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Aerosol Influences on Enhanced Riming Events in Low-Level Arctic Mixed-Phase Clouds of the North Slope of Alaska & the Central Arctic

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Lindsay Dedrickson

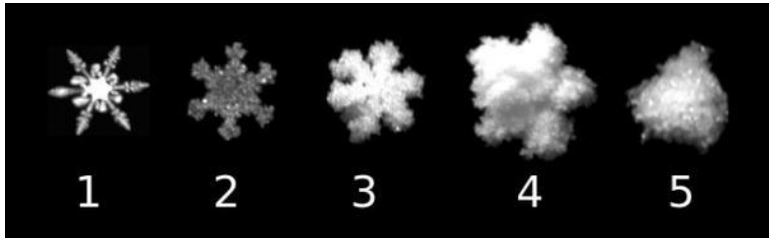
Air Force Institute of Technology



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Why Riming in the Arctic?

- Very efficient loss mechanism for CCN/INP/water & thus
  - **Energy** budget/radiative balance
  - **Cloud** sustainment/dissipation
- Surprisingly common in low-level, mixed-phase Arctic stratiform clouds; e.g., for Oliktok Point (2016-2018, $\sim 42K$ particles)
  - **2/3** of frozen hydrometeors **at least moderately rimed**
  - About **half** (45%) **heavily rimed** (graupel or graupel-like)
  - **Despite** typical values of $\boldsymbol{LWP < 50\ g/m^2}$

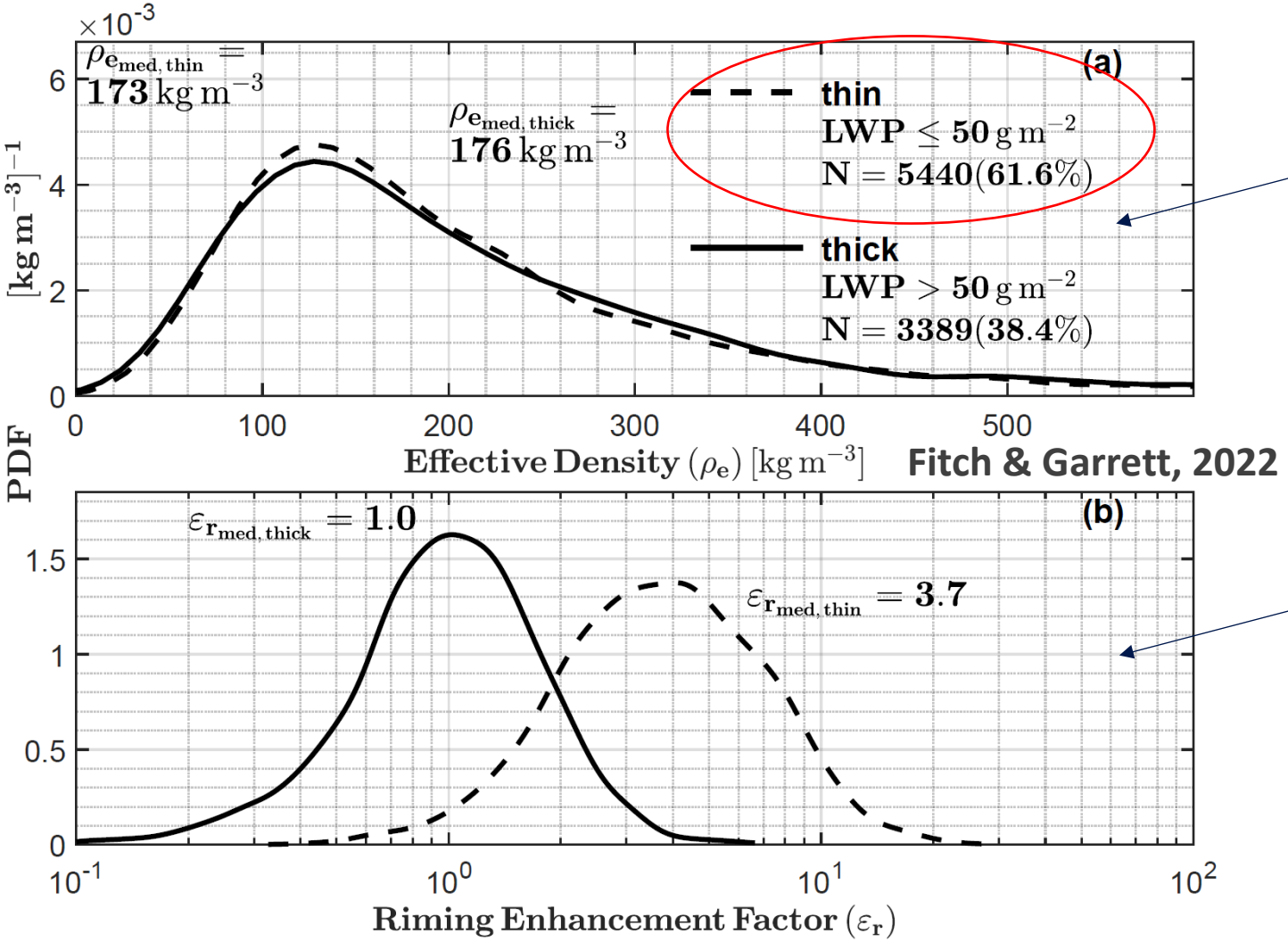


Degree of riming from Praz et al. (2017)

$\sim 10^5$ to 10^6 collisions

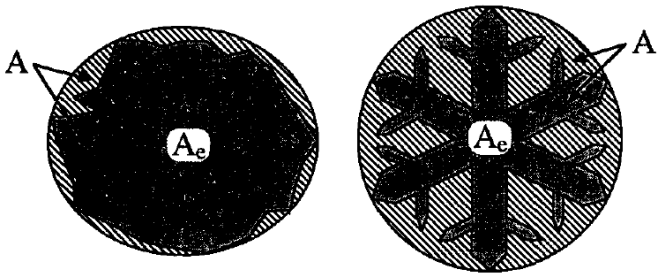
$100 - 1,000$ collisions every second (for typical precipitation time scale of 10^3 seconds)

Enhanced Riming: Oliktok Point (Sep 2016 – Sep 2018)



Fitch & Garrett, 2022

Effective density from Böhm (1989)



$\rho_e = \rho_e(v, D_{max}, D, p, T)$

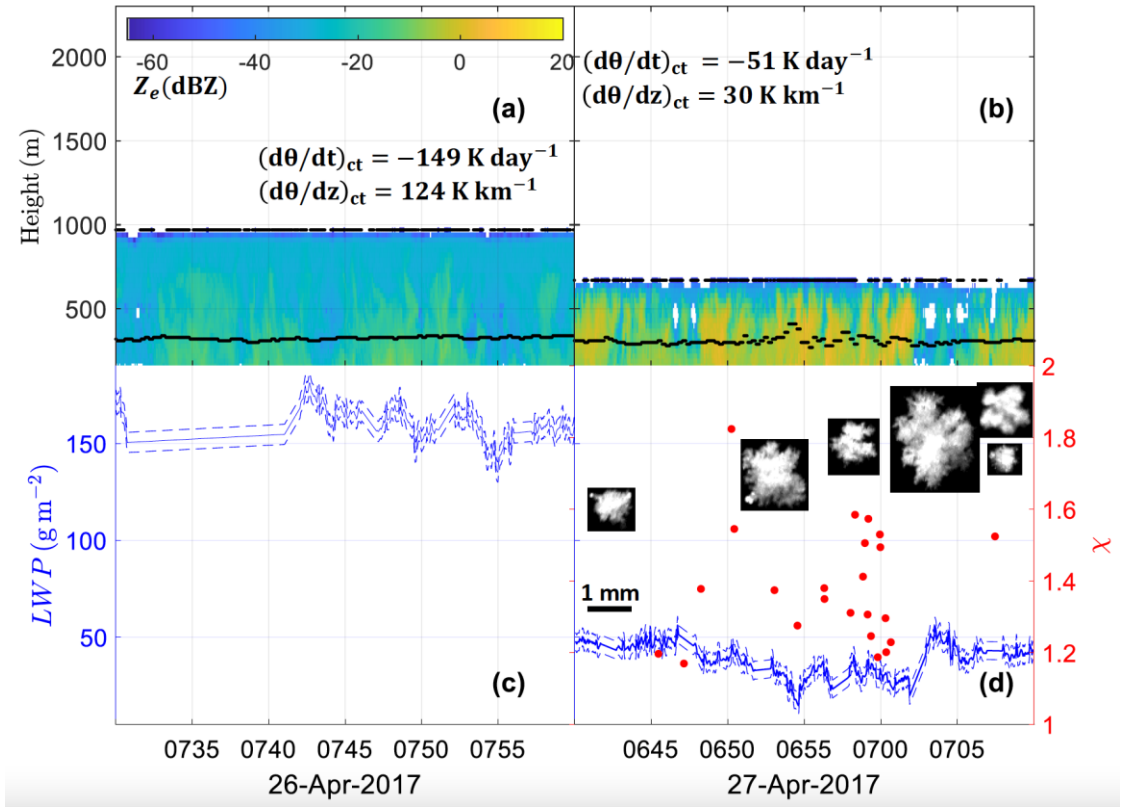
Riming Enhancement Factor (REF)

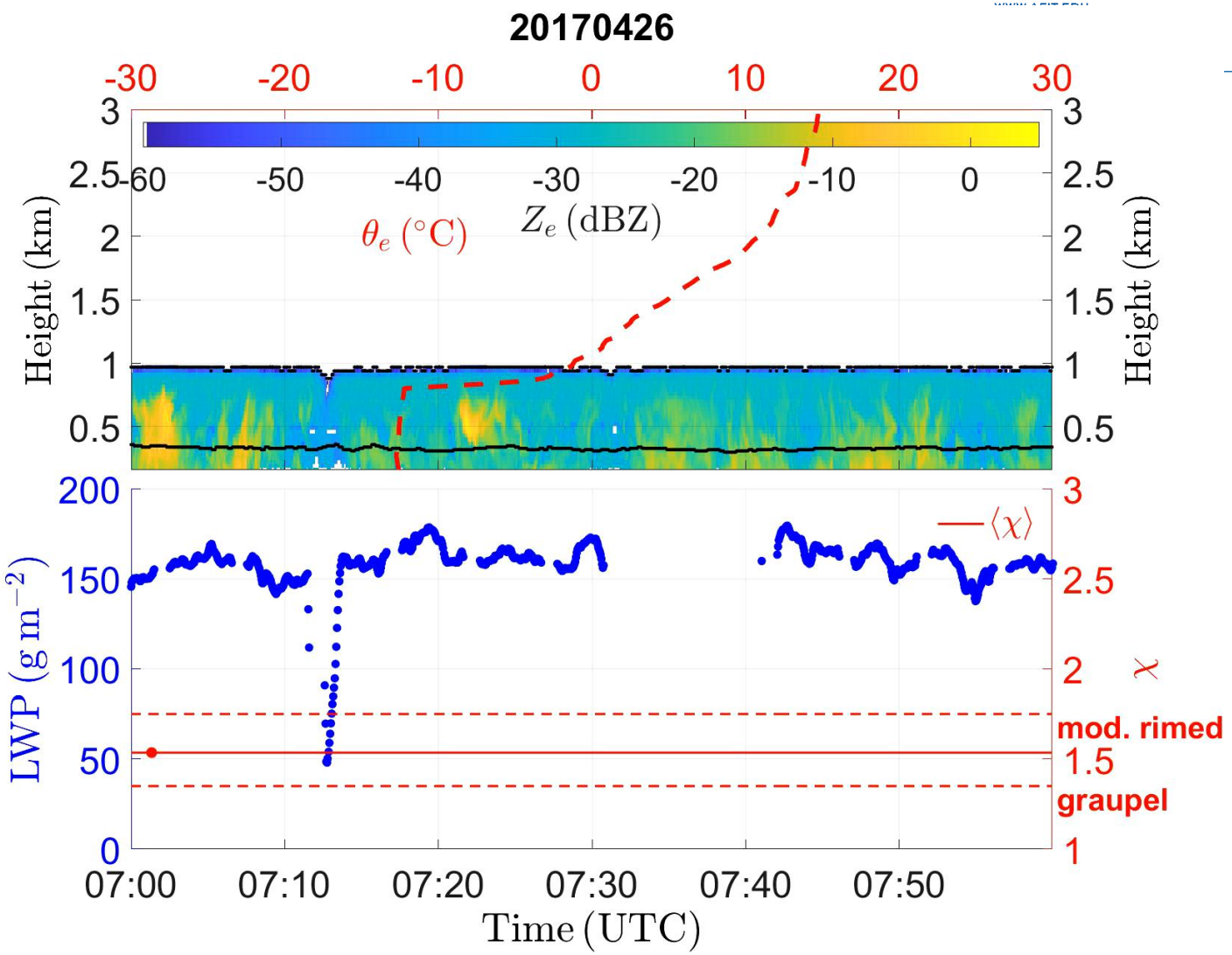
$\varepsilon \propto \rho_e D \cdot LWP^{-1}$

Snow crystal type	D_{eff} (mm)	ρ_{MS} (kg m^{-3})	$\rho_{SLR-DEID}$ (kg m^{-3})	Uncertainty (%)	R^2
Planar	2.4–4.3	89 ± 40	98 ± 46	9.6	0.96
Columnar	1.4–3.4	157 ± 82	140 ± 92	11.4	0.95
Graupel	1.4–4.6	120 ± 87	130 ± 89	3.7	0.97
Small particle	0.8–1.2	141 ± 109	138 ± 110	2.1	0.98
Aggregate	3.1–10.2	188 ± 72	170 ± 64	10.1	0.91

Singh et al., 2024

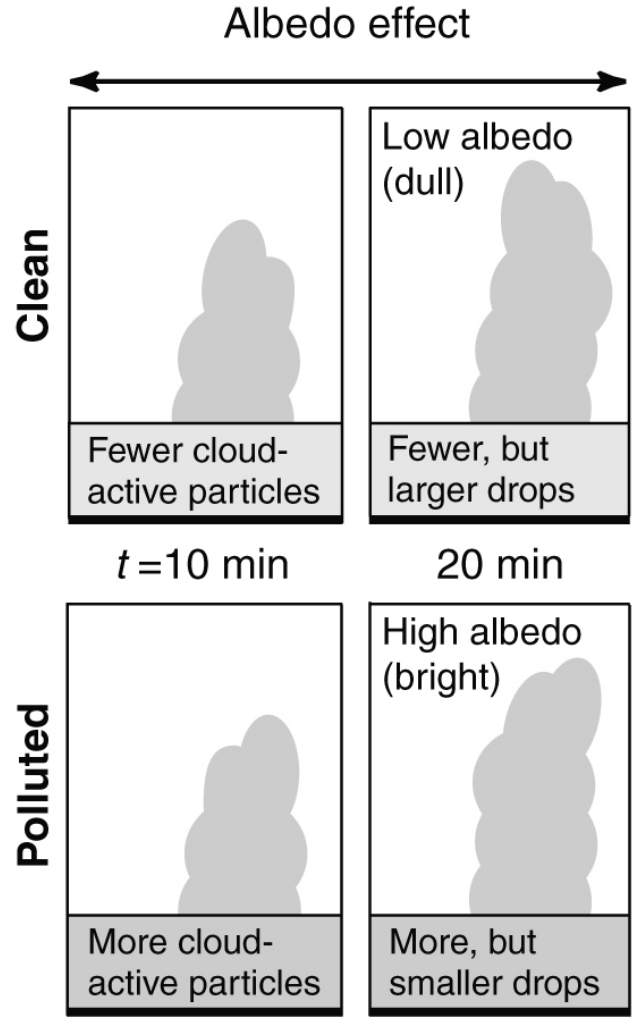
“Enhanced” Riming Events





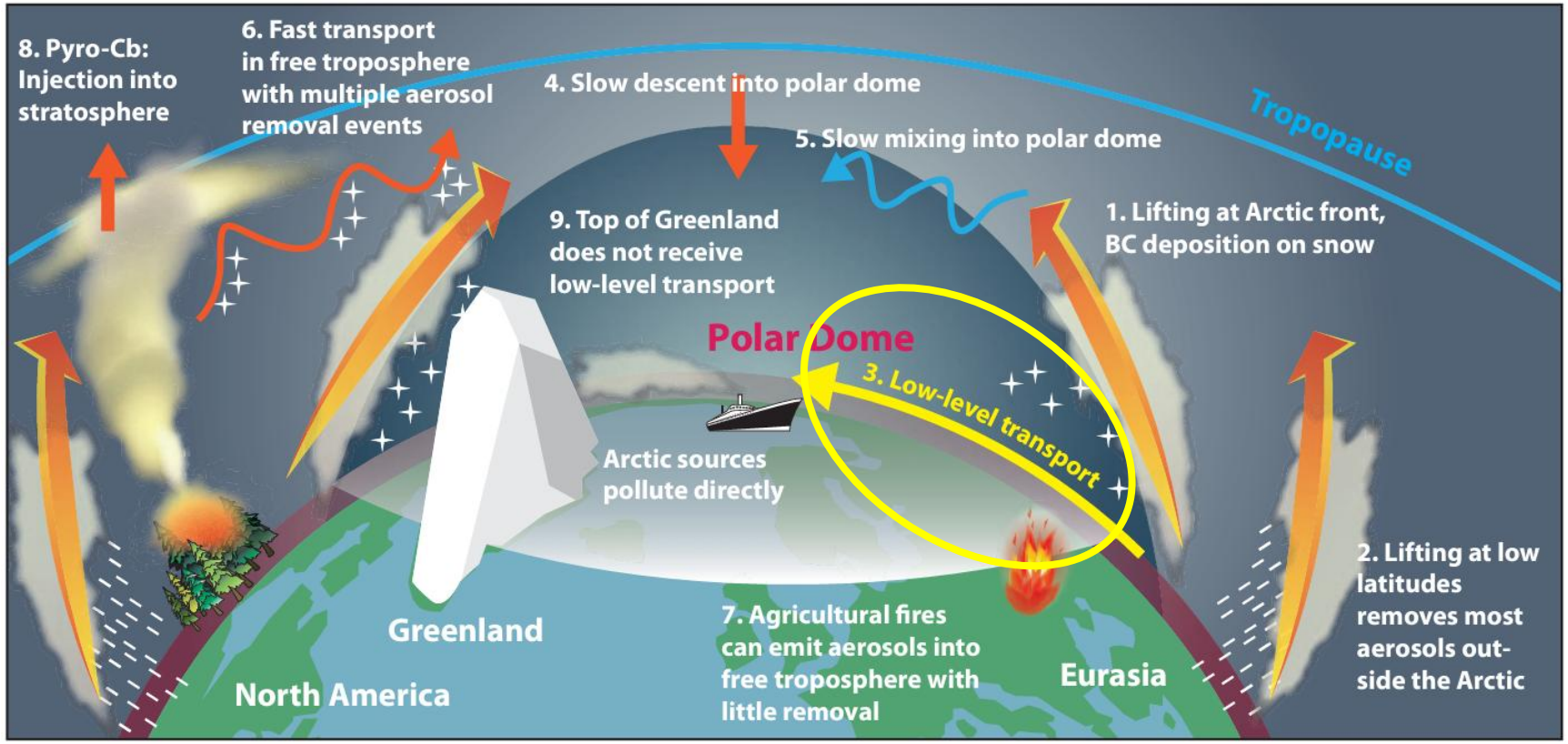
2 Competing Hypotheses for Enhanced Riming

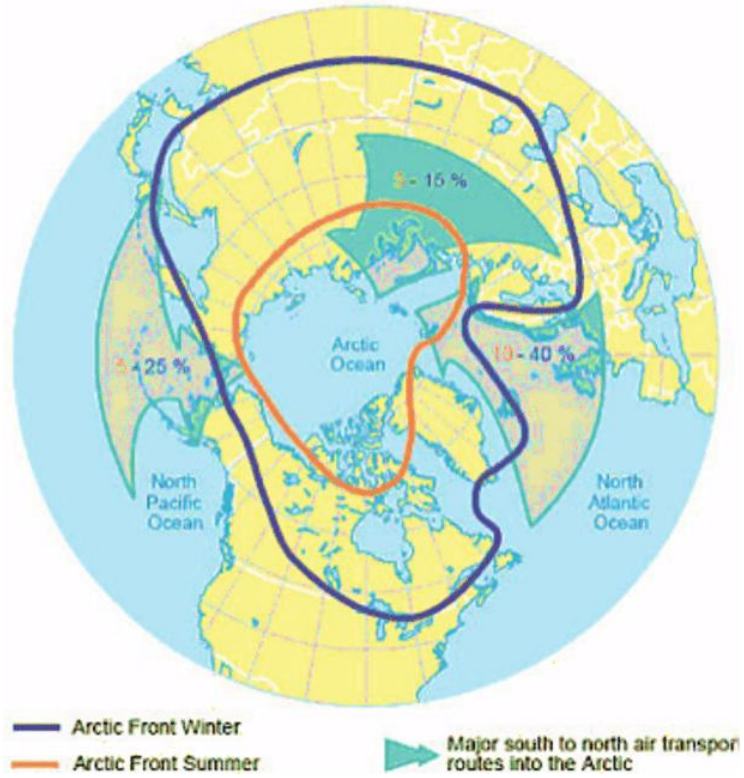
- Hypothesis #1: "Clean" clouds favor enhanced riming
  - Lower CCN concentrations & **fewer, larger cloud droplets**
  - Larger droplets → **higher riming efficiency** (Tridon et al., 2022)
  - **Immersion freezing** may be an important nucleation process in this case (Lance et al., 2011; Creamean et al., 2018)
- Hypothesis #2: "Polluted" clouds favor enhanced riming
  - Higher CCN concentrations & **smaller, more numerous cloud droplets**
  - i.e., 1st Indirect Effect, but WRT longwave radiative cooling
  - **Stronger cloud-top radiative cooling** enhances buoyant production of turbulent kinetic energy (TKE)



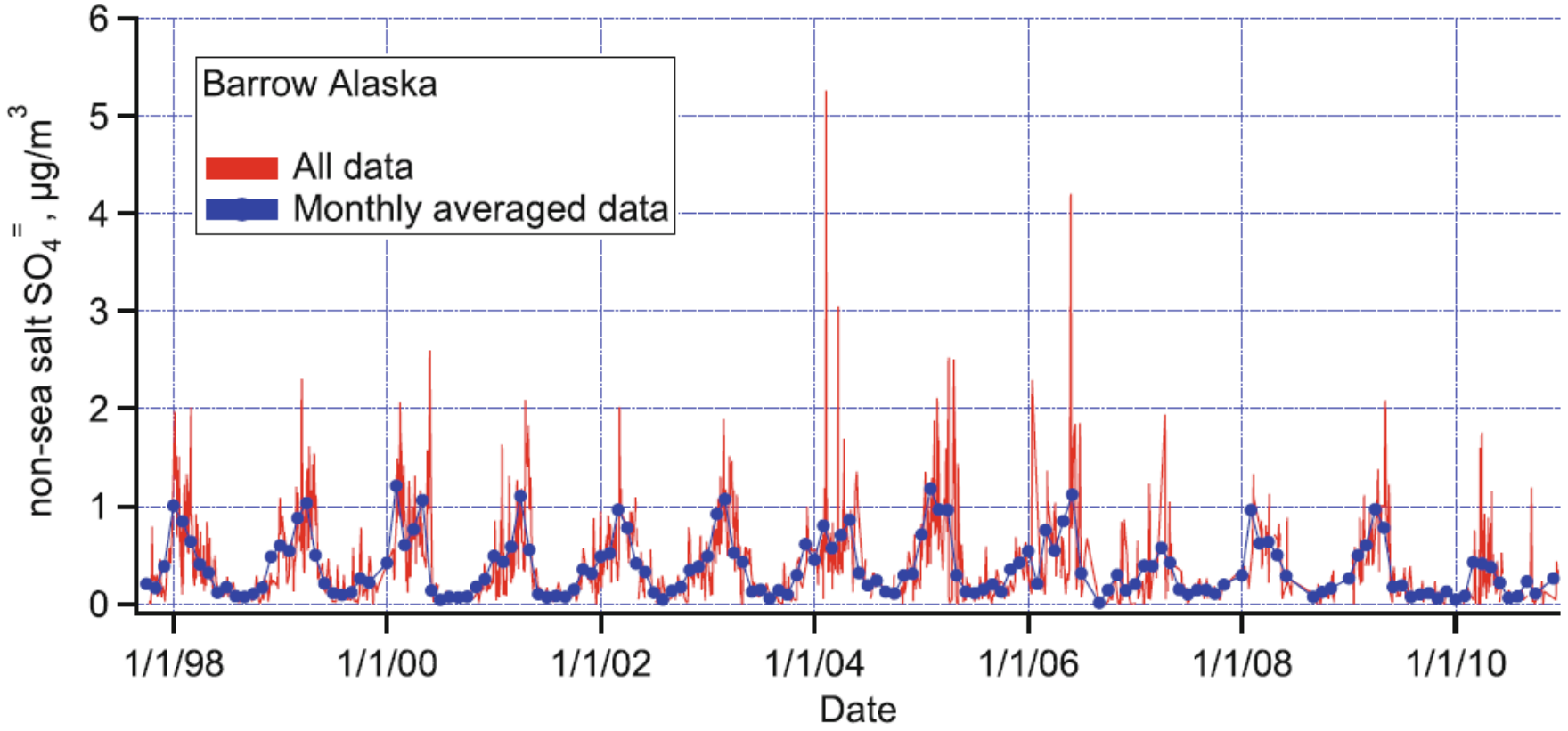
Lamb & Verlinde, 2011

Transport into the Arctic: Arctic Haze (Dec-Apr)

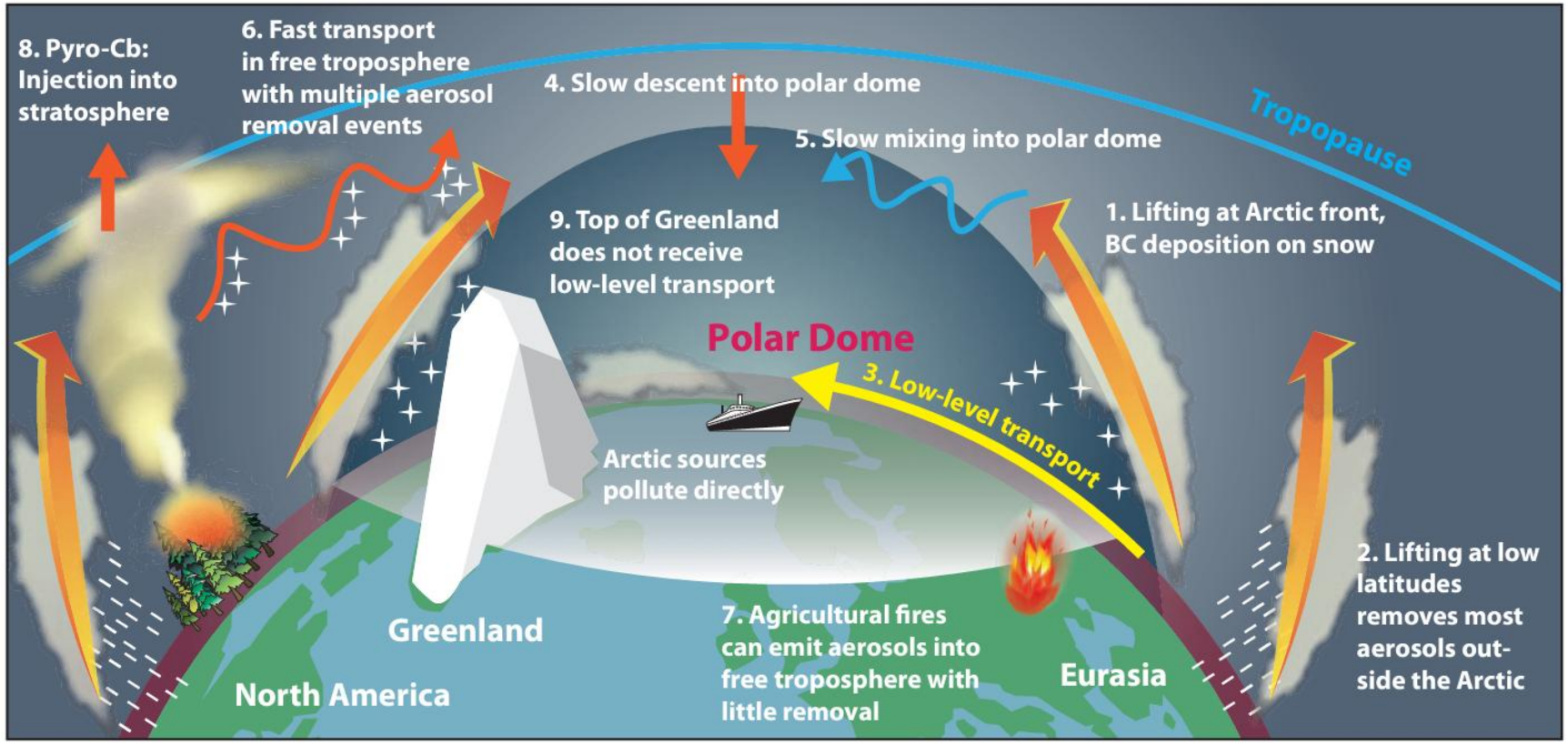


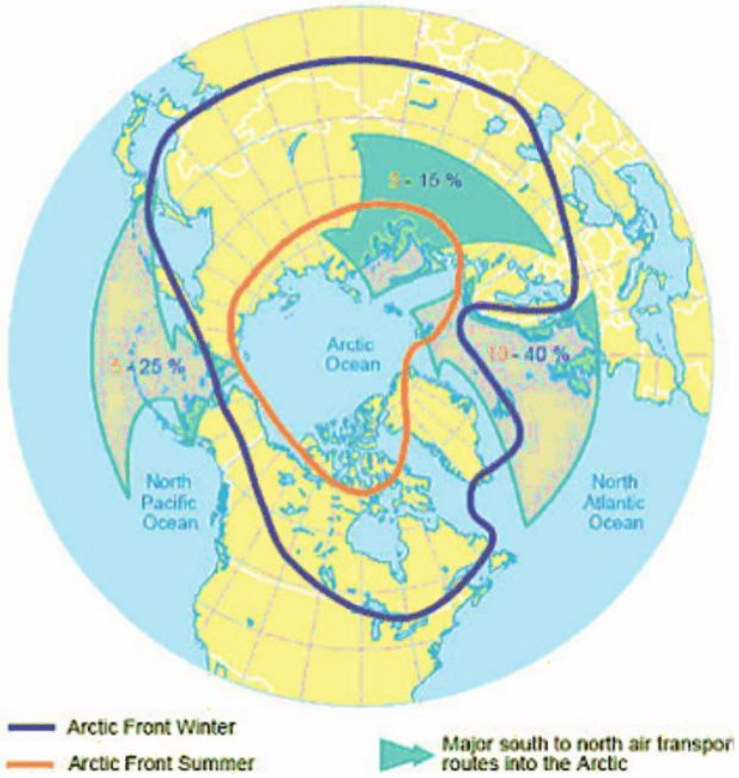


Arctic Haze NSS Sulfate (CCN) at Utqiagvik: 1997-2014

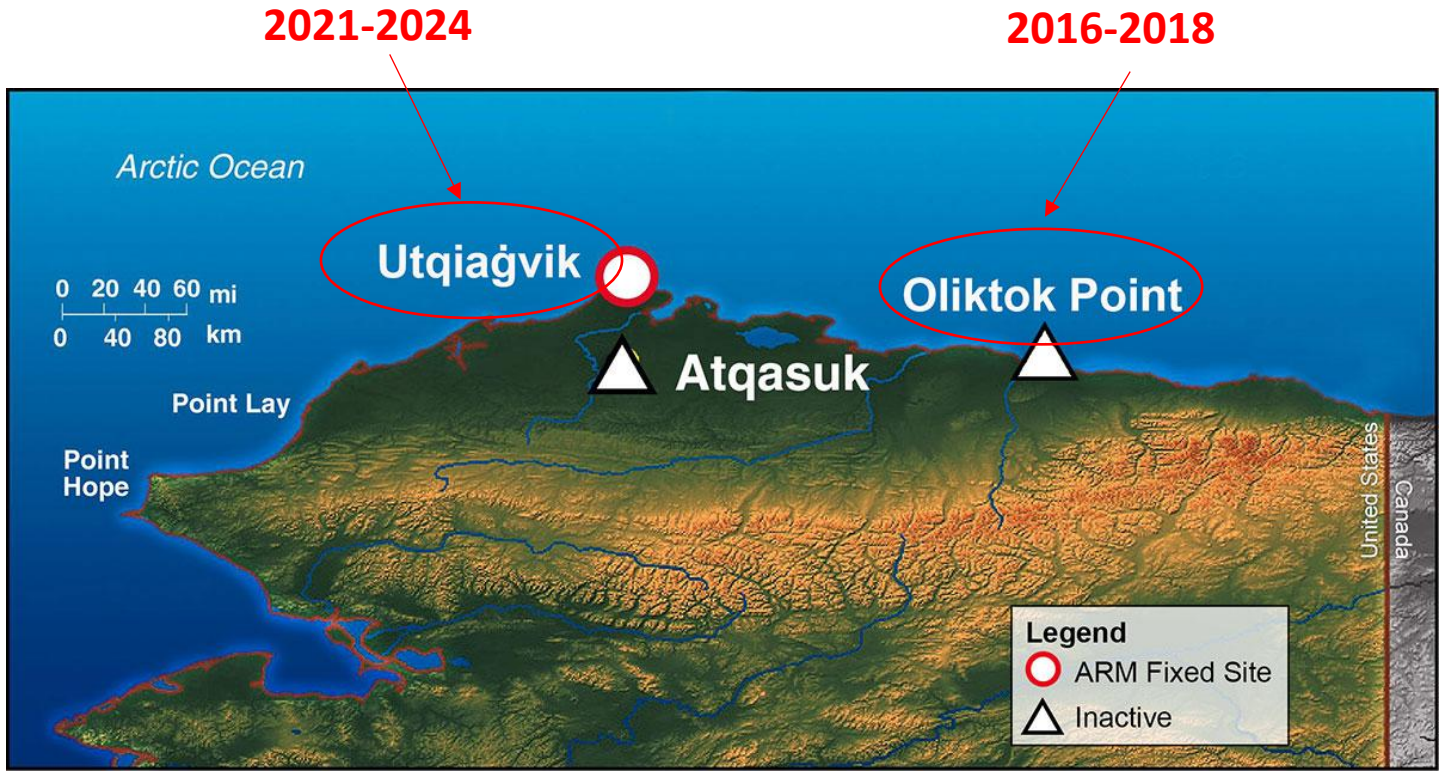


Transport into the Arctic: Long-range/Lofted Transport

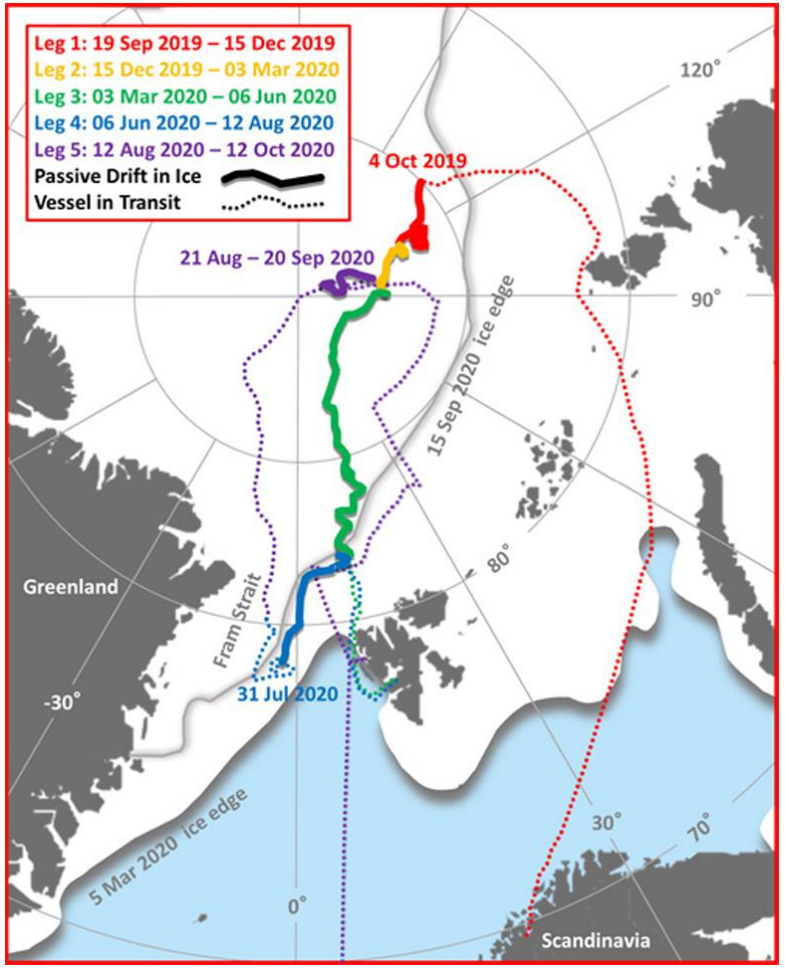




Locations of Interest

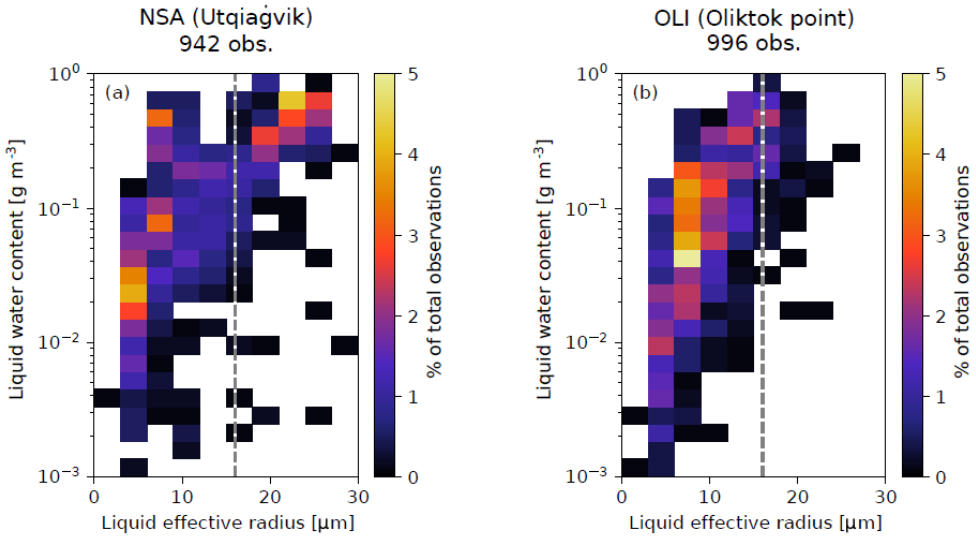


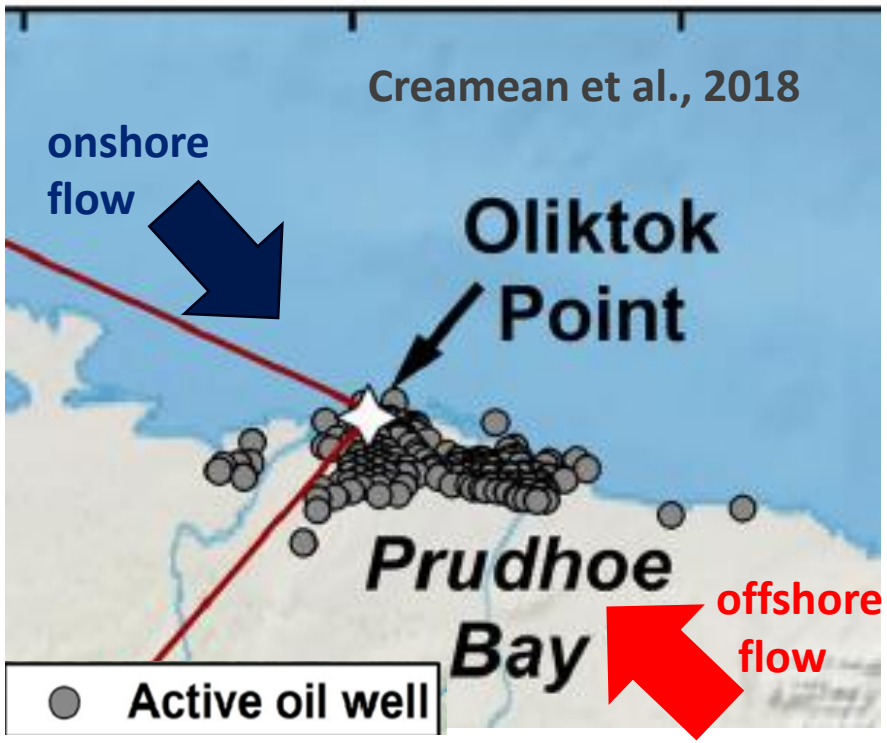
MOSAiC Expedition (2019-2020)



Local Anthropogenic Aerosol Source at Oliktok Point

- Prudhoe Bay oilfield
  - Onshore vs. offshore flow
  - Cosine of the direction to binarize the wind direction (northerly vs. southerly)
    - From surface to 2 km
    - 20 minutes leading up to event





MASC and Riming Enhancement Factor (REF): Oliktok Pt. & Utqiagvik

Multi-Angle Snowflake Camera (MASC)

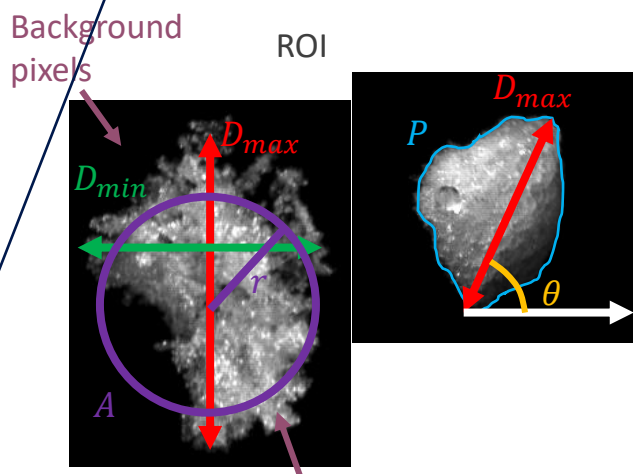
- Fall Speed (v)
- Geometric Cross-section ($A = N_{pix} * A_{pix}$)
- Area-equivalent radius ($r = \sqrt{A/\pi}$)
- Perimeter (P)
- Max Dimension (D_{max})
- Aspect Ratio ($\alpha = \frac{D_{min}}{D_{max}}$)
- Orientation (θ)
- Complexity $\chi = \frac{P}{2\pi r}(1 + \langle\sigma\rangle)$

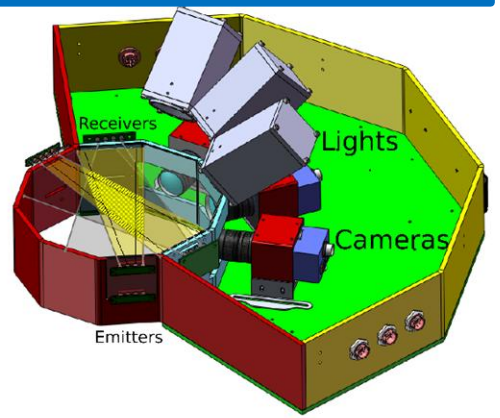
Riming Classes:

$\chi \leq 1.35$: heavily rimed graupel

$1.35 < \chi \leq 1.75$: moderately rimed

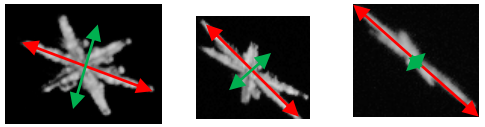
$\chi > 1.75$: sparsely rimed aggregates





Garrett *et al.* (2012)

$\alpha_0 = 0.63$ $\alpha_1 = 0.43$ $\alpha_2 = 0.16$



Flatness $\phi = \frac{\alpha_{max} - \alpha_{min}}{\alpha}$

$\phi = \frac{0.63 - 0.16}{0.41} = 1.15$

14

MASC and Riming Enhancement Factor (REF): Oliktok Pt. & Utqiagvik

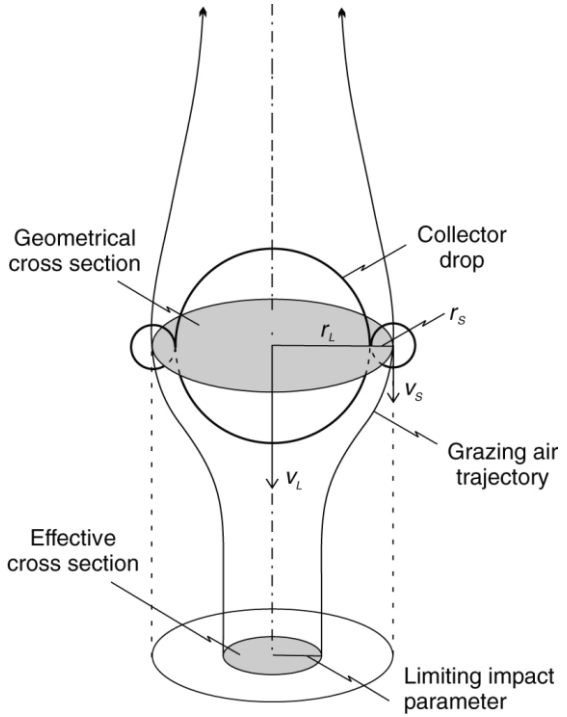
- Collection kernel: $K(r_p, r_d) = \pi(r_p + r_d)^2 E_c(r_p, r_d)|\Delta v_T|$
- Assumptions:
  - Ice particle large compared to droplets: $r_p \gg r_d$
  - Still air: $\Delta v_T \simeq v_p = dz_p/dt$
- Concentration of liquid water droplet mass: w_l
- Mass growth rate:

$$\frac{dm_p}{dt} = Kw_l = \pi r_p^2 E_c w_l \left|\frac{dz_p}{dt}\right|$$

- Further assuming $A_p = \pi r_p^2 \neq A_p(z)$ & $E_c = 1$
- Integrating dm_p from cloud top to cloud base & noting $LWP = \int_{z_{ct}}^{z_{cb}} w_l dz$,the total rimed mass from continuous collection is

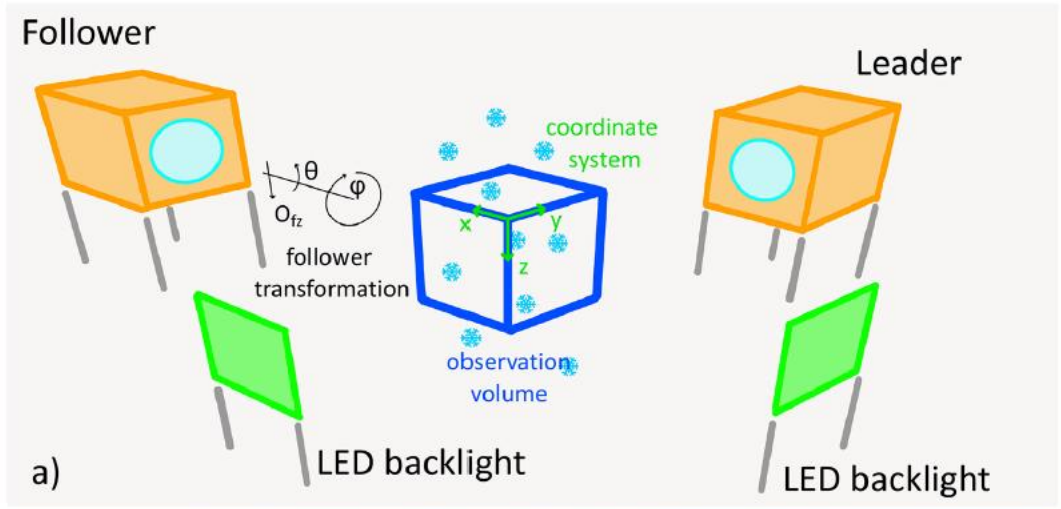
$$m_{cc} = A_p LWP$$

Riming Enhancement Factor (REF): $\varepsilon_r = \frac{m_{obs}}{m_{cc}} = \frac{\pi \rho_e D_p^3/6}{A_p \cdot LWP}$



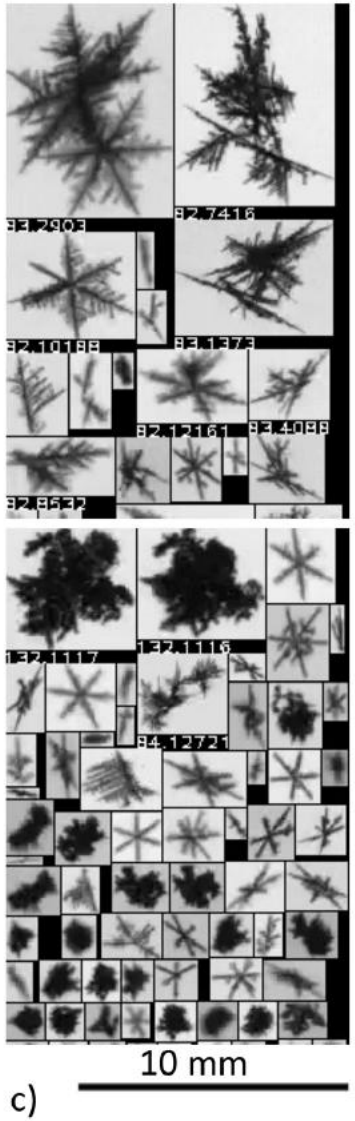
Lamb & Verlinde, 2011

VISSS and REF: MOSAiC Expedition

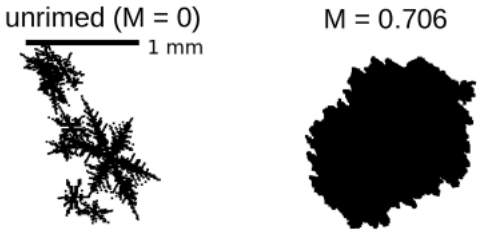




Maahn et al., 2024



Maherndl et al., 2024



- Shape-based estimation of REF (Maherndl et al., 2024):
  - Normalized rime mass (Seifert et al., 2019):

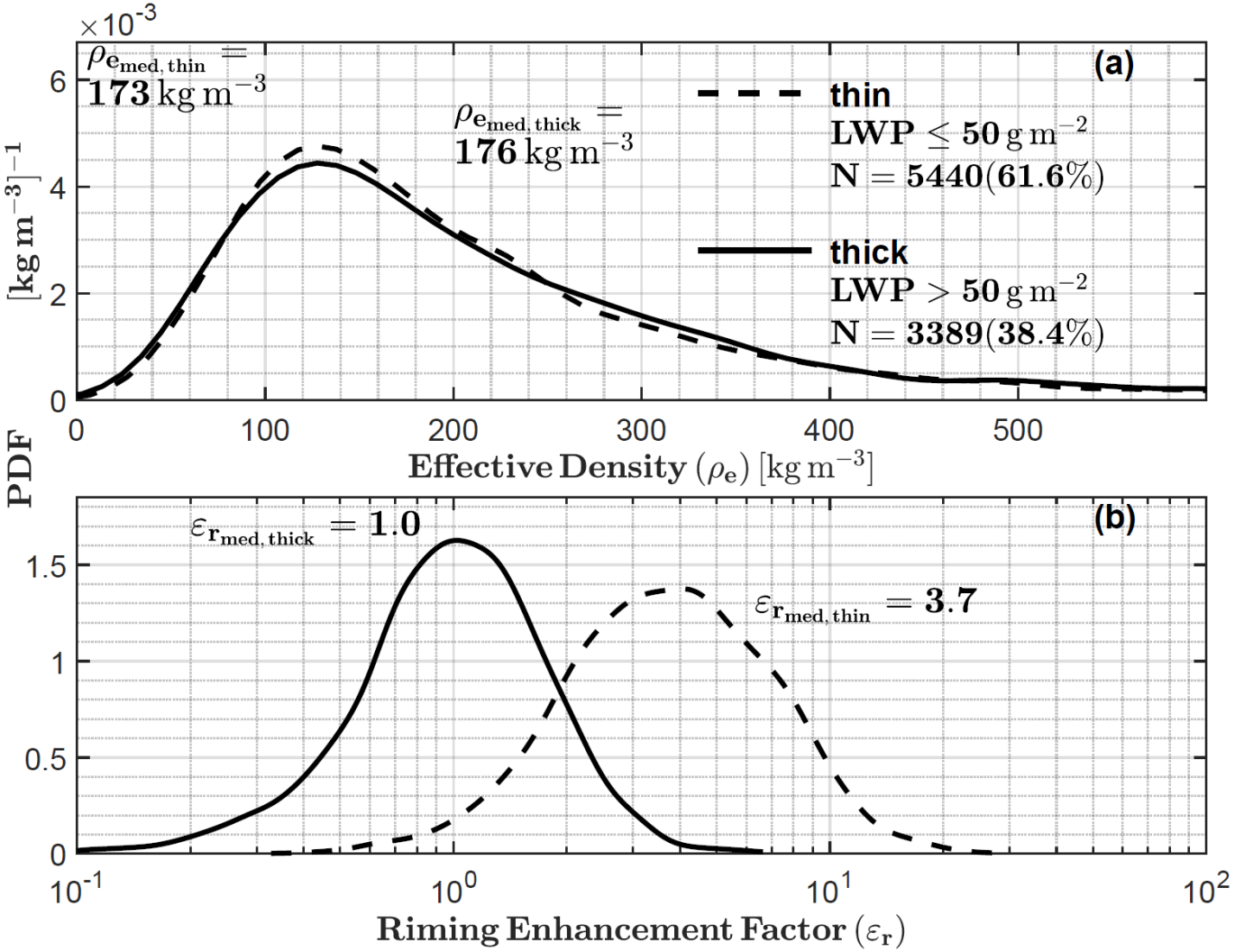
$$M = \frac{m_{rime}}{m_g} = \frac{m_{rime}}{\pi \rho_{rime} D_{max}^3 / 6}$$

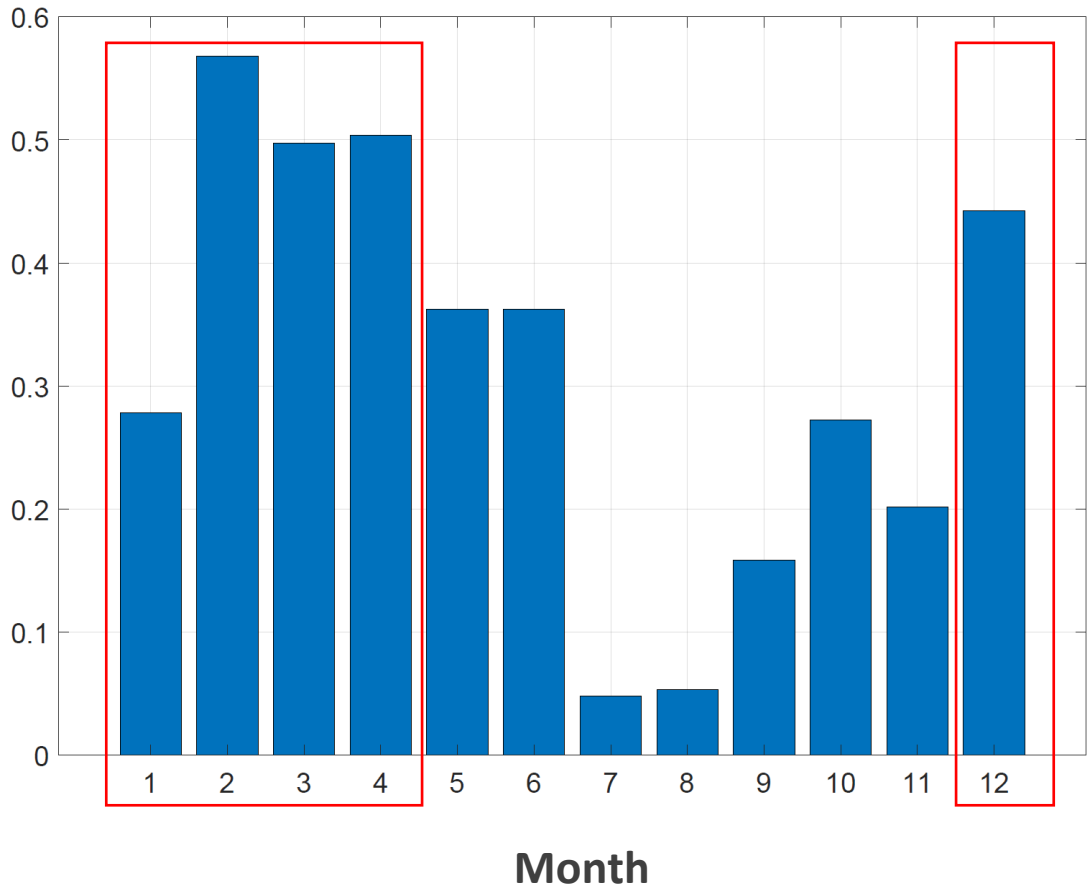
    - Where $\rho_{rime} = 700\ kg/m^3$
  - REF:

$$\boldsymbol{\varepsilon_r = \frac{m_{obs}}{m_{cc}} = \frac{M \pi \rho_{rime} D_{max}^3 / 6}{A_p \cdot LWP}}$$

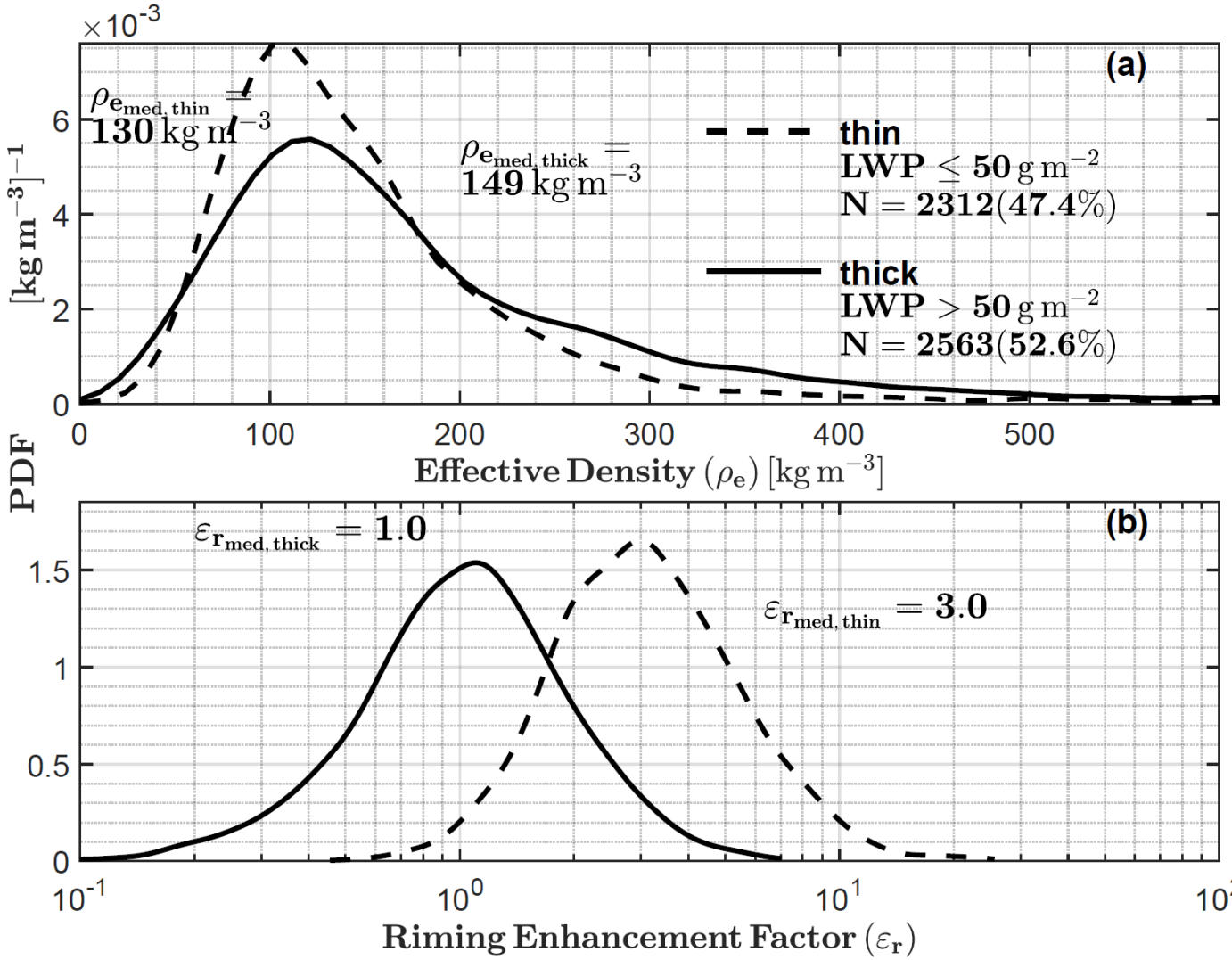
    - Sensitive to choice of ρ_{rime}

Enhanced Riming: Oliktok Point (Sep 2016 – Sep 2018)

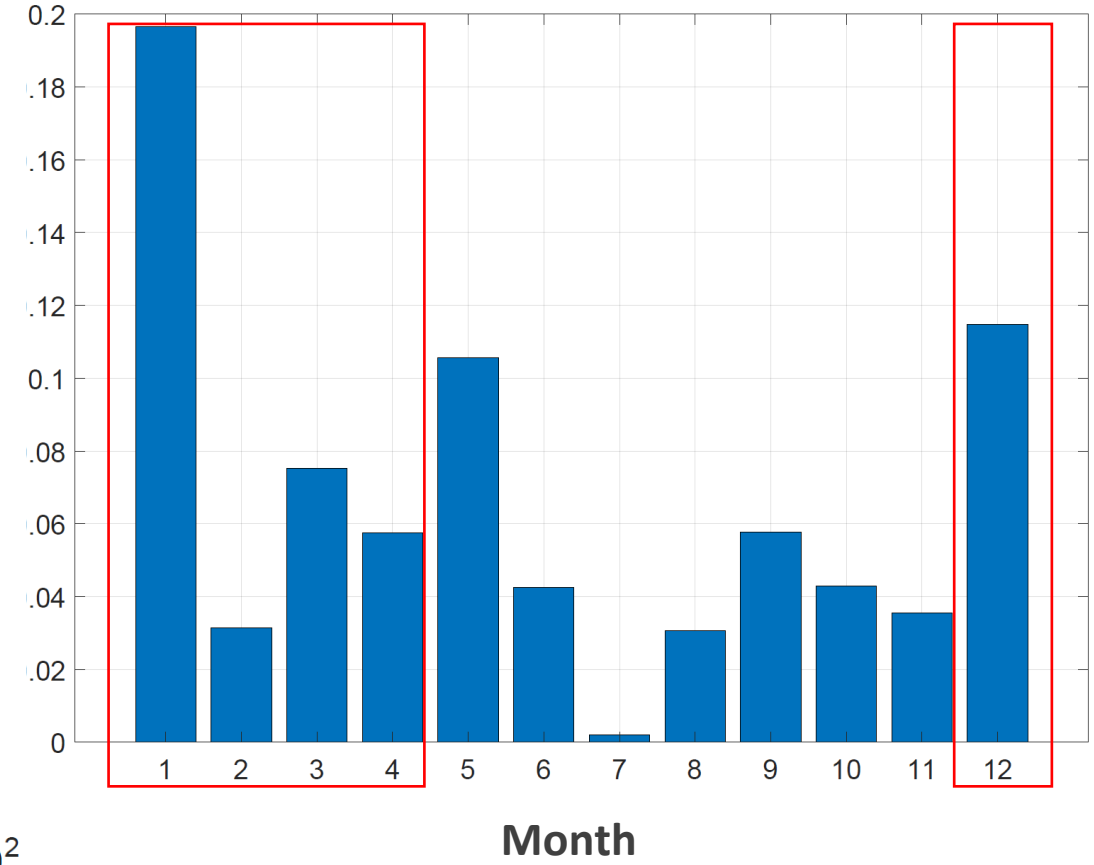




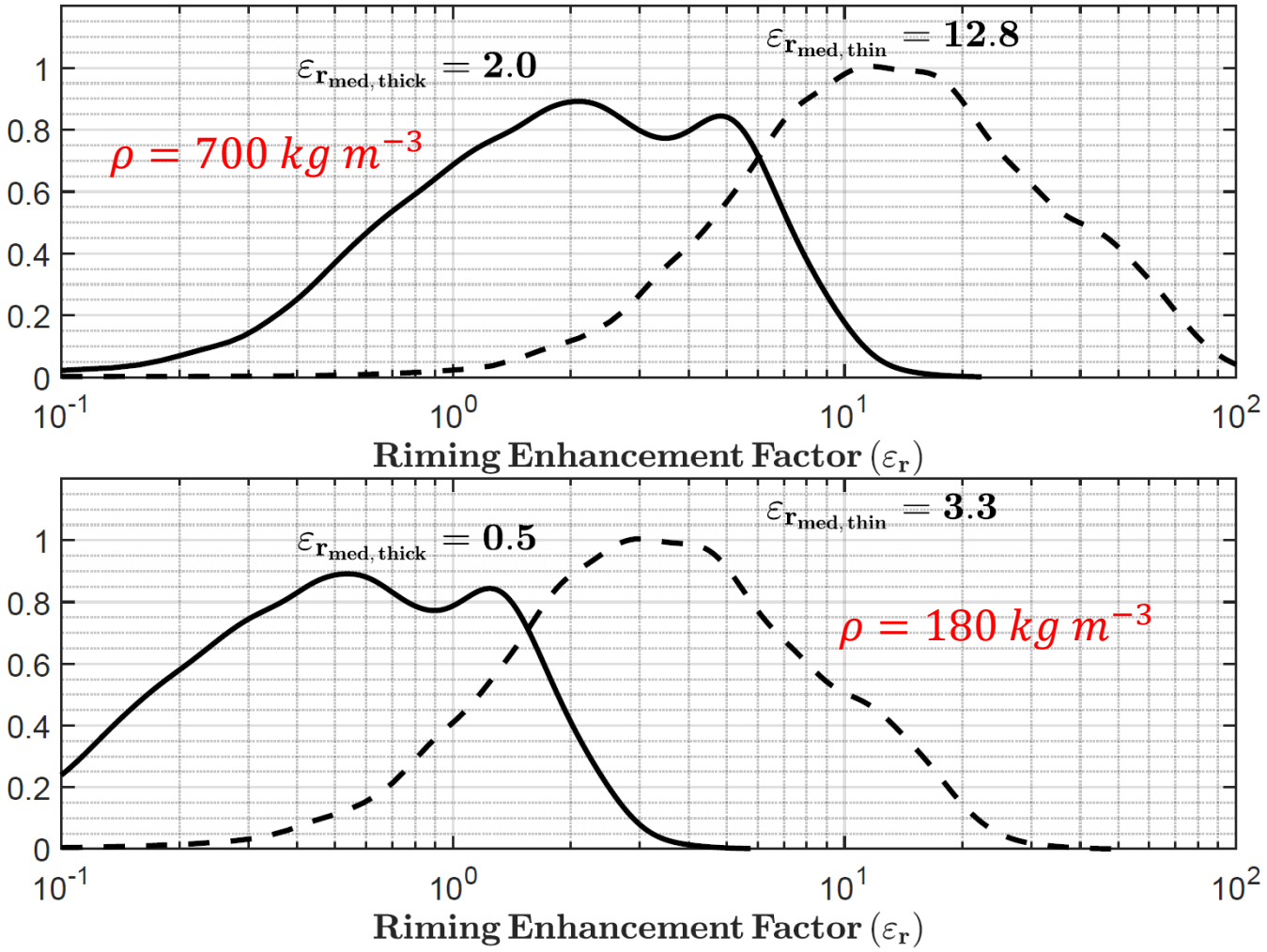
Enhanced Riming: Utqiagvik (Apr 2021 – Oct 2024)

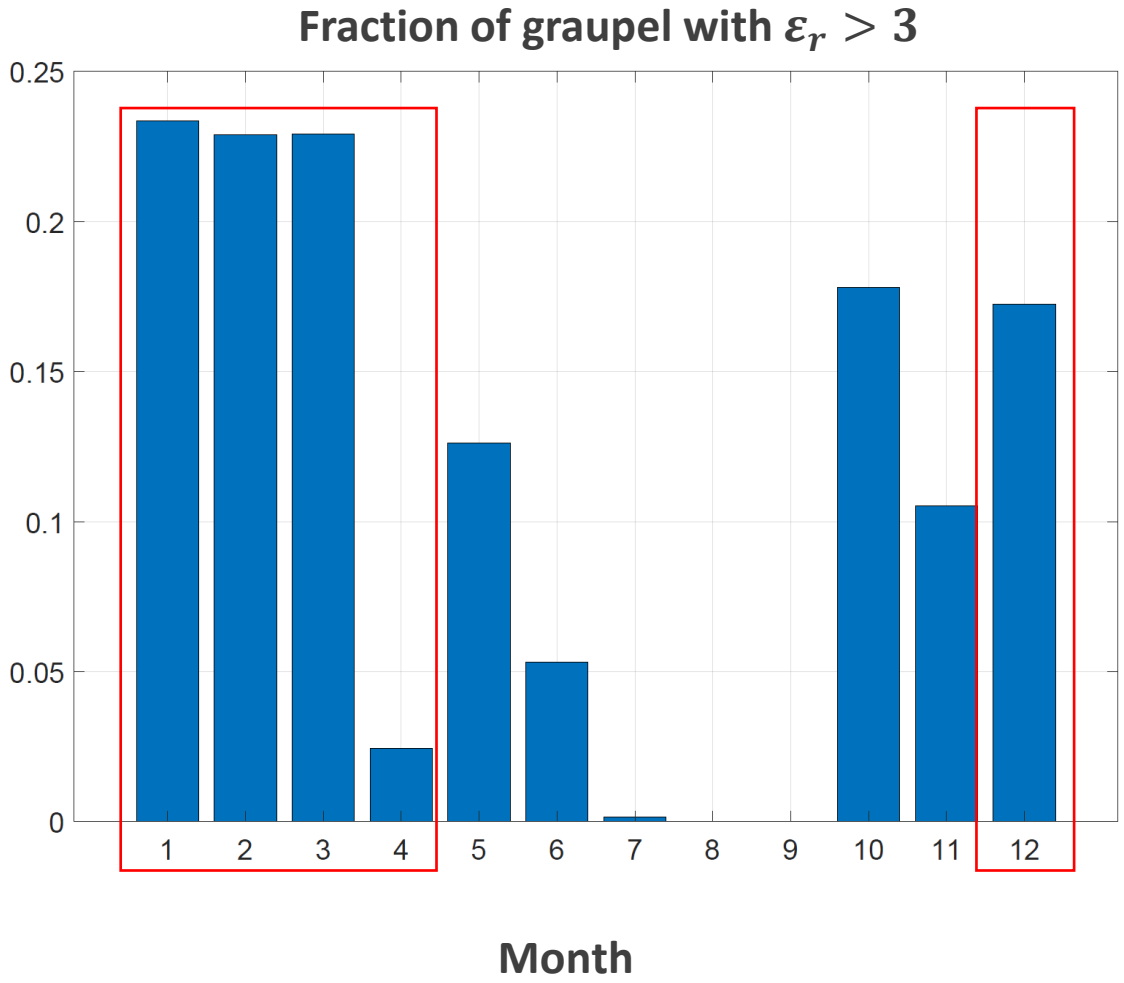


Fraction of graupel with $\varepsilon_r > 3$



Enhanced Riming: MOSAiC (Oct 2019 – Oct 2020)





Conclusions/Future Work

- Preliminary results indicate enhanced riming more likely during Arctic haze season (Dec-Apr)
  - **Suggests early support for Hypothesis #2**: “polluted” clouds
    - smaller & numerous droplets
    - enhanced radiative cooling in turn enhancing dynamics/TKE
- However, more work to do:
  - Analyze local influence WRT low-level flow regime (**onshore vs. offshore**)
  - Include **cloud-level measurements** (limited)
  - Attempt to **classify types/sources**
  - And more…