Azores Virga Depth: Analytical Expression as a Function of Cloud Depth Evaluated with Observations

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1. Motivation

Stratocumulus clouds are common in tropical and subtropical oceans and play a critical role in the Earth's hydrological cycle and energy balance. Drizzle drops are frequently observed in marine stratocumulus clouds and play a crucial role in cloud lifetime, sub-cloud scavenging, and evaporative cooling below cloud base. Understanding where drizzle exists in the sub-cloud layer, which depends on **drizzle virga depth**, can help us better understand where below-cloud scavenging and evaporative cooling and moisturizing occur. Two related questions are:

1. What is the drizzling fraction for marine stratocumulus clouds?
2. What controls the drizzle virga depth?

2. Data

- Data were collected between Oct. 6, 2015 and Nov. 23, 2016 at the Eastern North Atlantic.
- Ka-band cloud radar and ceilometer were used to get **cloud thickness (Hc)** and **drizzle virga depth (Hv)**. The vertical resolutions of the radar and lidar are 30 m and 15 m respectively.
- Single layer stratocumulus clouds are manually chosen from days having boundary layer clouds that preferably have long duration and minimal variation of cloud base height.

3. Marine stratocumulus clouds are frequently drizzling

An example of a drizzling cloud:

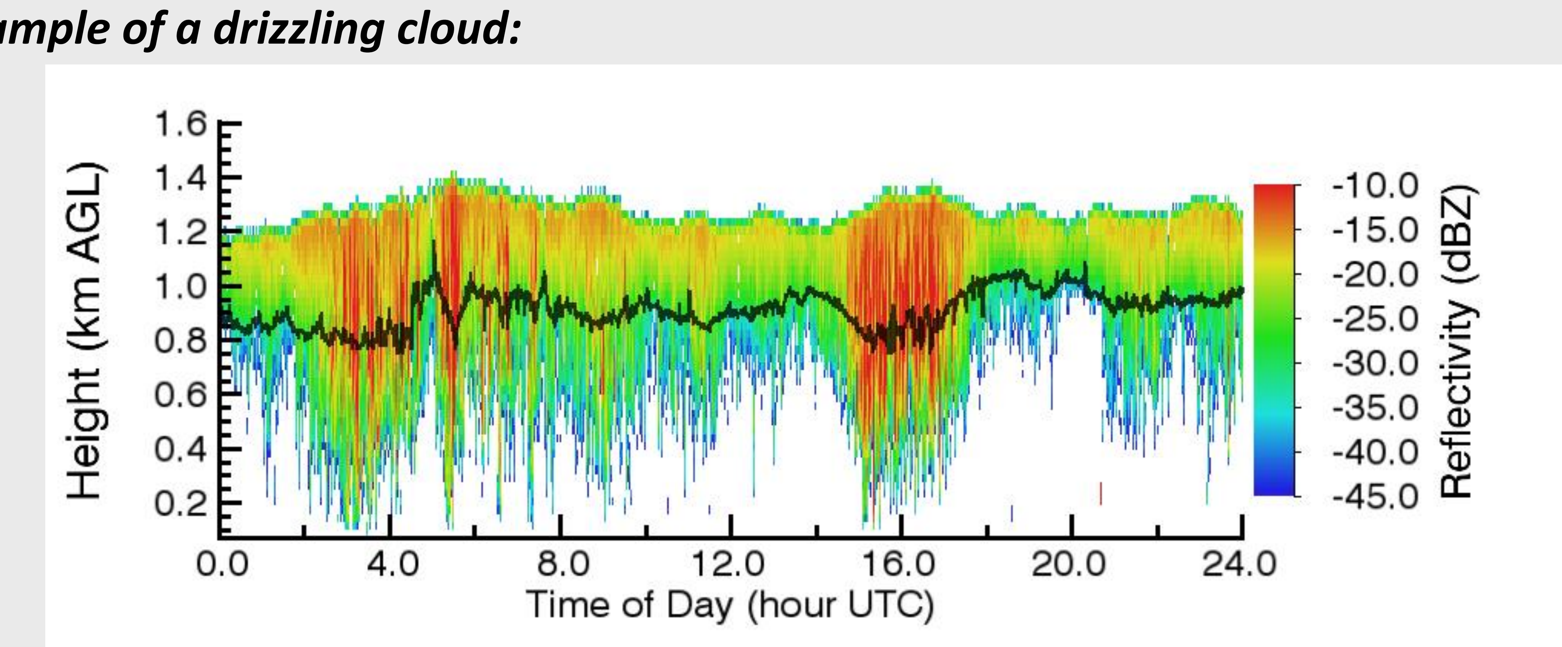


Fig. 1. Time series of radar reflectivity of a marine stratocumulus cloud at the ENA site on March 4, 2016. The black line is the cloud base as detected by the ceilometer. Drizzle virga exist when the lowest radar range gate with detected signal is at least three range gates below cloud base, but also above surface.

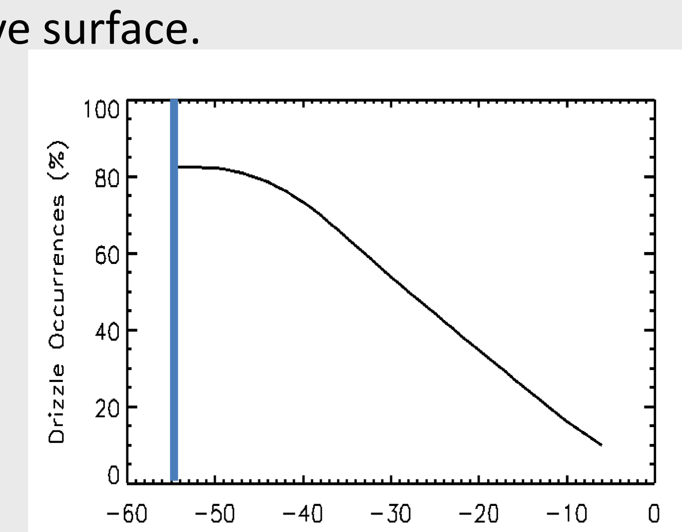


Fig. 2. Drizzling fraction as a function of radar reflectivity threshold at three range gates below cloud base. **83% of our cloud profiles are drizzling** in a 42 day dataset of stratocumulus clouds.

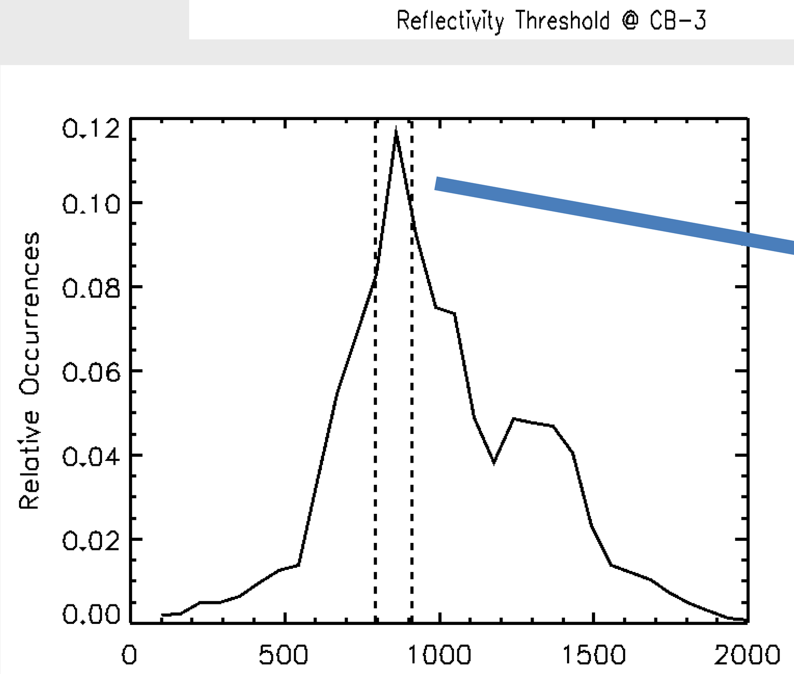


Fig. 3. Relative occurrence of cloud base height for all the selected stratocumulus clouds in this study at the ENA site. The subset bounded by vertical dashed lines centered at the maximum relative occurrence of cloud base height, consisting of five radar range gates (852±75 m), is used for our statistical analysis.

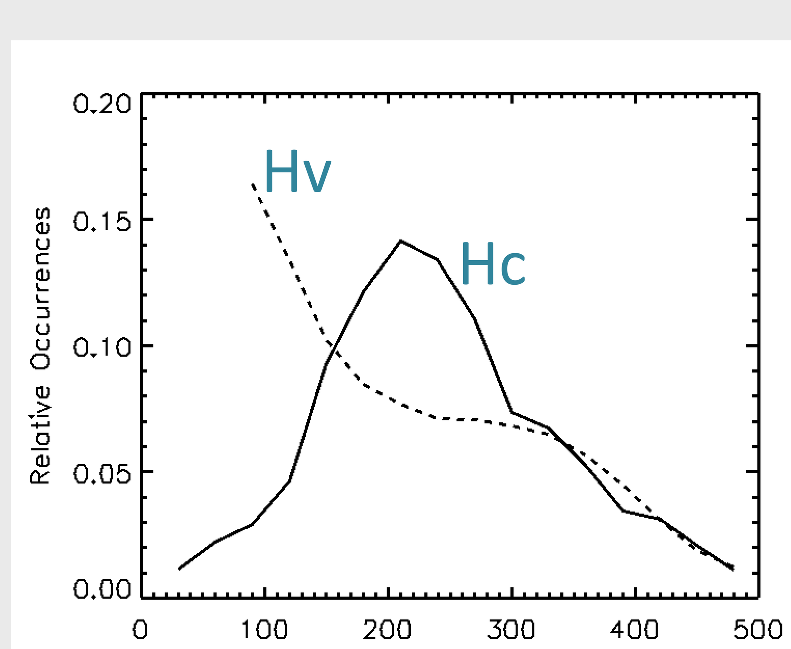
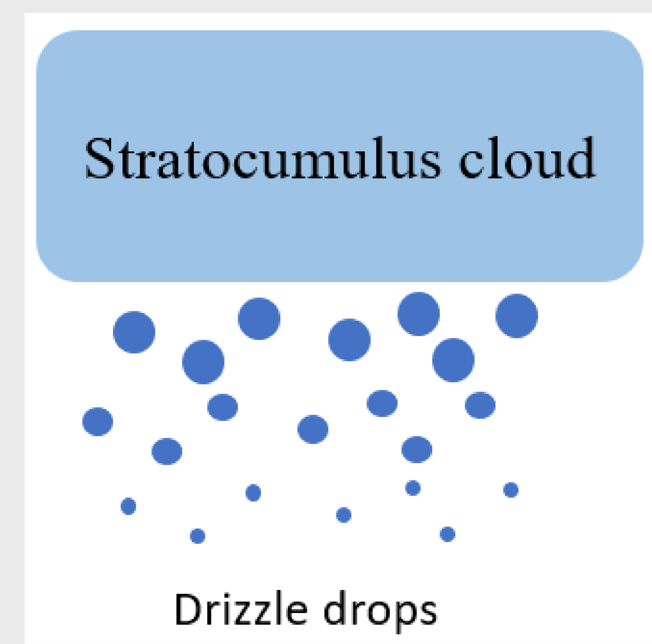


Fig. 4. The relative occurrences of cloud thickness (solid line) and drizzle virga thickness (dashed line) for the subset data in Fig. 3

4. Deriving a Minimalist Model



In cloud, Kostinski (2008):

$$v\rho_w L \approx \rho_a V c_a \Delta T$$

Droplet volume fraction: $f = \frac{v}{V} = 0.4 \times 10^6 \Gamma H_c$

Continuous collection: $4\pi r^2 dr = \pi r^2 f dz$

$$r_{cb} \propto f H_c \propto H_c^2$$

Derivation below cloud base:

$$r\frac{dr}{dt} = r\frac{dr}{dz}v(r) = Gs(z)$$

Assume v(r)~r and s(z)=k(z-z$_{cb}$):

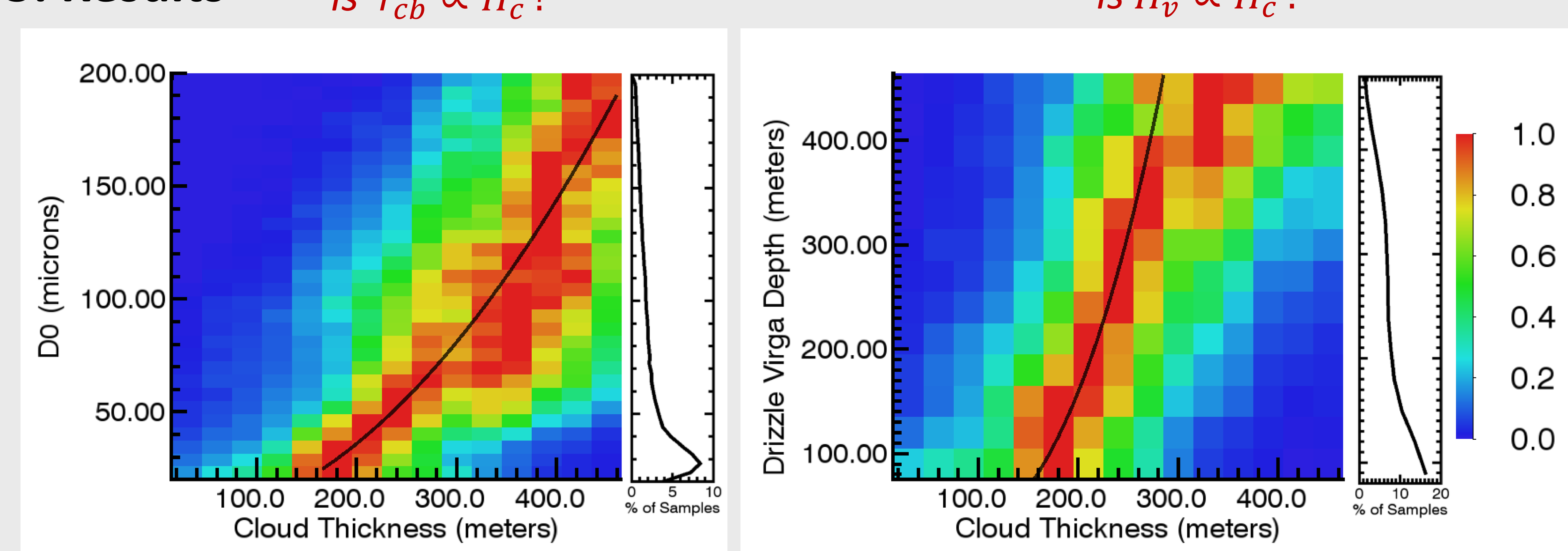
$$r_{cb}^3 \propto H_v^2 k$$

Derived Relationship

$$H_v \propto H_c^3/k^{0.5}$$

5. Results

Is $r_{cb} \propto H_c^2$? *Is $H_v \propto H_c^3$?*



Prefactor from fitting curve: $9 \times 10^{-4} \mu m\ m^{-2}$
Prefactor from equation: $12 \times 10^{-4} \mu m\ m^{-2}$

Prefactor from fitting curve: $2 \times 10^{-5}\ m^{-2}$
Prefactor from equation: $0.5 \times 10^{-5}\ m^{-2}$

Fig. 5. (left) Median volume diameter of drizzle (D0) retrieved at 90 m (three range gates) below cloud base versus cloud thickness. The color represents the occurrence frequency per range bin normalized horizontally, and the black line is the best 2nd-order power law fit. Panel on the right shows the relative occurrence of different D0. (right) Drizzle virga thickness versus cloud thickness. The color represents the horizontally normalized occurrences, and the black line is the best 3rd-order power law fit. Panel on the right shows the relative occurrence of different drizzle virga depths.

humid *Is $H_v \propto k^{-1}$?* dry

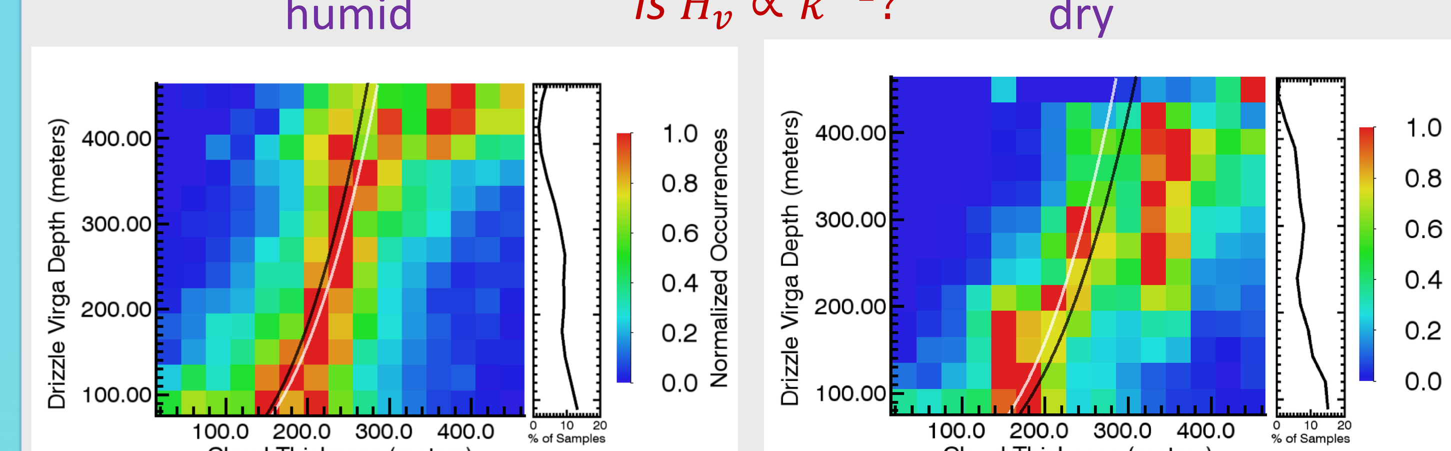


Fig 6. Results for the relatively humid (left) and dry (right) subsets. White lines are the best fitted lines for all data.

6. Take home messages

- Marine stratocumulus clouds are frequently drizzling.
- We derive $H_v \propto H_c^3/k^{0.5}$ that shows good agreement with independent observations.

Acknowledgments

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