Thin Clouds Producing Graupel in the Arctic

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INTRODUCTION

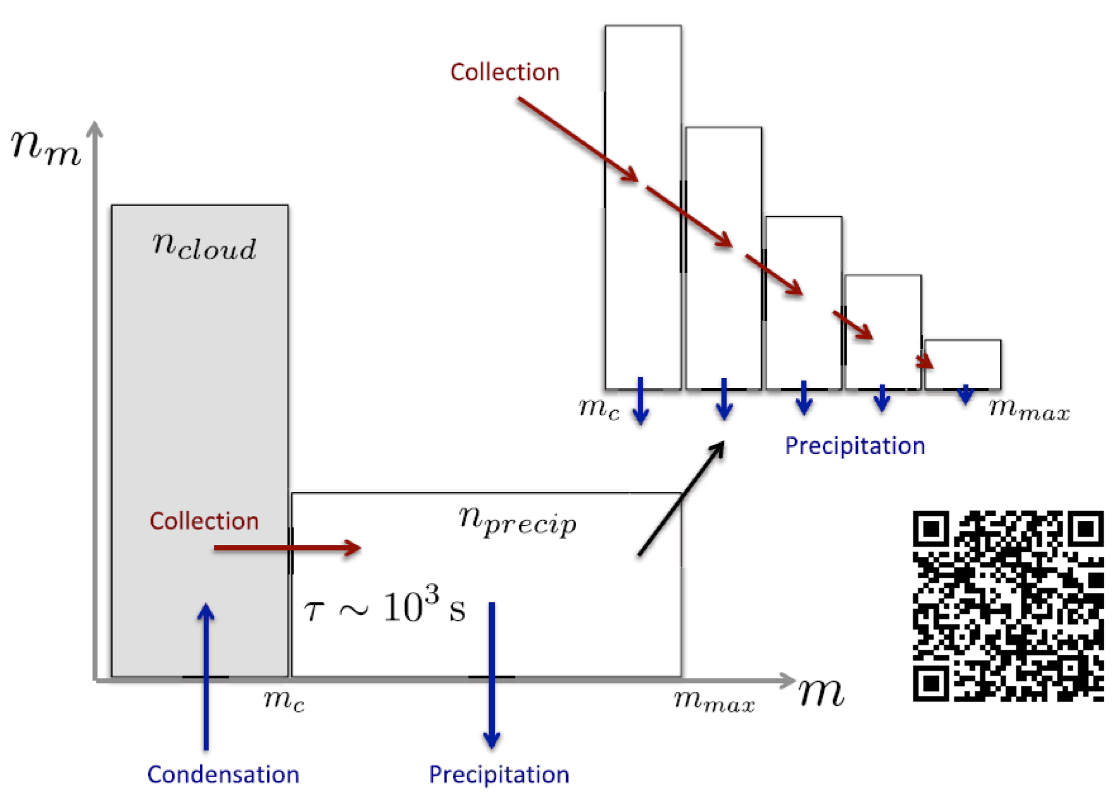
- A common continuous collection approach for riming growth is to assume a relatively massive ice crystal with cross-section $\sigma \propto D^2$ falls at terminal velocity v_T through a homogeneous, suspended field of supercooled liquid cloud droplets with concentration ρ_c, collecting with efficiency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

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

- 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 convective precipitation intensities (Lee et al., 2014; Lee and Baik, 2016). A similar effect may be occurring in the Arctic.

UPDRAFTS DECREASE PSD SLOPE

- Analytical solutions for precipitation size distributions derived by assuming timescales of collection and precipitation are approximately the same – i.e., $\tau_{coll} \sim \tau_{precip} \sim 10^3\ s$ (Garrett, 2019)



- General solution for exponential tail of resulting gamma size distribution is

$$n_D = n_{D_0} exp\left\{-\lambda\left[1 - \frac{w}{aD^b(1-b)}\right]D\right\}$$
$$= exp\{-\lambda' D\} \qquad (2)$$

where the slope of the tail λ is modified based on the magnitude of the updraft speed w relative to the fall speed $v_p = aD^b$

- If $w \ll v_p(1-b)$ ($\ll \sim 0.4\ m\ s^{-1}$ for lump graupel)

$$exp\{-\lambda D\} \qquad (3)$$

- & slope is related to bulk density ρ_e & liquid water path LWP

$$\lambda = \frac{2\rho_e}{LWP} \qquad (4)$$

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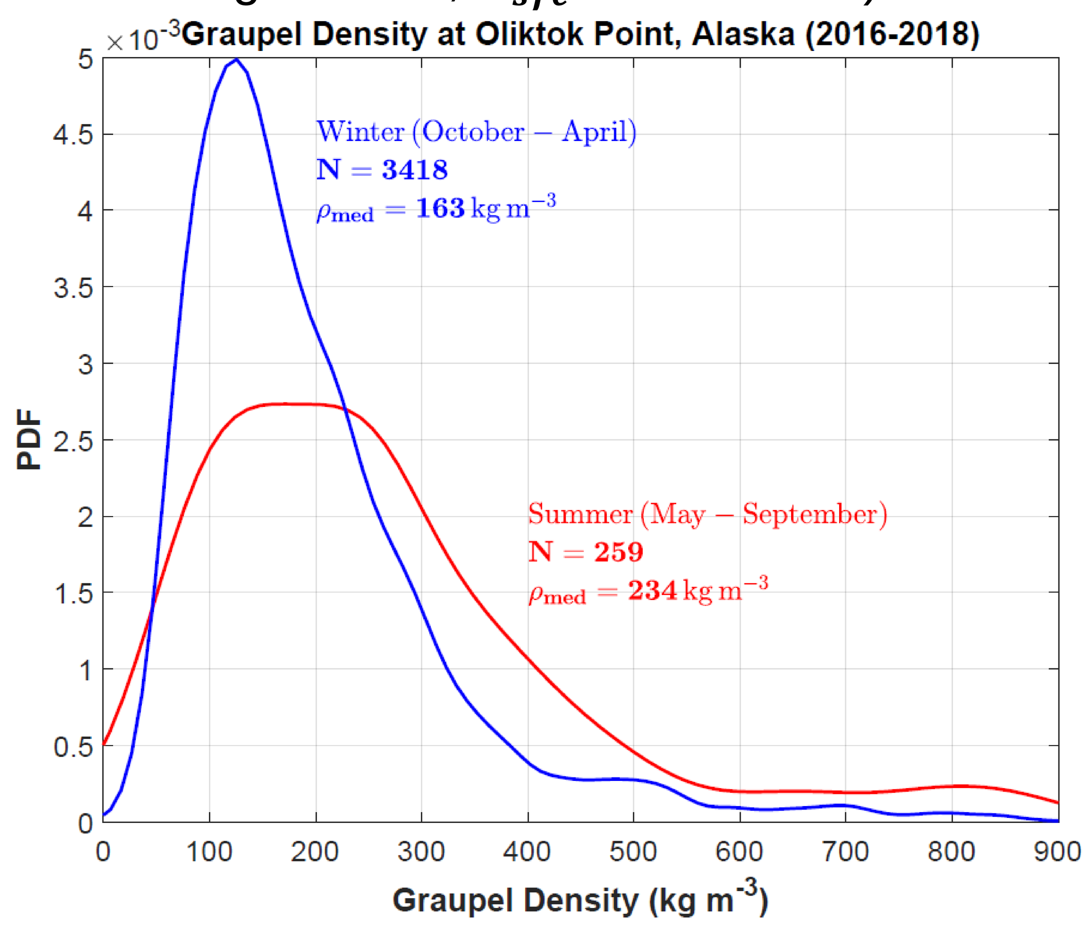
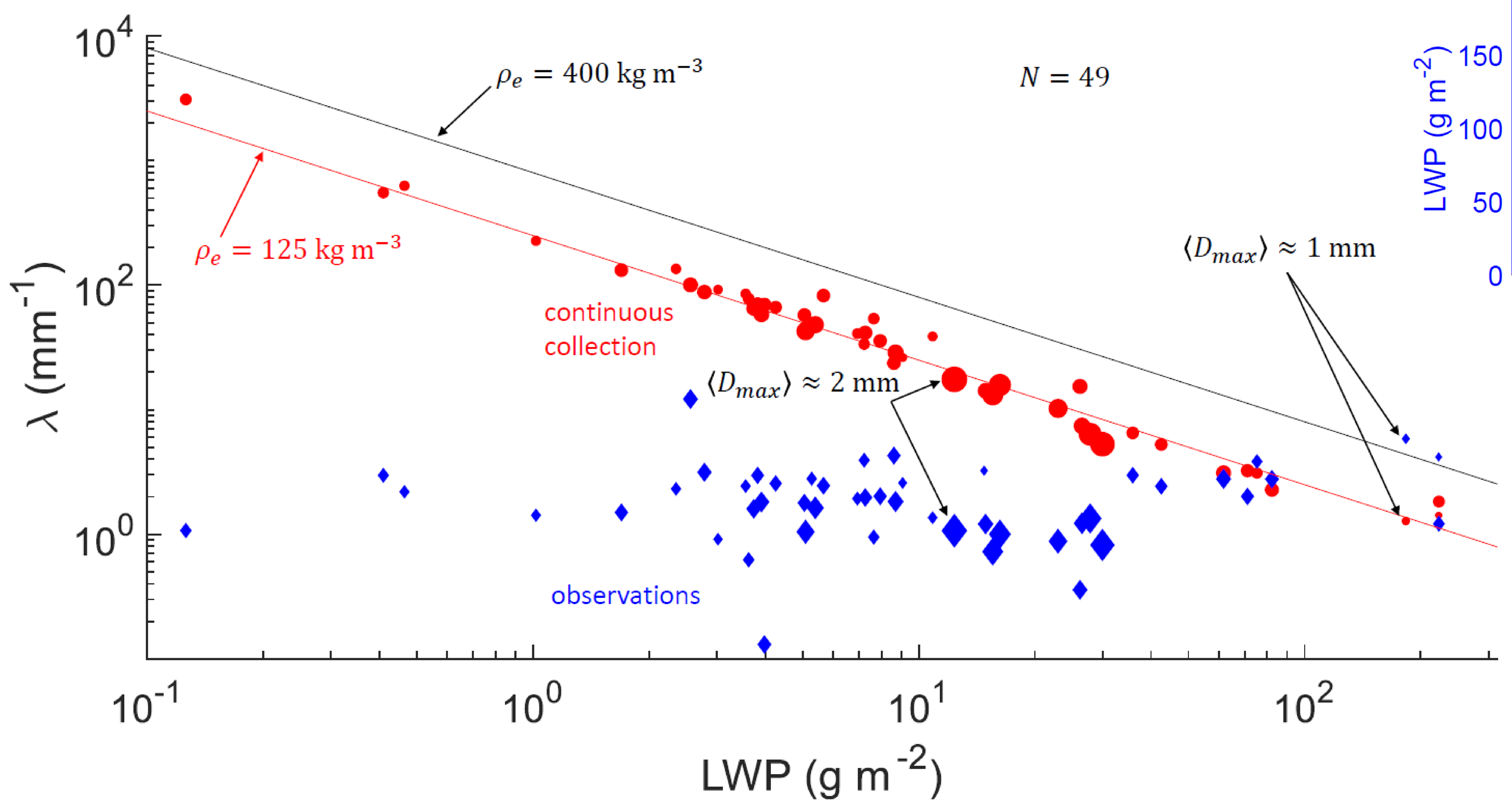
SUMMERTIME GRAUPEL MORE DENSE THAN WINTERTIME GRAUPEL

- Assumes spherical graupel & $v_p \simeq v_T$
- Measurements made in still air (shielding + light winds, $U_{sfc} < 4.5\ m\ s^{-1}$)

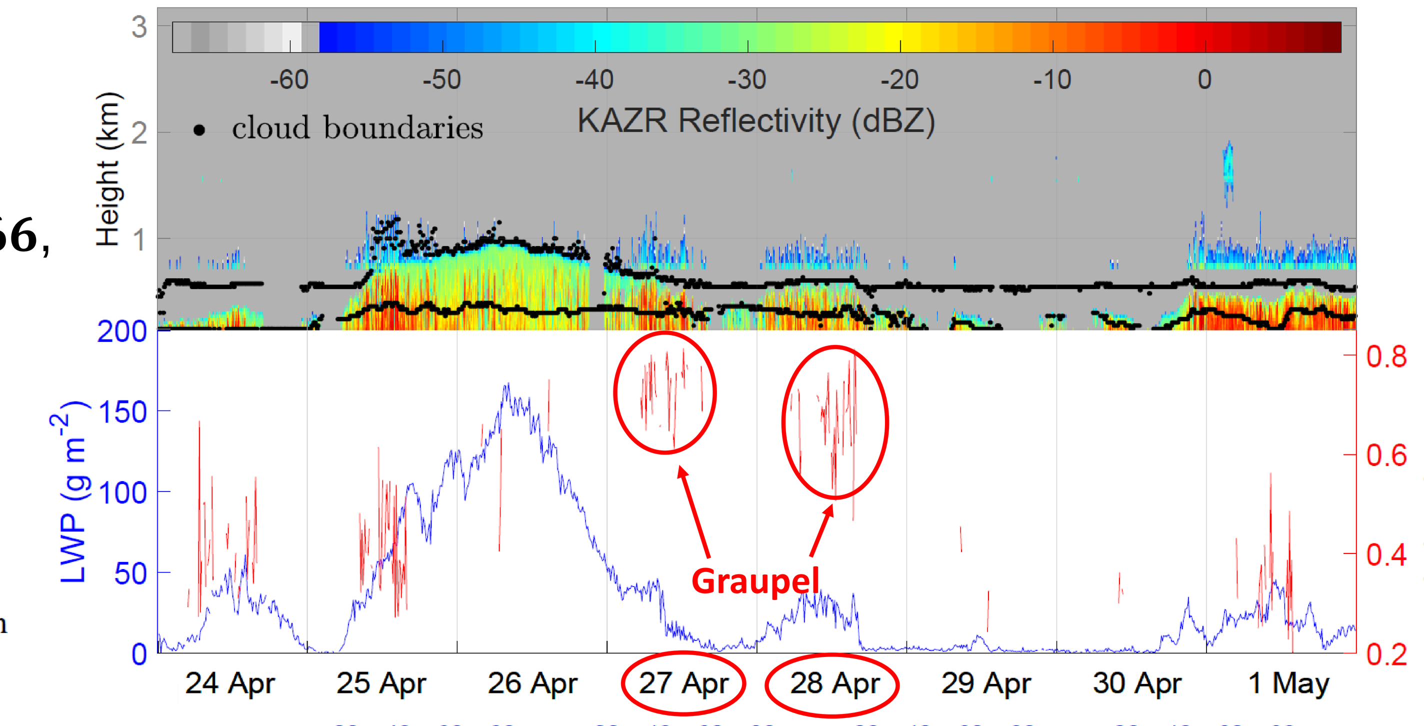


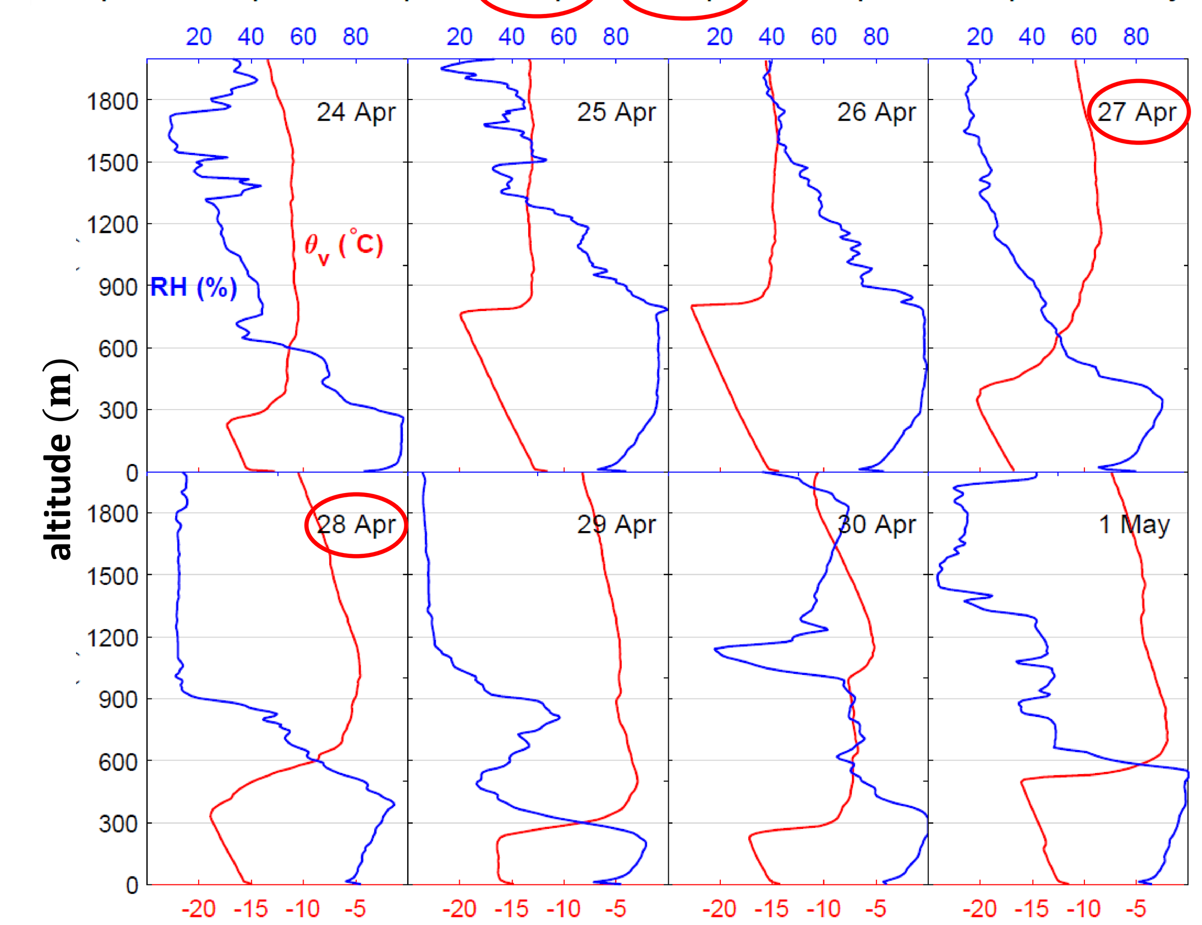
CONTINUOUS COLLECTION DOESN'T ALWAYS EXPLAIN RIMING

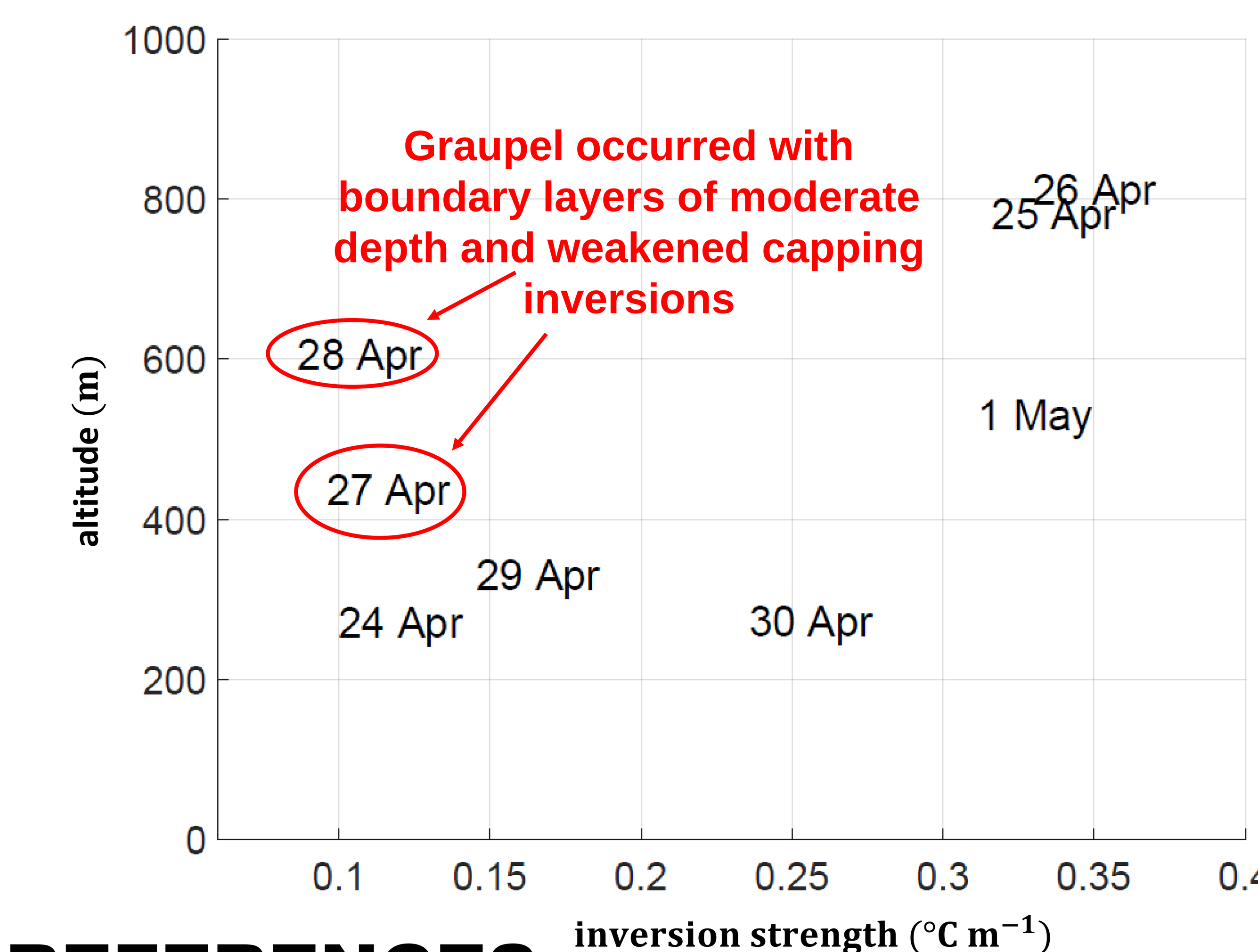
- Observed λ' is the slope of the least-squares, best-fit line passing through the tail of a 10-minute size distribution
- Continuous collection λ is calculated from Eqn. (4)
- $\lambda' \ll \lambda$ for $LWP < 50\ g\ m^{-2}$; to satisfy Eqn. (2) with $b = 0.66$, $w \simeq v_p/3$ is implied – or more generally $w/v_p \simeq 1 - b$



THIN-CLOUD GRAUPEL WITH WEAK CAPPING INVERSION





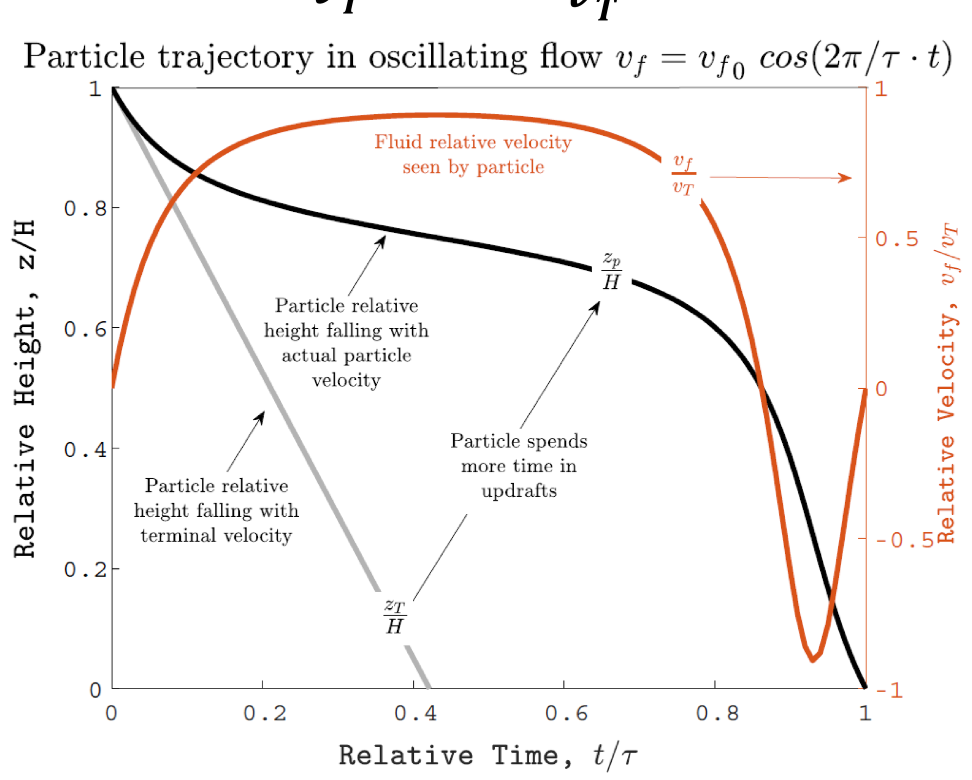


Turbulence and updrafts combining to enhance riming in thin Arctic clouds

OSCILLATING FLOW EXTENDS RIMING TIME

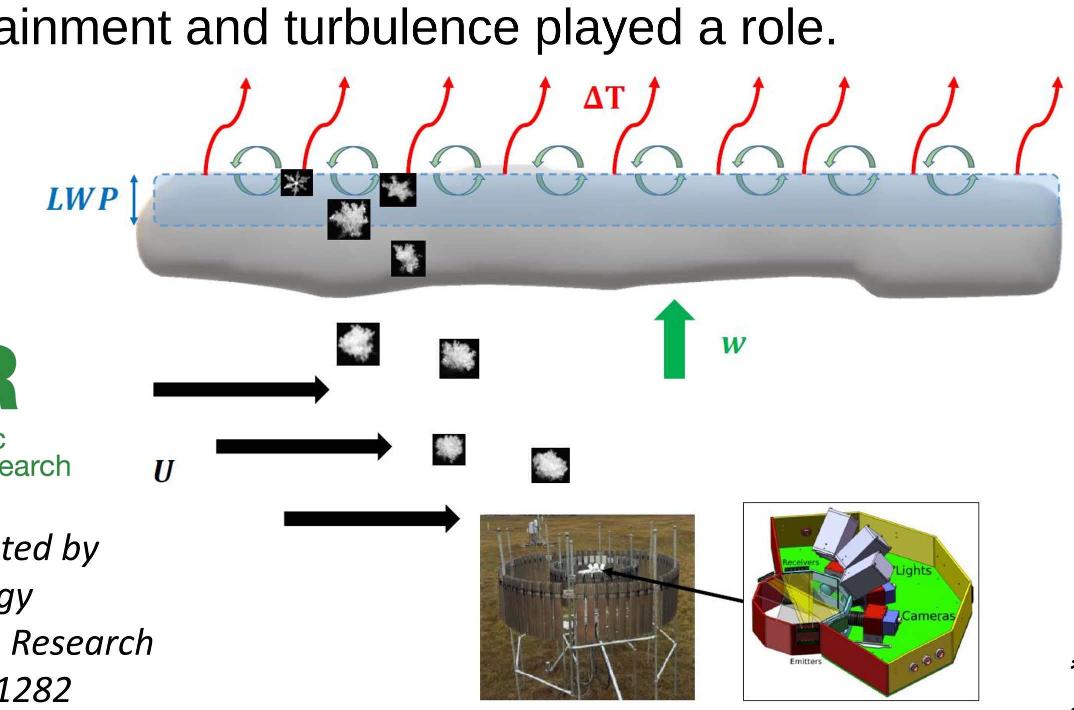
- Oscillating, turbulent fluid velocity (v_f') is "frozen" with respect to particle ($v_f' \ll v_T$)
- Lagrangian frame of reference
- Relative particle velocity parameterized as

$$\frac{\langle v_p \rangle}{v_T} \simeq 1 - \frac{\langle v_f'^2 \rangle}{v_T^2} \qquad (5)$$



CONCLUSIONS

- In simulated turbulent (oscillating) flow, the particle spends more time in the updraft than in the downdraft, thereby increasing the time spent riming in the cloud.
- Continuous collection theory and observations only agree on λ for cases where $LWP > 50\ g\ m^{-2}$. Below that, updraft strength and turbulence may help to explain enhanced riming.
- Thin cloud case showed graupel occurring with weak inversions. The weakening of the boundary layer top suggests cloud top entrainment and turbulence played a role.



ASR Atmospheric System Research

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**Dr. Garrett is a co-owner of Particle Flux Analytics, Inc., the manufacturer of the Multi-Angle Snowflake Camera (MASC)*