Thin Clouds Producing Graupel in the Arctic

Kyle Fitch, Ahmad Talaei,
and Tim Garrett

THE UNIVERSITY OF UTAH
Atmospheric Sciences

Turbulence enhancing riming growth by an order of magnitude in thin Arctic clouds

INTRODUCTION

- A typical continuous collection approach for riming growth is to assume a relatively massive ice crystal with cross-section $\boldsymbol{\sigma \propto D^2}$ falls at terminal velocity $\boldsymbol{v_T}$ through a homogeneous, suspended field of supercooled liquid cloud droplets with concentration $\boldsymbol{w_l}$, collecting with efficiency $\boldsymbol{E_c}$:

$$\frac{dm}{dt} = E_c \sigma v_T w_l \qquad (1)$$

- In reality, these hydrometeors are exposed to turbulent motions that enhance the role of inertia (Naso et al., 2018) and lead to changes in localized precipitation intensities (Lee et al., 2014; Lee and Baik, 2016).

METHODS

- Numerical simulations demonstrate the effect of turbulent flow on the settling velocities of spherical particles for a variety of turbulent magnitudes, particle sizes, and particle densities.

- Analytical solutions were derived for steady-state size distributions of precipitating rain and snow particles assuming growth by collection of smaller, suspended cloud droplets, leading to the expressions

$$\lambda = \frac{2\rho_e}{LWP} \qquad (2)$$

$$\mu = \frac{\lambda w}{a} - 1 \qquad (3)$$

where $\boldsymbol{\lambda}$ is the slope in the exponential tail of the size distribution, $\boldsymbol{\rho_e}$ is the effective density defined to satisfy the spherical relationship between $\boldsymbol{D}$ and $\boldsymbol{m}$, $\boldsymbol{LWP}$ is the liquid water path, $\boldsymbol{\mu}$ is the prefactor exponent controlling the number of smaller particle sizes in the size distribution, $\boldsymbol{w}$ is the updraft speed, and $\boldsymbol{a}$ is the leading coefficient in the fallspeed-size relationship $\boldsymbol{v = aD^b}$.

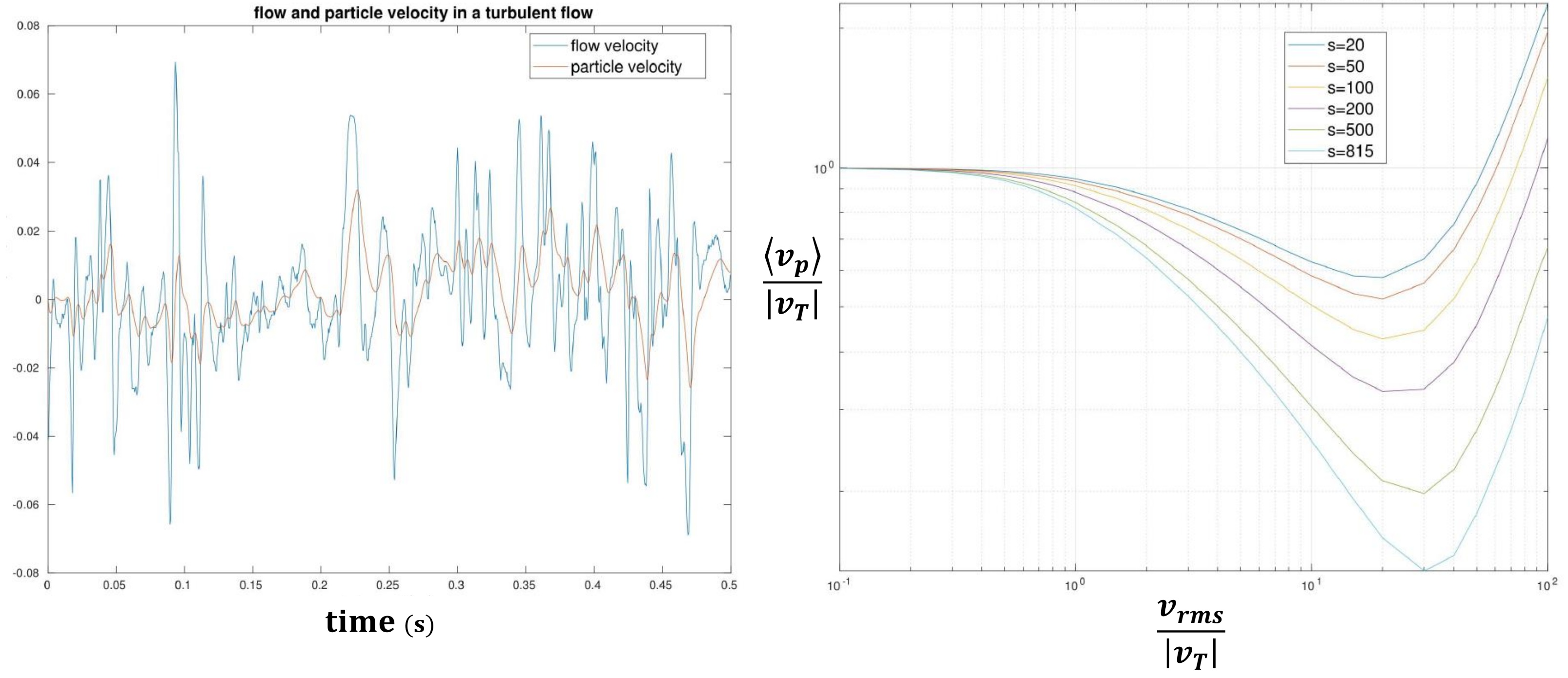
- These expressions are compared to coincident measurements of $\boldsymbol{\lambda}$, $\boldsymbol{\rho_e}$ (from Multi-Angle Snowfla Camera) and $\boldsymbol{LWP}$ (from 3-channel microwave radiometer) during 16 months at AMF3, Oliktok Point, Alaska. The riming enhancement factor

$$\varepsilon_r = \frac{\rho_e V}{E_c \sigma LWP} = \frac{2}{3}\frac{\rho_e}{E_c}\frac{D}{LWP} \qquad (4)$$

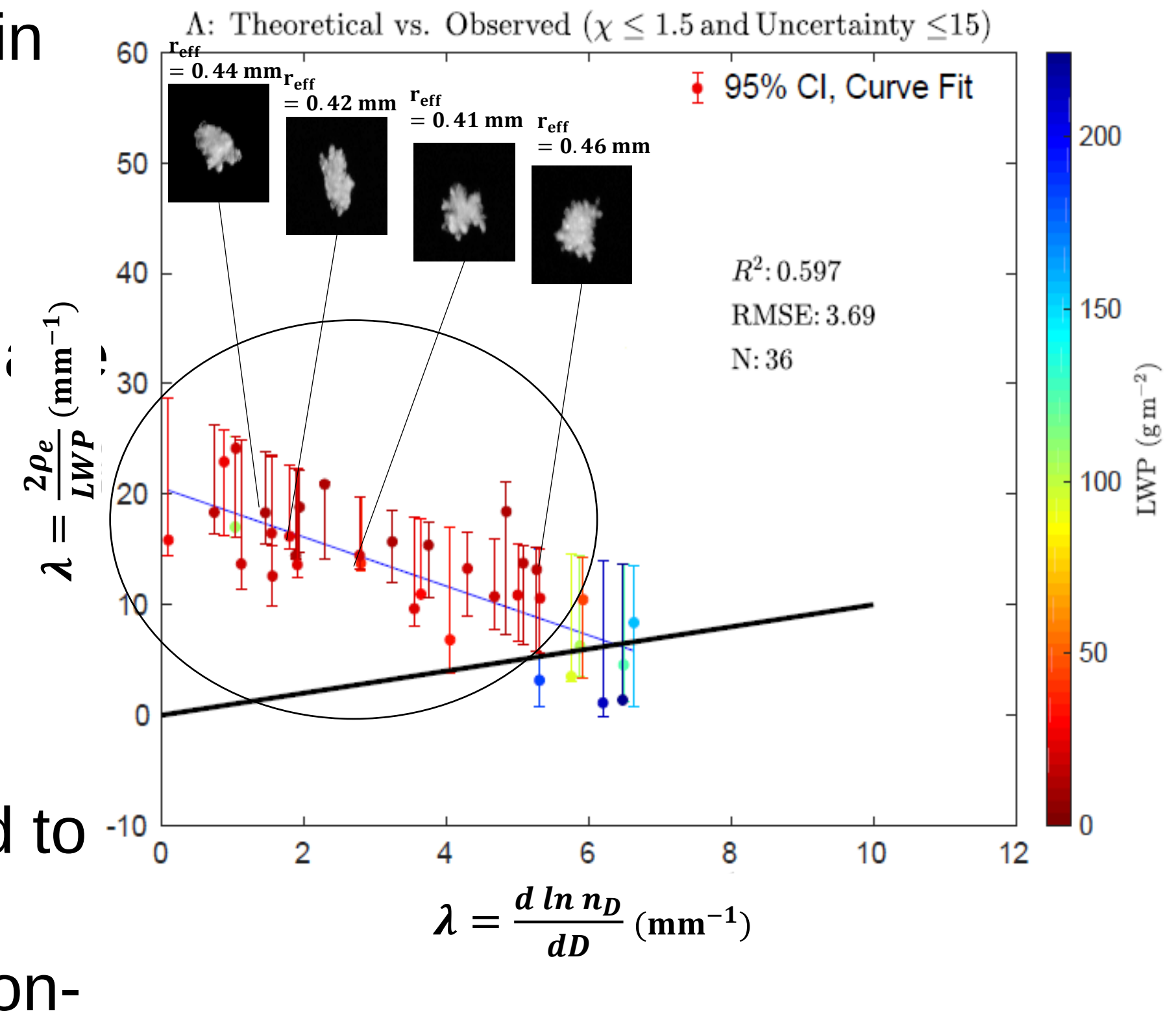
of a graupel with spherical volume $\boldsymbol{V}$ is compared to spectral width from Ka-band ARM Zenith Radar (KAZR) and thermodynamic variables from balloon-borne soundings.

RESULTS

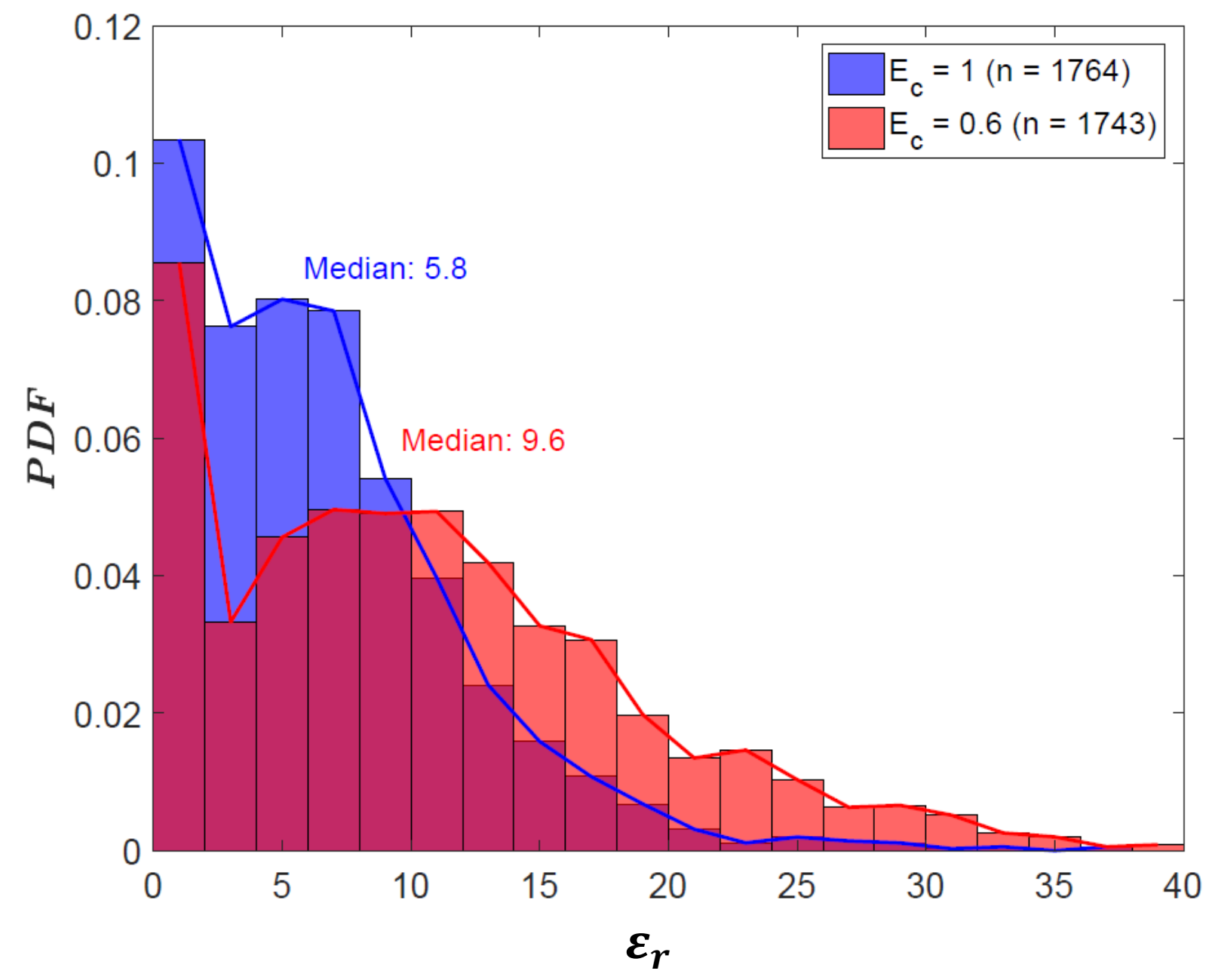
- Settling velocity inertial response and reduction in turbulent flow



- Graupel falling from thin clouds (i.e., low $\boldsymbol{LWP}$)



- Riming enhancement factor ($\boldsymbol{\varepsilon_r}$) for $\boldsymbol{LWP < 50\ g\ m^{-2}}$



DISCUSSION

- Resulting simulations using derived equations showed a settling velocity reduction of approximately 50% for an ice particle with a diameter of less than 0.1 mm falling in turbulent flow.

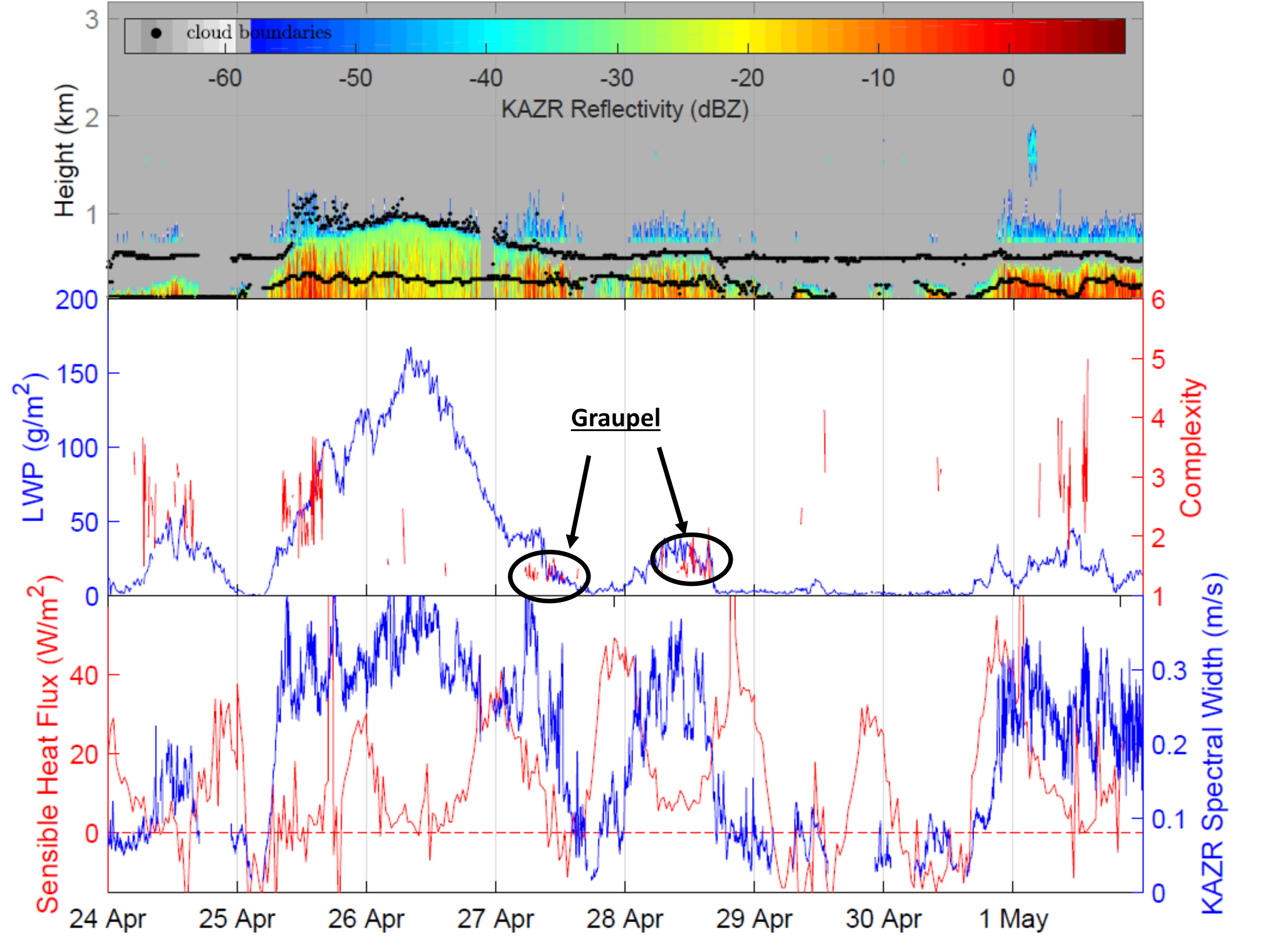
- This decrease in settling velocity lengthens the in-cloud residence time, thereby increasing the number of potential collisions with droplets that are subject to random motions.

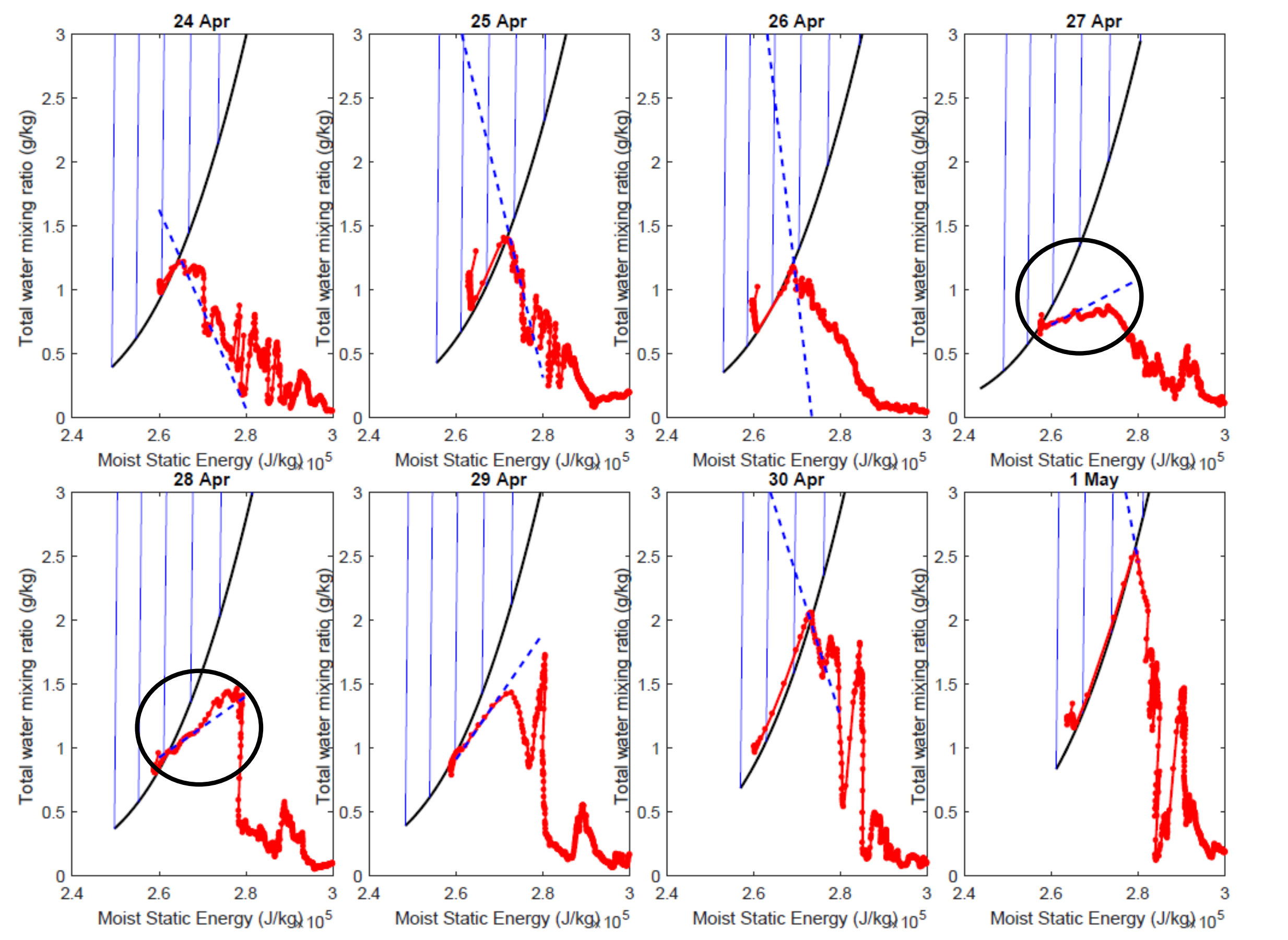
- Due to their small Stokes numbers, the inertial response of the droplets to turbulence increases their likelihood of being moved into the collection path of the crystal, thus lengthening the riming path relative to that of a simple gravitational collection scenario.

- Simulations further showed that the mean updraft velocity ($\boldsymbol{w}$) plays an important role in increasing the in-cloud residence time of the growing crystal, allowing even more time for collection of droplets.

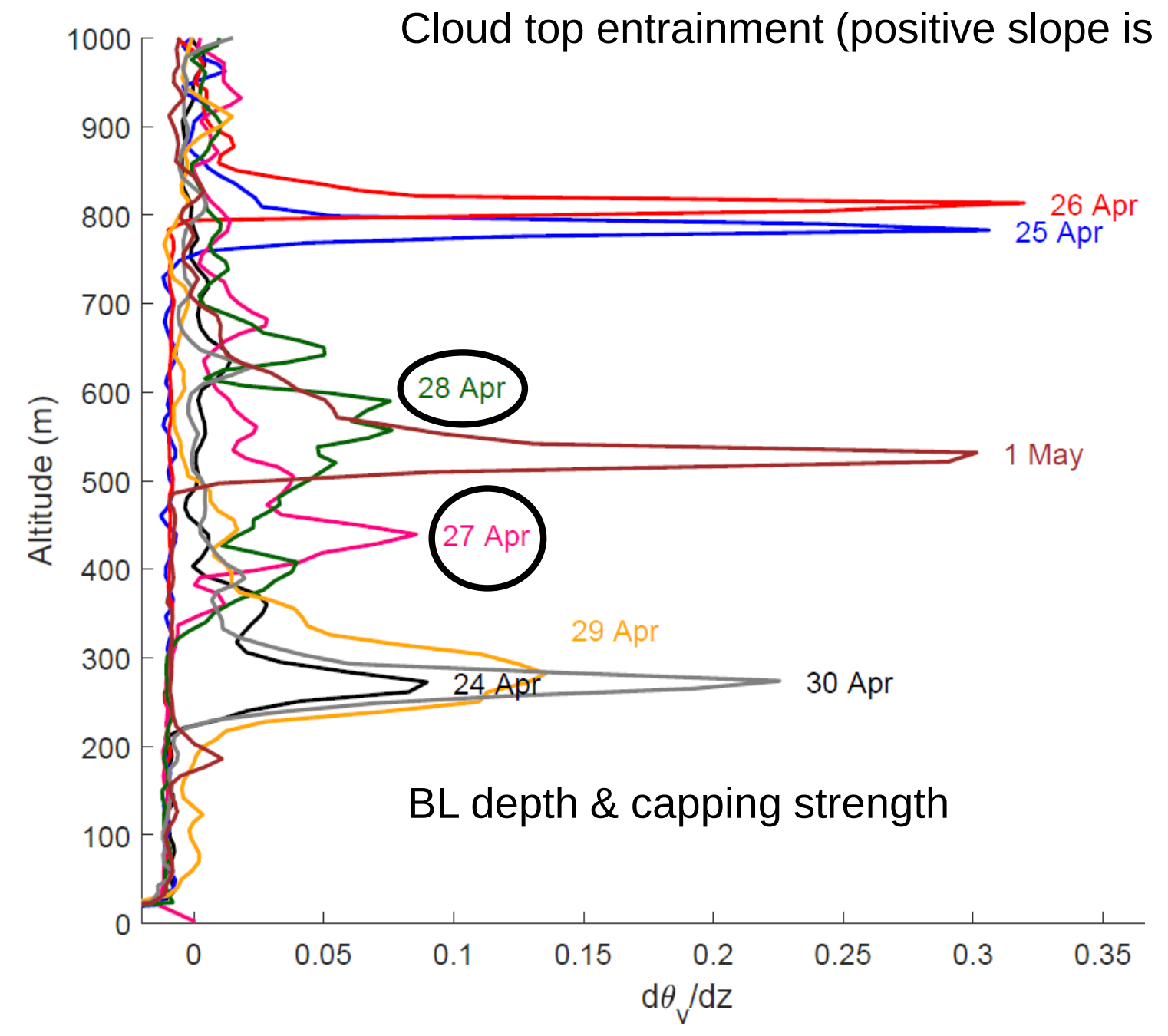
- During periods of "thin" clouds ($\boldsymbol{LWP < 50\ g\ m^{-2}}$), a median riming enhancement factor of $\boldsymbol{\varepsilon_r \sim 10}$ appears to be occurring in conjunction with a higher susceptibility to cloud-top entrainment instability – likely generated by strong cloud-top radiative cooling.

A week-long thin cloud case from 2017:

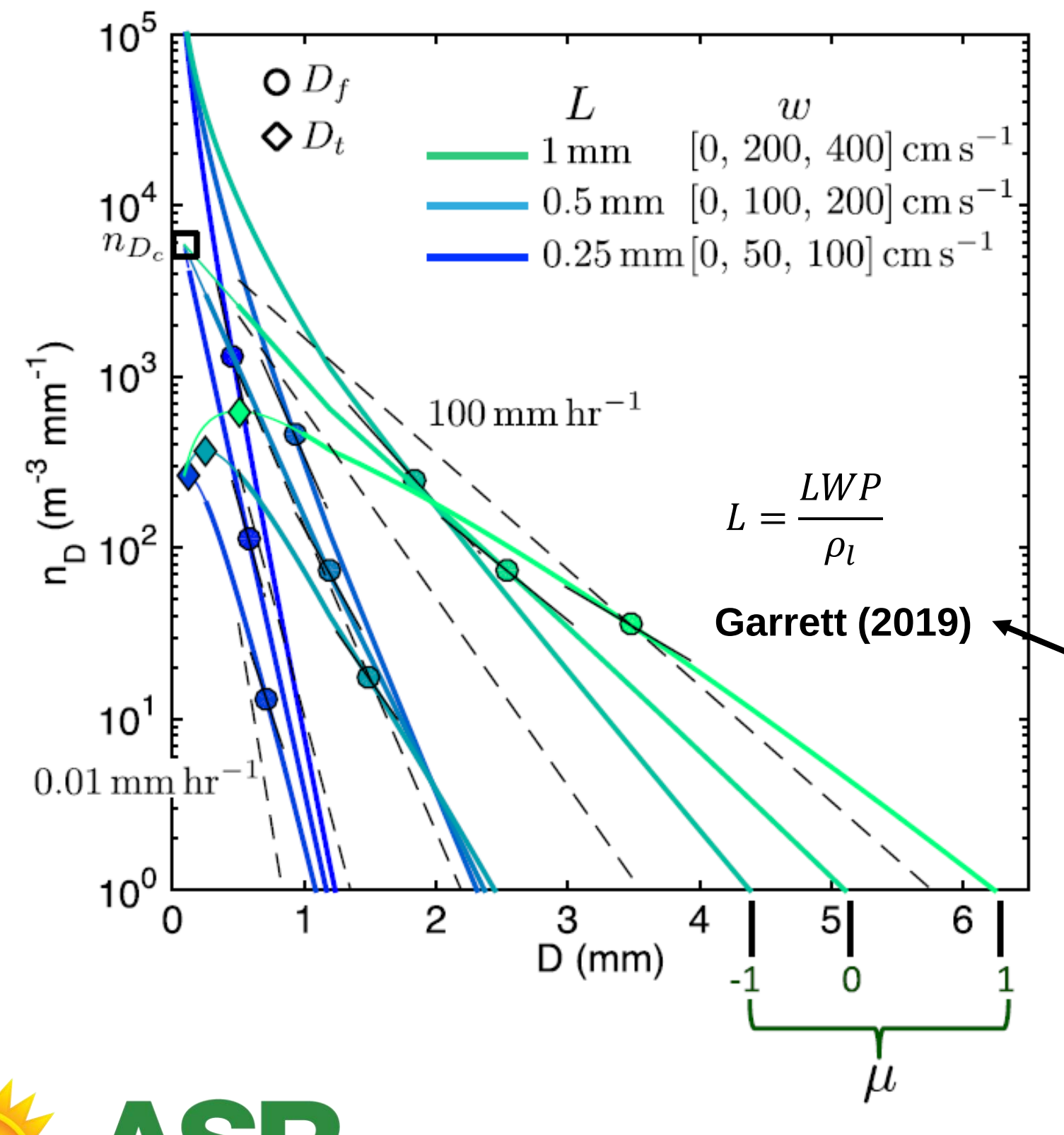




Cloud top entrainment (positive slope is more susceptible to entrainment)



Hypothetical curves for precipitation size distributions:



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