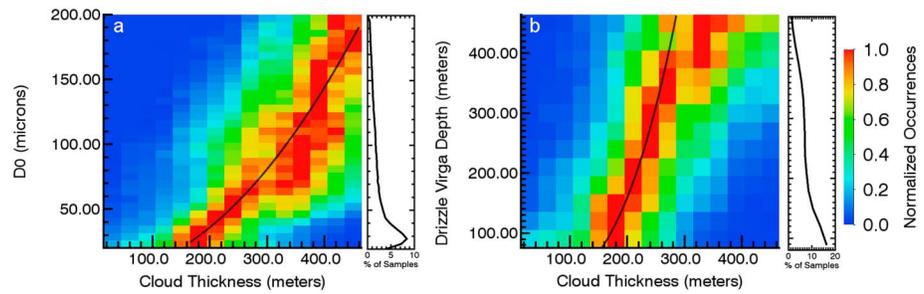
Figure 3. (a) Median volume diameter of drizzle (D_o) retrieved at 90 m (three range gates) below cloud base versus cloud thickness. The color represents the occurrences frequency per range bin normalized horizontally, and the black line is the best second-order power law fit. Panel on the right shows the relative occurrence of different D_o. (b) Drizzle virga thickness versus cloud thickness. The color represents the horizontally normalized occurrences, and the black line is the best third-order power law fit. Panel on the right shows the relative occurrence of different drizzle virga depths.

To test the quadratic relationship between r_{cb} and H_c predicted by equation (1), the median volume diameter of drizzle at 90 m below the cloud base (D_o) are retrieved from radar and lidar based on O'Connor et al. (2005). The reason we choose a level below, rather than at, cloud base is that the retrieval method does not work in the presence of cloud droplets. However, evaporation exists below cloud base. We find that the mean drizzle number concentration decreases monotonically toward the surface indicating that evaporation occurs below cloud base (see Figure S2 in the supporting information), which is consistent with the virga case in Wu et al. (2015). Therefore, D_o is only a proxy for the size of drizzle drops at cloud base, and we expect that the lower bias would not affect the power law relationship between drizzle size at cloud base and cloud thickness. Figure 3a shows the frequency occurrence of cloud thickness for different D_o with a black line providing the best second-order power law fit: $D_o = 9.0 \times 10^{-4} H_c^2$. Although several factors can affect our fitted curve, such as the uncertainties in retrieved H_c and D_o and the effect of subcloud evaporation, it is interesting to note that the fitting curve captures well the general trend of the maximum normalized occurrences. The spread of the data is larger for thicker cloud. This might be because (1) in-cloud turbulence might either enhance or suppress the accretional growth of drizzle drops and (2) there are fewer samples for thicker clouds corresponding to larger D_o which makes them less statistically significant (see sample percentages for different D_o on the right side of Figure 3a). For a last check, the prefactor for the r_{cb} and H_c relationship predicted by Kostinski (2008), based on equations 4 and 5 in his paper, is $10^{-7} \times \Gamma$, where Γ is the temperature lapse rate. Assuming $\Gamma = 6$ K/km (the moist adiabatic lapse rate), the prefactor is 6×10^{-10} m^{-1}, which is 12×10^{-4} μm/m^2 after converting to diameter in units of μm. This is a little bit larger than the value obtained from the fitted curve (9.0×10^{-4} μm/m^2). A contributing factor might be subcloud evaporation in the observations, which would act to reduce the prefactor.

It is also interesting to note that D_o peaks at around 30 μm (right panel in Figure 3a). This value is smaller than the value for virga derived at the same site by Wu et al. (2015), where they obtain a value of ~70 μm using a different radar from June 2009 to December 2010. The difference is mainly due to a relatively lower radar sensitivity threshold in our case of about −55 dBz, while their threshold is about −37 dBz (Figure 2a in their paper). If we choose a random subset of our data to have a similar probability density function of radar reflectivity to that used in their study, the retrieved effective radius is larger (see Figure S3 in the supporting information). This means that with more radar sensitivity, we can detect more lightly drizzling stratocumulus cloud. It also means that the retrieved D_o strongly depends on the choice of radar reflectivity threshold. Therefore, D_o is only a proxy of drizzle size at cloud base. It would be worthwhile to obtain the drizzle size at cloud base through in situ measurements and reexamine the relationship in the future.

Figure 3b shows the frequency occurrence of H_v for different H_c, and the black line the best third-order power law fit: $H_v = 2.0 \times 10^{-5} H_c^3$. It can be seen that the fit captures the general trend of the maximum normalized occurrences except for larger H_c and H_v, where H_v is usually thinner than predicted for a given H_c. Some possible reasons for this are as follows: (1) the simple continuous accretion model and the sedimentation-evaporation model do not consider the effect of cloud and subcloud dynamics, (2) the fewer samples for high H_v might not be statistically significant (see panel on the right side of Figure 3b), and (3) time-varying relative humidity profiles might not be linear far below the cloud base. The prefactor based on our analytical model is $\sqrt{2a^3 b/3Gk}$ (see section 2). By taking $b = 8 \times 10^3$ s^{-1} and $G = 70$ μm^2/s

(Yau & Rogers, 1996), the value would be 0.7×10^{-5} m^{-2}. It is smaller than the value from the best fit (2.0×10^{-5} m^{-2}). A possible reason for this could be that dynamics can generate larger spectrum of drizzle drops through either stochastic collision or through recycling, which can extend the range of virga depth, while our model assumes a monodisperse drizzle size distribution in a still environment.

Finally, we will test the effect of subcloud relative humidity on the H_v versus H_c relationship. All profiles in the subset of Figure 2a are split evenly into a relatively dry and a relatively humid subset based on their corresponding relative humidity profiles. Results show that all three average relative humidity profiles are approximately linear in the subcloud layer, especially in the region where most drizzle virga exist (between 800 m and 400 m), and the dry subset has a larger lapse rate than the humid subset as we expected (see Figure S4 in the supporting information). The slopes of the average subcloud relative humidity profiles for all, dry, and humid subsets are 3.4×10^{-4}, 4.3×10^{-4}, and 2.8×10^{-4} m^{-1}, respectively.

The horizontally normalized occurrences of H_v versus H_c for the two subsets are shown in Figures S4b (dry) and S4c (humid) and the best third-order power law fits are $H_v = 1.6 \times 10^{-5} H_c^3$ (dry) and $H_v = 2.3 \times 10^{-5} H_c^3$ (humid). Equation (5) states that the prefactor is proportional to $k^{-0.5}$ where k is the slope of the subcloud relative humidity profile, suggesting a larger prefactor for a humid boundary layer. This is qualitatively consistent with our best fits, meaning that drizzle virga thickness is expected to be larger in a wetter boundary layer (see Figures S4b and S4c where the best fits shift to the right for the dry subset and shift to the left for the humid subset). The ratio of the humid prefactor from the best fit to that for all profiles, 1.17, is larger than the 1.09 estimated from equation (5). Conversely, the ratio of the dry prefactor from the best fit to that for all profiles, 0.83, is smaller than the 0.91 estimated from equation (5). We note that the low temporal resolution of measured relative humidity profile used in this study can lead to a lower degree of accuracy for prefactor estimation. It should be mentioned that different choices of subset will have different relative humidity profiles, but the influence of the variation in relative humidity profile on the estimation of drizzle virga depth is relatively small. This is because, statistically, the mean relative humidity profile does not change significantly (see Figure S4a) and the drizzle virga thickness has little sensitivity to the relative humidity compared with cloud thickness (see equation (5)).

5. Discussion and Conclusions

In this study, we analyzed the high-resolution Ka-band cloud radar and lidar data at the Eastern North Atlantic Atmospheric Radiation Measurement Facility site between 6 October 2015 and 23 November 2016. More than 1.2 million cloud profiles, comprising 42 days of single-layer marine stratocumulus clouds, are used to investigate the statistical properties of drizzling cloud. Results show that 83% of our cloud sampling profiles are drizzling although only 31% generate surface precipitation. This suggests that drizzle is a common feature of marine stratocumulus cloud and that most of the drizzle drops evaporate in the subcloud layer before reaching the ground. The drizzle drops that evaporate before reaching the ground are termed drizzle virga in this study. This is the region where subcloud scavenging and evaporative cooling occur, which might play an important role in the dynamic, thermodynamic, and microphysical properties of the boundary layer (e.g., Feingold et al., 1996; Yamaguchi et al., 2017; Zhou et al., 2017).

Based on an idealized sedimentation-evaporation drizzle model, which considers that drizzle drops fall and evaporate in a still environment that has a linear relative humidity profile, H_v strongly depends on drizzle drop size at cloud base r_{cb}. Meanwhile, r_{cb} is expected to have a quadratic relationship with H_c based on a minimalist continuous-collision cloud model (Kostinski, 2008). We combine these two models to predict that H_v has a cubic power law relationship with H_c and that the prefactor depends on the slope of the subcloud relative humidity profile. The beauty of this relationship is that it does not depend on cloud droplet number concentration, which is difficult to retrieve from remote sensing instruments, while H_v and H_c are readily measured by radar and lidar.

The median volume diameter of drizzle at 90 m below cloud base (D_o) retrieved from radar and lidar measurements is used to approximate the drizzle size at cloud base. Results show that the best second-order power law fit follows the maximum normalized occurrences of the retrieved D_0 and H_c and that the prefactor predicted by equation (1) is on the same order but slightly larger than the fit. The best third-order power fit for the retrieved H_v and H_c also follows the general trend of the maximum normalized occurrences except for

$H_c > 300$ m. Data are separated into two groups, dry and humid, based on the subcloud relative humidity profiles from radiosondes. The best fits for these two groups follow equation (5) qualitatively, where drizzle virga thickness is expected to be larger for a humid boundary layer. However, the ratio of the prefactor (humid:dry) predicted based on equation (5) is somewhat smaller than that from the best fits. The reasonably good agreement between the observations and our analytical result suggests that our minimalist model is a valid tool for investigating other properties of the stratocumulus-topped boundary layer, such as understanding where below-cloud scavenging and evaporative cooling and moisturizing occur. In addition, our analytical result can also help us to better predict the surface precipitation, because surface precipitation occurs when the predicted drizzle virga depth is equal to or larger than the CBH. In fact, it is nice to see that H_v is very sensitive to H_c, $H_v \sim H_c^3$, as a small increase of cloud thickness can lead to significant increase of drizzle virga depth. Therefore, surface precipitation is possible even for a relatively thin cloud.

Although the general agreement is good, there are several factors that can lead to the observational data spread around the predicted value. First, there is the uncertainty of the heights involved. The uncertainties in the radar representations of cloud top and cloud base are each half of one range gate (± 15 m), and thus a full range gate for cloud thickness. There are also temporal and spatial mismatches of the cloud base detected by the ceilometer compared with radar that can also increase the observational uncertainty of the measured H_c and H_v. Another reason might be that the number of samples at large H_c are much fewer than at small H_c so the result for large H_c might be underconstrained. Second, the low temporal resolution of the radiosonde profiles limits our accuracy of the prefactor prediction. Third, our model does not consider the influence of dynamics on drizzle growth in the cloud region and the drizzle evaporation in the subcloud region. The interactions between drizzle evaporation and dynamics (e.g., Xue et al., 2008) are also not considered here. This might explain that the deviations are larger at large H_c. Fourth, as our model assumes a monodisperse drizzle size distribution and a linear subcloud relative humidity profile, assuming a polydisperse drizzle size distribution and different shapes of relative humidity profiles would have different H_v and r_{cb} relationships based on the sedimentation-evaporation model (Comstock et al., 2004) and, thus, would also affect the power law relationship between H_v and H_c. Fifth, our model assumes a steady state condition for both the cloud and subcloud regions, which is a reasonable assumption if the time scales for drizzle growth in the cloud and drizzle evaporation in the subcloud layer are much shorter than the time scale for the change of dynamic and thermodynamic properties in the boundary layer. However, this might not be true under some conditions, which can also affect our results. Finally, our expressions are not applicable when drizzle is not present, such as in the cases of very thin or very polluted clouds.

Drizzle virga are a bridge connecting the cloud and subcloud regions. The frequent observation of drizzle virga suggests that drizzle drops are a common feature in marine stratocumulus clouds. Our fits cannot extend to the origin because there might not be drizzle in very thin clouds or very polluted clouds. The variation of drizzle virga thickness affects the region for subcloud scavenging and evaporative cooling. Our equation provides a simple way to estimate H_v, which can be used in large-scale models that do not simulate drizzle. More research is needed to study the dynamic effects on H_v and to quantify within the virga region the profiles of precipitation, scavenging, and radiative cooling. In addition, our model predicts that H_v does not depend on the cloud droplet number concentration (N_d), because equation (1) does not depend on N_d. The successful applications of equation (1) in the scaling analysis of rain rate (Kostinski, 2008) and drizzle virga depth suggest that cloud droplet number concentration probably only plays a minor role. It is worth to investigate the role of N_d on our prediction and whether N_d would lead on the spread in the data in the future.

References

Best, A. (1952). The evaporation of raindrops. *Quarterly Journal of the Royal Meteorological Society*, *78*(336), 200–225. https://doi.org/10.1002/qj.49707833608

Comstock, K. K., Wood, R., Yuter, S. E., & Bretherton, C. S. (2004). Reflectivity and rain rate in and below drizzling stratocumulus. *Quarterly Journal of the Royal Meteorological Society*, *130*(603), 2891–2918. https://doi.org/10.1256/qj.03.187

Dong, X., Xi, B., Kennedy, A., Minnis, P., & Wood, R. (2014). A 19-month record of marine aerosol–cloud–radiation properties derived from DOE ARM mobile facility deployment at the azores. Part I: Cloud fraction and single-layered MBL cloud properties. *Journal of Climate*, *27*(10), 3665–3682. https://doi.org/10.1175/JCLI-D-13-00553.1

Feingold, G. (1993). Parameterization of the evaporation of rainfall for use in general circulation models. *Journal of the Atmospheric Sciences*, *50*(20), 3454–3467. https://doi.org/10.1175/1520-0469(1993)050<3454:POTEOR>2.0.CO;2

Feingold, G., Cotton, W. R., Kreidenweis, S. M., & Davis, J. T. (1999). The impact of giant cloud condensation nuclei on drizzle formation in stratocumulus: Implications for cloud radiative properties. *Journal of the Atmospheric Sciences*, *56*(24), 4100–4117. https://doi.org/10.1175/1520-0469(1999)056<4100:TIOGCC>2.0.CO;2

Feingold, G., Koren, I., Wang, H., Xue, H., & Brewer, W. A. (2010). Precipitation-generated oscillations in open cellular cloud fields. *Nature*, *466*(7308), 849. https://doi.org/10.1038/nature09314

Feingold, G., Kreidenweis, S. M., Stevens, B., & Cotton, W. (1996). Numerical simulations of stratocumulus processing of cloud condensation nuclei through collision-coalescence. *Journal of Geophysical Research*, *101*(D16), 21,391–21,402. https://doi.org/10.1029/96JD01552

Fraser, A. B., & Bohren, C. F. (1992). Is virga rain that evaporates before reaching the ground? *Monthly Weather Review*, *120*(8), 1565–1571. https://doi.org/10.1175/1520-0493(1992)120<1565:IVRTEB>2.0.CO;2

Frisch, A., Fairall, C., & Snider, J. (1995). Measurement of stratus cloud and drizzle parameters in ASTEX with a k_α-band Doppler radar and a microwave radiometer. *Journal of the Atmospheric Sciences*, *52*(16), 2788–2799. https://doi.org/10.1175/1520-0469(1995)052<2788:MOSCAD>2.0.CO;2

Glienke, S., Kostinski, A., Fugal, J., Shaw, R., Borrmann, S., & Stith, J. (2017). Cloud droplets to drizzle: Contribution of transition drops to microphysical and optical properties of marine stratocumulus clouds. *Geophysical Research Letters*, *44*, 8002–8010. https://doi.org/10.1002/2017GL074430

Kollias, P., Rémillard, J., Luke, E., & Szyrmer, W. (2011). Cloud radar Doppler spectra in drizzling stratiform clouds: 1. Forward modeling and remote sensing applications. *Journal of Geophysical Research*, *116*, D13201. https://doi.org/10.1029/2010JD015237

Kollias, P., Szyrmer, W., Rémillard, J., & Luke, E. (2011). Cloud radar Doppler spectra in drizzling stratiform clouds: 2. Observations and microphysical modeling of drizzle evolution. *Journal of Geophysical Research*, *116*, D13203. https://doi.org/10.1029/2010JD015238

Kostinski, A. (2008). Drizzle rates versus cloud depths for marine stratocumuli. *Environmental Research Letters*, *3*(4), 45019. https://doi.org/10.1088/1748-9326/3/4/045019

Lamb, D., & Verlinde, J. (2011). *Physics and chemistry of clouds*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511976377

Leon, D. C., Wang, Z., & Liu, D. (2008). Climatology of drizzle in marine boundary layer clouds based on 1 year of data from CloudCat and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). *Journal of Geophysical Research*, *113*, D00A14. https://doi.org/10.1029/2008JD009835

Luke, E. P., & Kollias, P. (2013). Separating cloud and drizzle radar moments during precipitation onset using Doppler spectra. *Journal of Atmospheric and Oceanic Technology*, *30*(8), 1656–1671. https://doi.org/10.1175/JTECH-D-11-00195.1

O'Connor, E. J., Hogan, R. J., & Illingworth, A. J. (2005). Retrieving stratocumulus drizzle parameters using Doppler radar and lidar. *Journal of Applied Meteorology*, *44*(1), 14–27. https://doi.org/10.1175/JAM-2181.1

Petterssen, S. (1968). *Introduction to meteorology*. New York: McGraw Hill.

Rémillard, J., Kollias, P., Luke, E., & Wood, R. (2012). Marine boundary layer cloud observations in the Azores. *Journal of Climate*, *25*(21), 7381–7398. https://doi.org/10.1175/JCLI-D-11-00610.1

Wang, H., & Feingold, G. (2009). Modeling mesoscale cellular structures and drizzle in marine stratocumulus. Part I: Impact of drizzle on the formation and evolution of open cells. *Journal of the Atmospheric Sciences*, *66*(11), 3237–3256. https://doi.org/10.1175/2009JAS3022.1

Wood, R. (2005). Drizzle in stratiform boundary layer clouds. Part I: Vertical and horizontal structure. *Journal of the Atmospheric Sciences*, *62*(9), 3011–3033. https://doi.org/10.1175/JAS3529.1

Wood, R. (2012). Stratocumulus clouds. *Monthly Weather Review*, *140*(8), 2373–2423. https://doi.org/10.1175/MWR-D-11-00121.1

Wu, P., Dong, X., & Xi, B. (2015). Marine boundary layer drizzle properties and their impact on cloud property retrieval. *Atmospheric Measurement Techniques*, *8*(9), 3555–3562. https://doi.org/10.5194/amt-8-3555-2015

Wu, P., Dong, X., Xi, B., Liu, Y., Thieman, M., & Minnis, P. (2017). Effects of environment forcing on marine boundary layer cloud-drizzle processes. *Journal of Geophysical Research: Atmospheres*, *122*, 4463–4478. https://doi.org/10.1002/2016JD026326

Xue, H., Feingold, G., & Stevens, B. (2008). Aerosol effects on clouds, precipitation, and the organization of shallow cumulus convection. *Journal of the Atmospheric Sciences*, *65*(2), 392–406. https://doi.org/10.1175/2007JAS2428.1

Yamaguchi, T., Feingold, G., & Kazil, J. (2017). Stratocumulus to cumulus transition by drizzle. *Journal of Advances in Modeling Earth Systems*, *9*(6), 2333–2349. https://doi.org/10.1002/2017MS001104

Yau, M. K., & Rogers, R. (1996). *A short course in cloud physics*. Woburn, MA: Butterworth-Heinemann.

Zhou, X., Heus, T., & Kollias, P. (2017). Influences of drizzle on stratocumulus cloudiness and organization. *Journal of Geophysical Research: Atmospheres*, *122*, 6989–7003. https://doi.org/10.1002/2017JD026641