Jet aircraft lubrication oil droplets as contrail ice-forming particles

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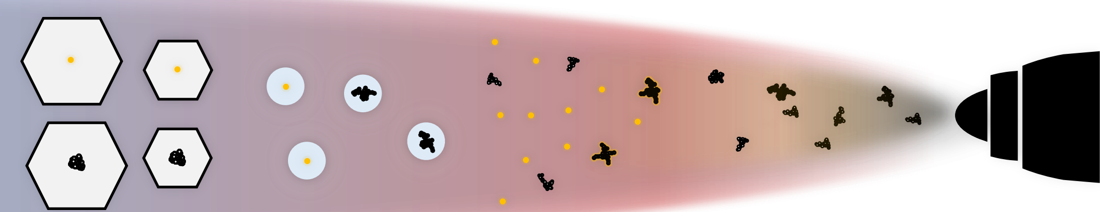

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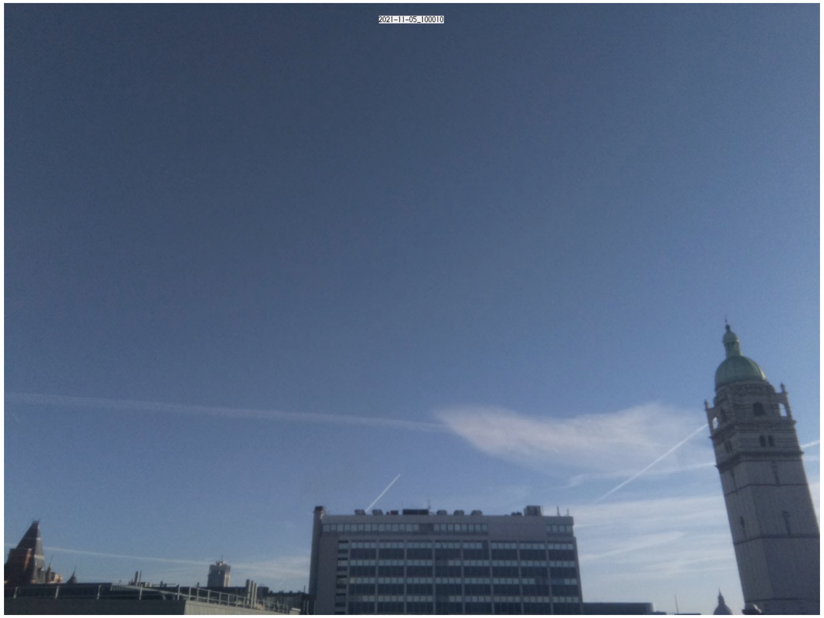
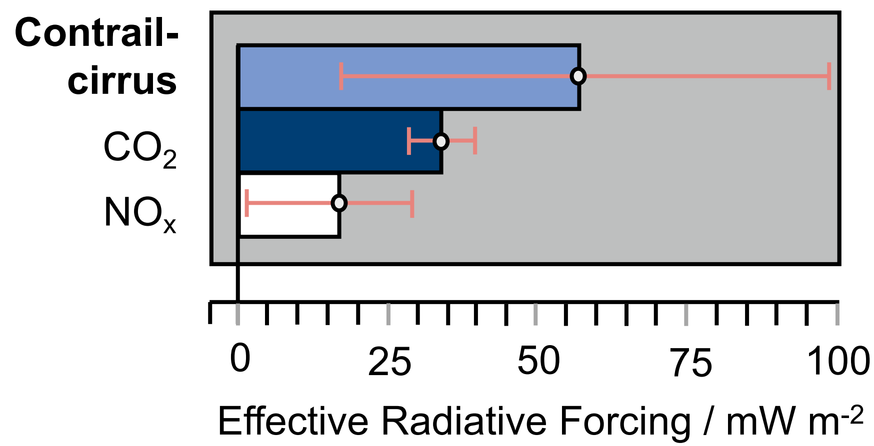
Context - I/II



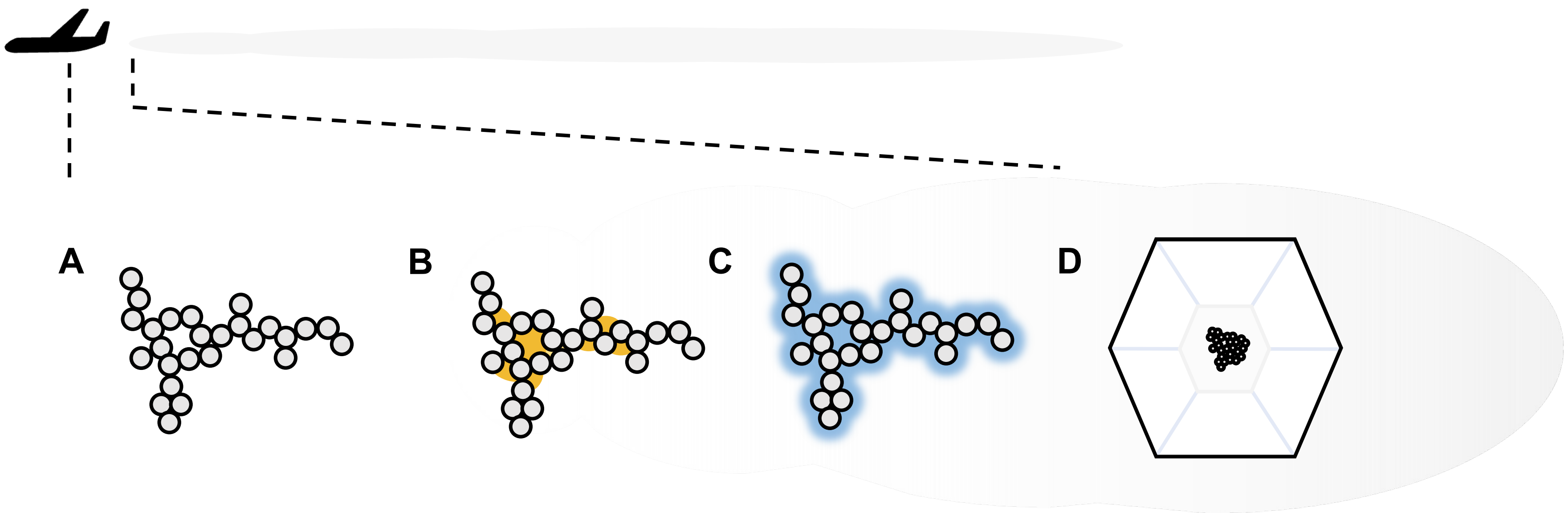
"[**Contrails**] are line-shaped **ice** clouds generated by jet aircraft cruising in the upper troposphere [between] 8 – 13 km" [1]



- Global aviation contributed 3.5% to net effective radiative forcing (ERF) in 2011.
- **Non-CO_2** forcing agents contributed 66% to aviation-derived **ERF** in 2018 [2]

[1] B Kärcher., 2018; [2] Lee et al., 2018

Context - II/II



(A) Exhaust nvPM **emissions**: $10^{11} – 10^{16}$ particles (kg fuel)$^{-1}$ [3]

(B) Adsorption of (semi) volatile material modifies nvPM properties [4]

(C) Activation of nvPM particles to form droplets

(D) Nucleation to form ice crystals, which grow by deposition of water vapour

[3] ICAO, 2023; [4] Kärcher et al., 2015

Is **nvPM** the only particle type we should be considering?

Future Emissions

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Regulatory/technological changes:

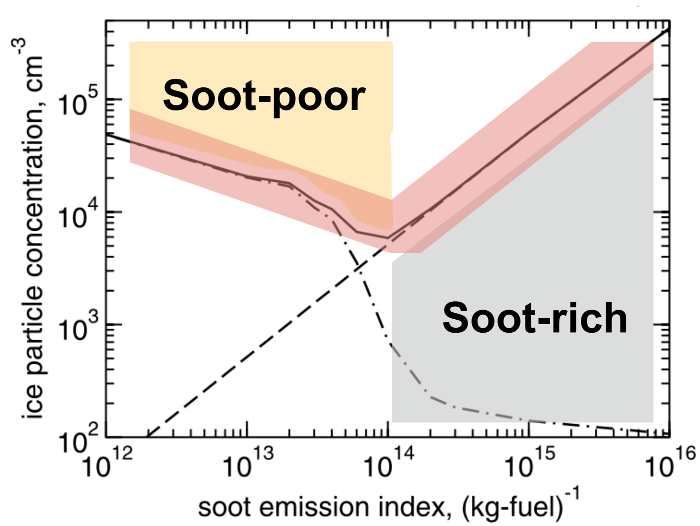
- Short-term: ICAO **regulations** on nvPM emissions [5]
- Mid-term: adoption of sustainable aviation fuels (**SAFs**)
- Long-term: development of **electric/hydrogen aircraft**

Consequences:

Decreased nvPM particle emissions

↓

Increased relative emissions of other, combustion-related sources



[5] ICAO, 2017; [6] (figure on right annotated from) Kärcher, B & Yu, F, 2012

Lubrication Oil

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"Lubrication oil emission can be a **significant component** of organic PM in aircraft engine exhaust."
[7 - Z Yu et al., 2012]

"We unambiguously attribute the **majority** of detected compounds [in near-runway sampled particles < 50 nm] to jet engine lubrication oils."
[8 - F Ungeheuer et al., 2020]

"[In near-runway samples] organic compounds in the ambient nanoparticles [< 30 nm] were **dominated** by nearly intact forms of jet engine lubrication oil."
[9 - A Fushimi et al., 2019]

"Jet oil nucleation… can explain the abundant observations of **high number concentrations** of non-refractory ultrafine particles near airports."
[10 - F Ungeheuer et al., 2022]

Research Objectives

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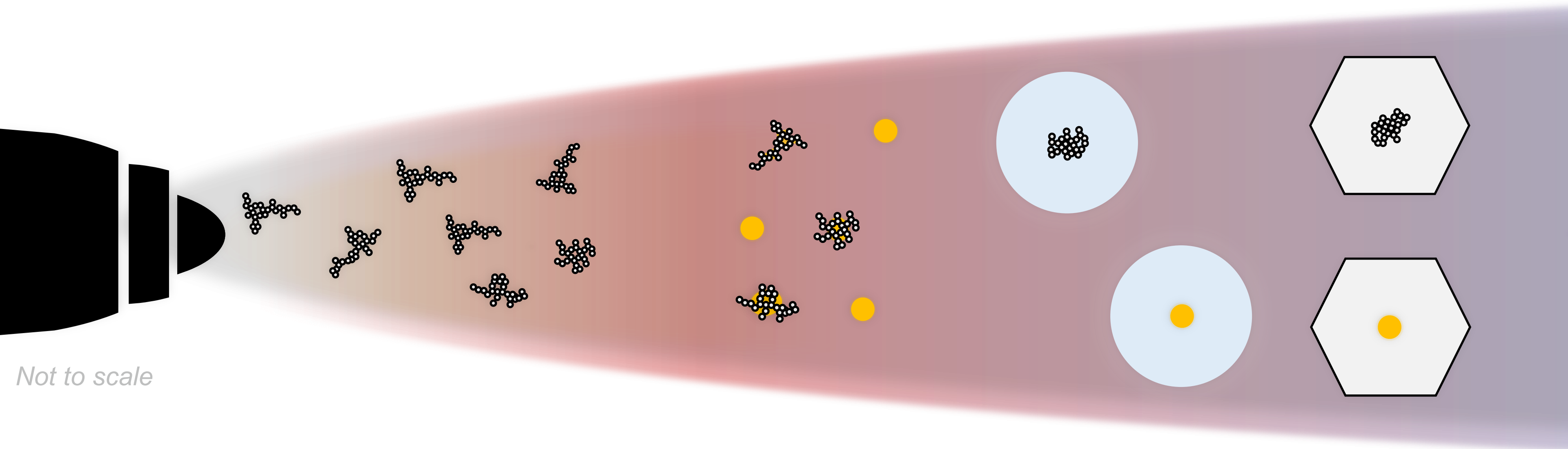
(1) Assess the ability of ultrafine lubrication oil droplets to act as **contrail ice-forming particles**

(2) Determine the **freezing pathway** of ultrafine lubrication oil droplets



Not to scale

(3) Comment on implications in the **soot-rich** and **soot-poor regime**

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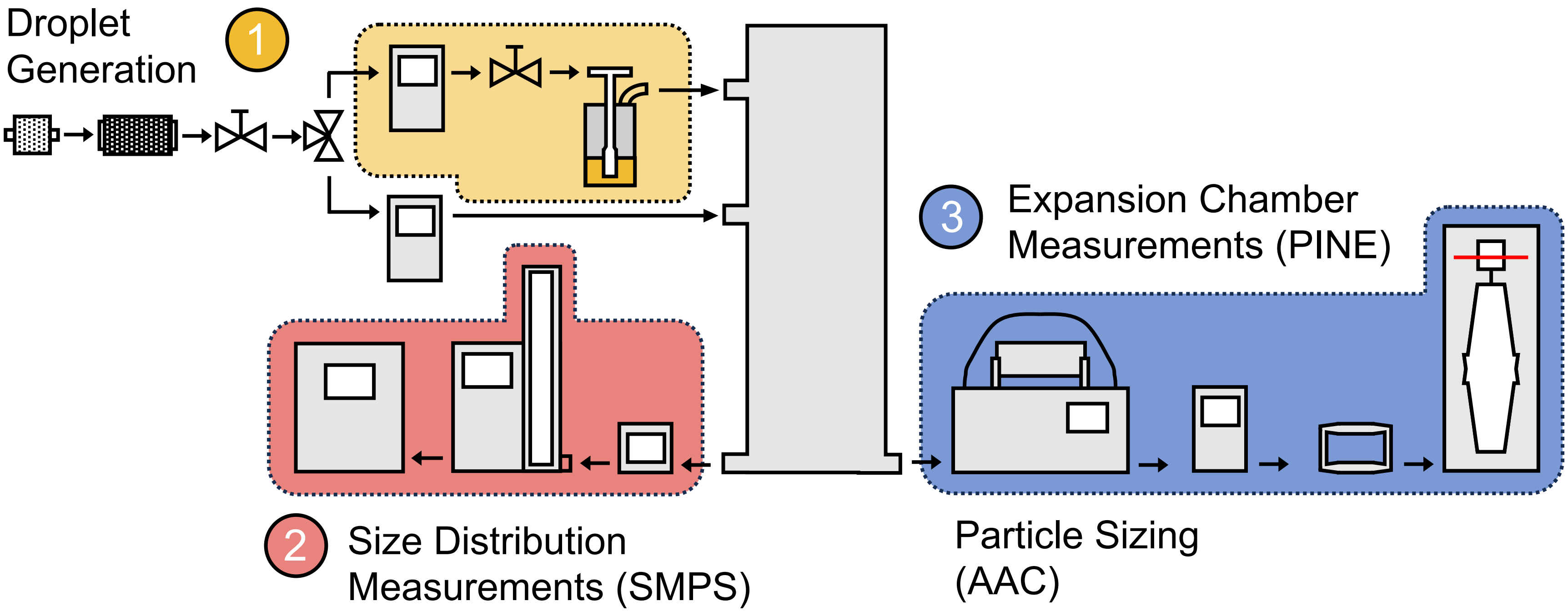
Methodology

1. Nebulize jet lubrication oil to produce droplets
2. Size select droplets: $\bar{D}_p$ = (100.9 ± 0.1) nm
3. Investigate activation/freezing microphysics of droplets



[11] O Möhler et al., 2021

Activation - I/IV

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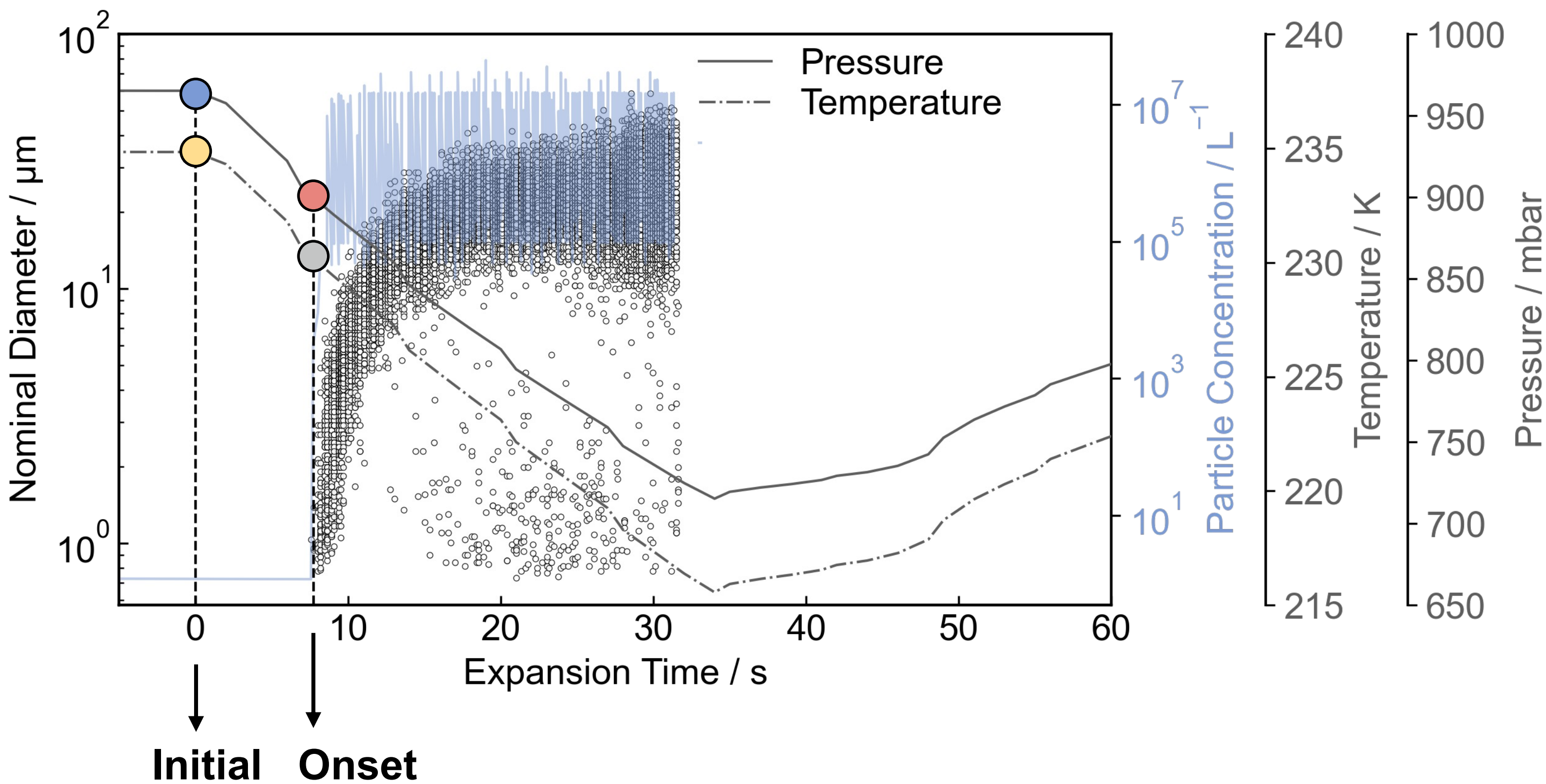
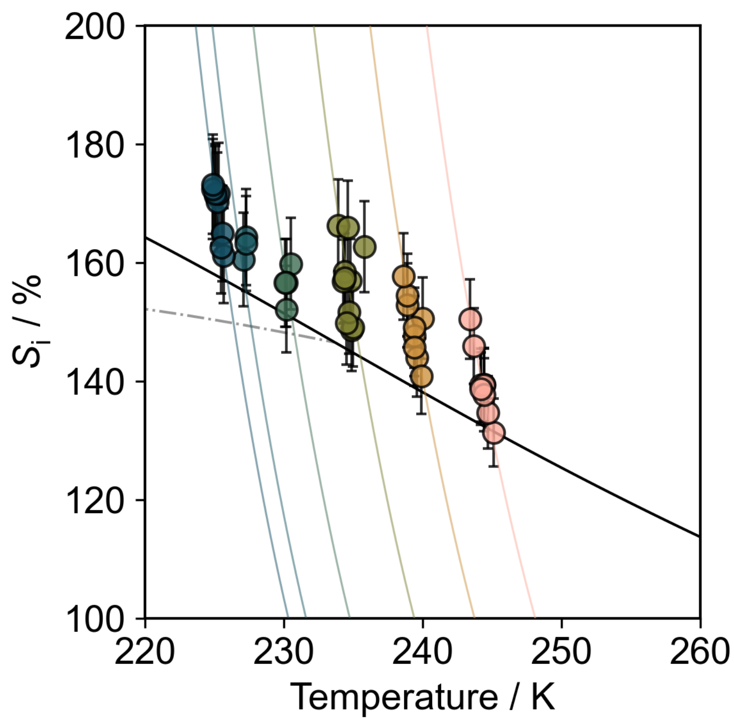
Example Individual Expansion



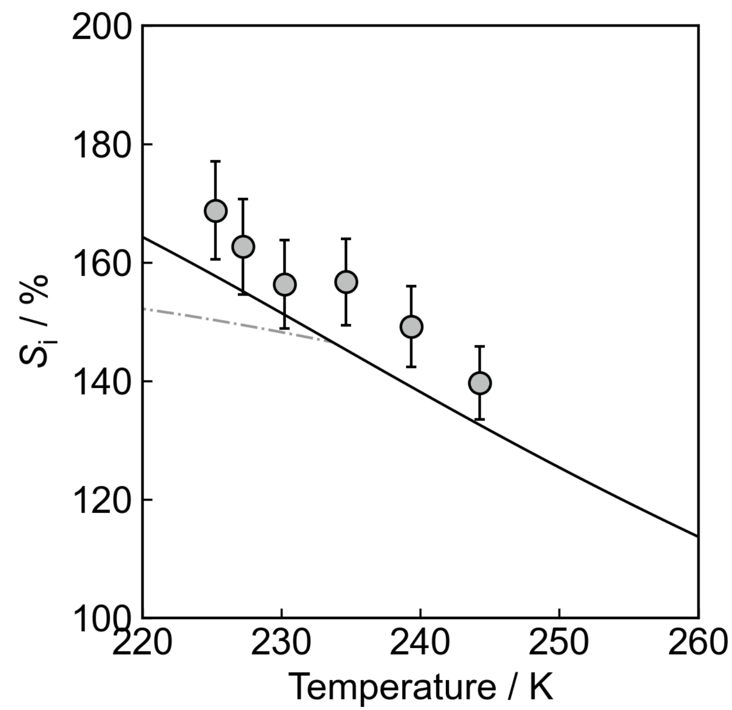
$$S_{\text{i, onset}} = \frac{p_{\text{water, onset}}}{p_{\text{ice, onset}}(T_{\text{onset}})} = \frac{P_{\text{chamber, onset}}\ (\bigcirc)}{P_{\text{chamber, initial}}\ (\bigcirc)}\ \frac{p_{\text{ice, initial}}\ (T_{\text{initial}}\bigcirc)}{p_{\text{ice, onset}}\ (T_{\text{onset}}\bigcirc)}$$

Activation - II/IV

Collective & Averaged Onset Positions



All Data
(45 expansions)



Averaged Data

Activation - III/IV

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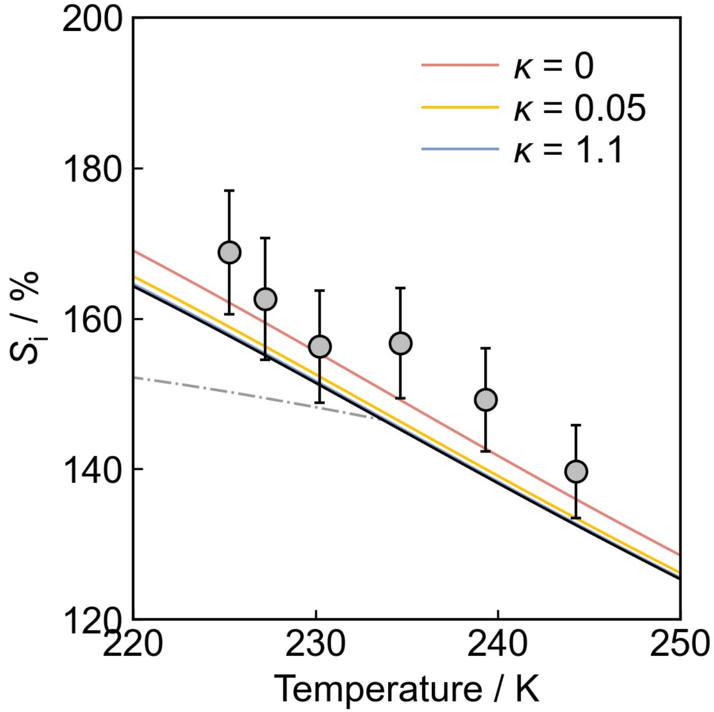
Hygroscopicity Analysis (*κ*-Köhler)



Material	Hygroscopicity parameter (*κ*)
Table salt (NaCl) [13]	1.1
α-Pinene (SOA) [12]	0.02 – 0.07
Lubrication oil	0

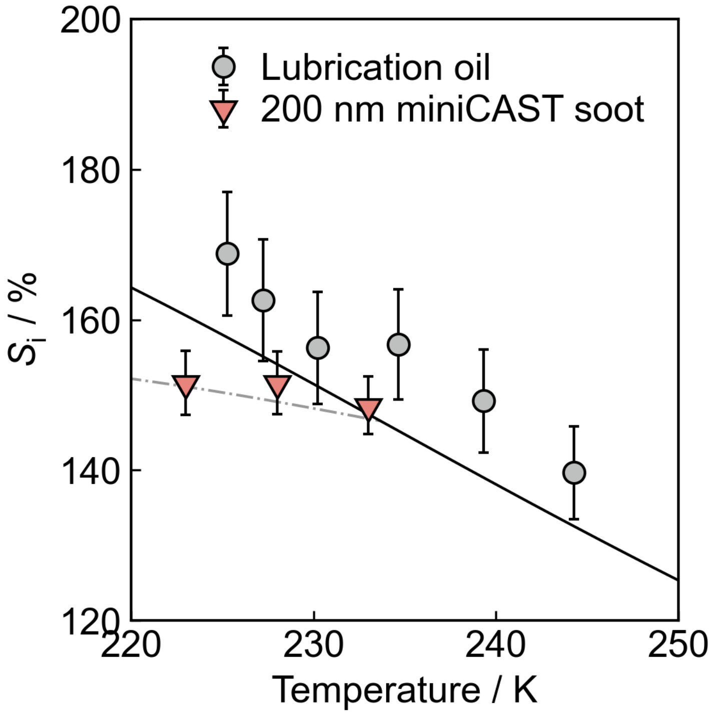
Hydrophilic

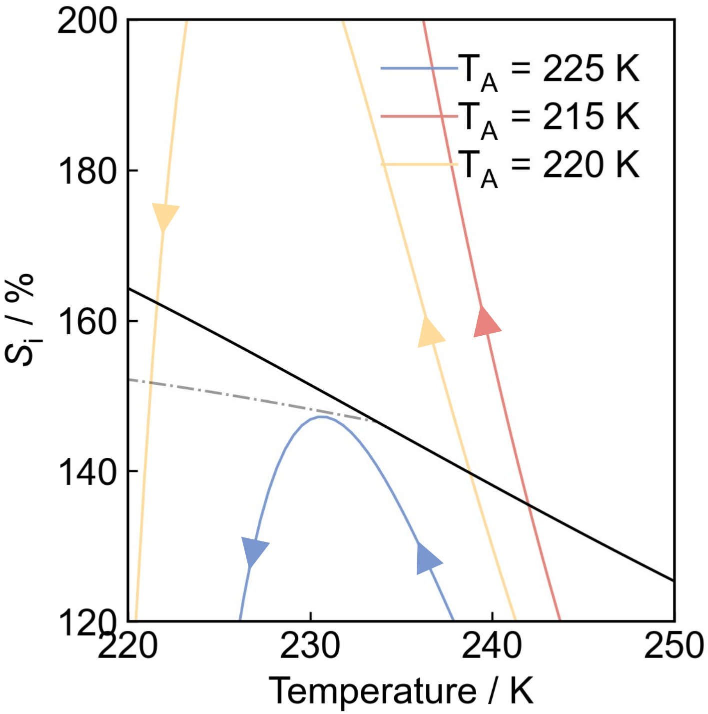
Hydrophobic

- Onset positions for lubrication oil droplets consistent with ***κ* ~ 0**
- Lubrication oil droplets are **insoluble** and **hydrophobic**

[12] M Petters & S Kreidenweis, 2007; [13] P Zieger et al., 2017

Activation - IV/IV





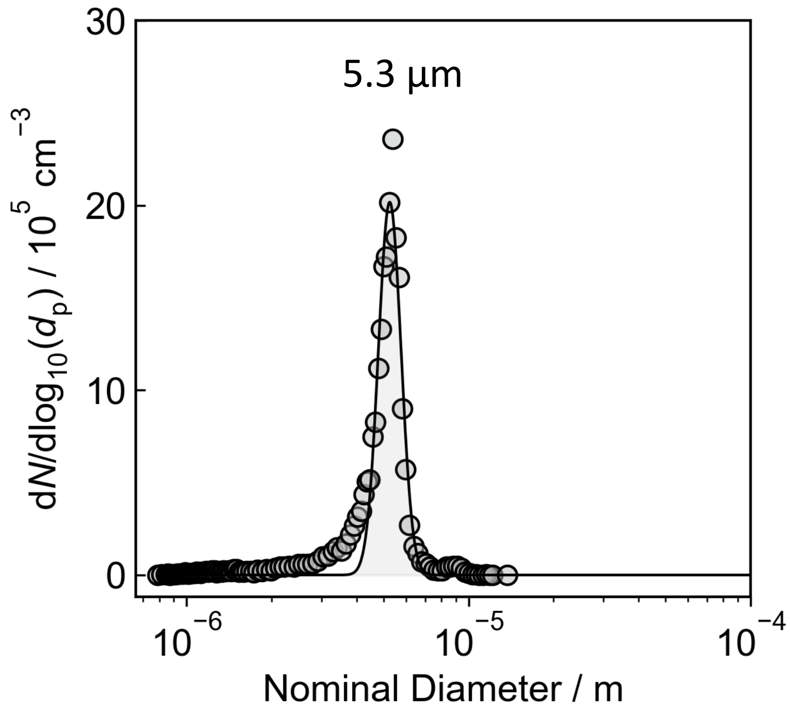
- **Soot particles [14] activate under milder supersaturations** than lubrication oil droplets.
- Lubrication oil droplets could **compete** for contrail plume supersaturations [15].

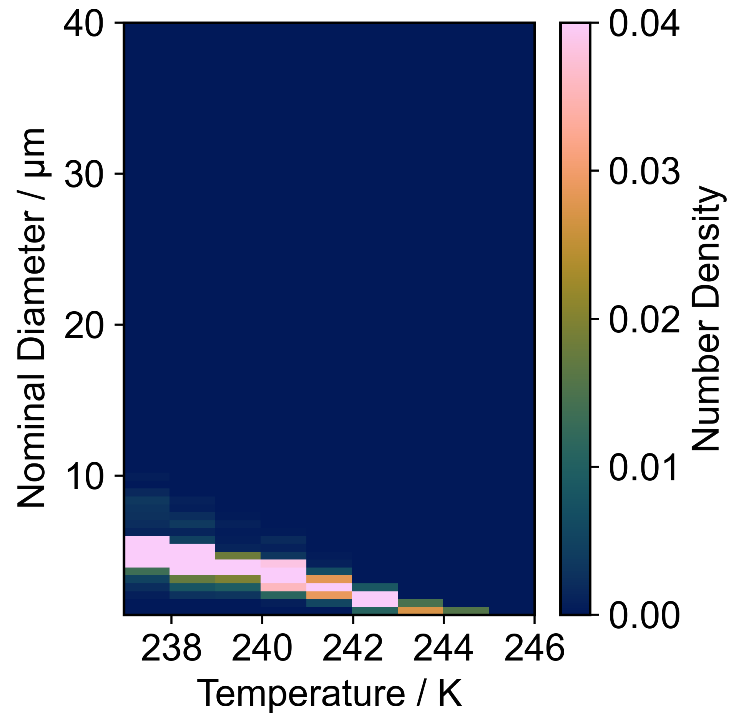
[14] K Gao & Z Kanji., 2022; [15] A Bier et al., 2022

What about the **freezing behaviour**?

Ice Nucleation - I/IV

Warmest **chamber temperature:** T_c = 248.0 K (T_o = 244.2 K)

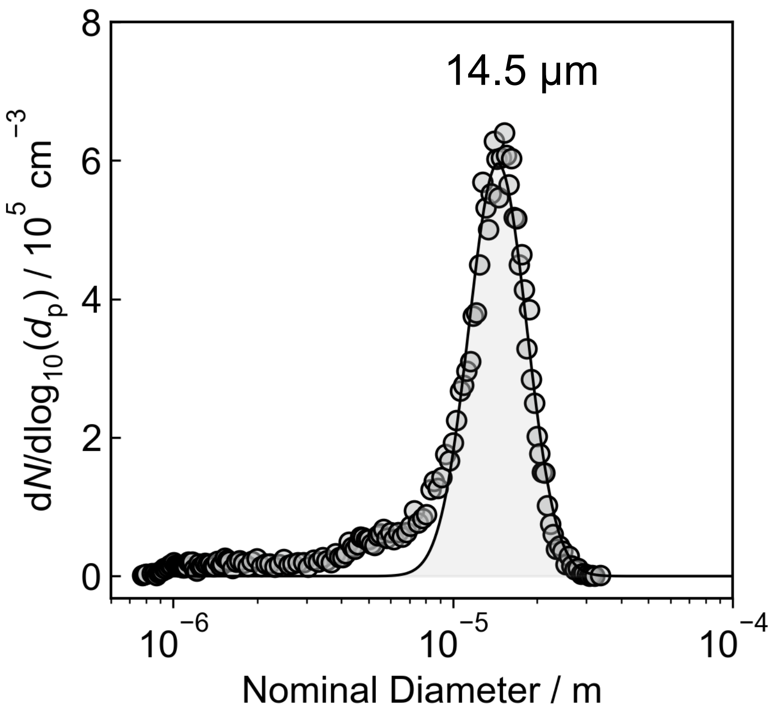


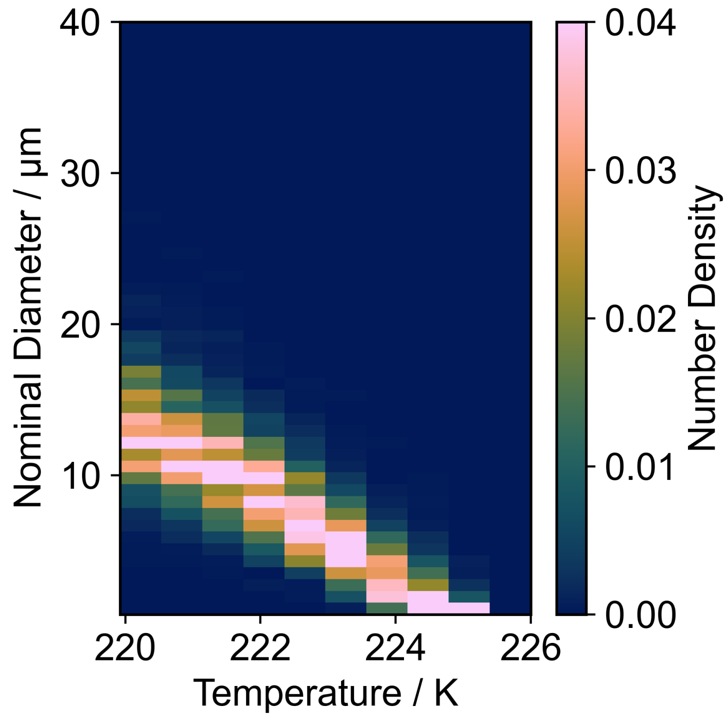


- Majority of particles identified in the **water droplet mode** (activated lubrication oil droplets) at the **warmest** chamber temperature.

Ice Nucleation - II/IV

Coolest **chamber temperature:** T_c = 230.2 K (T_o = 224.9 K)

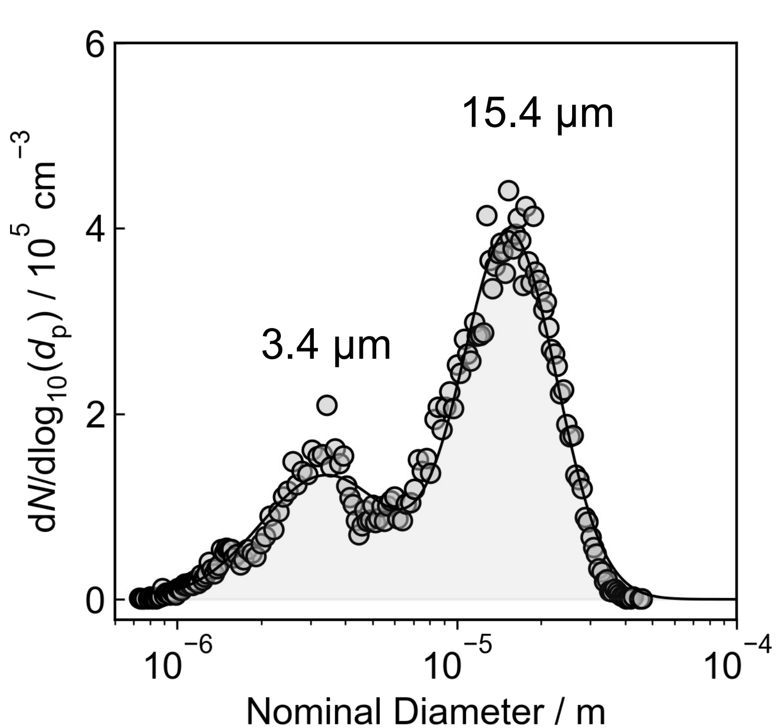


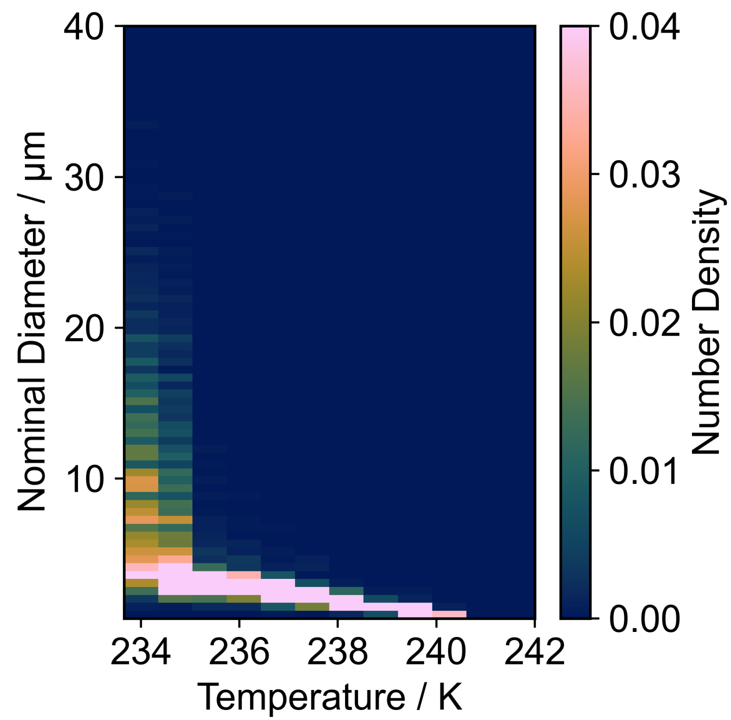


- Majority of particles identified in the **ice crystal mode** at the **coolest** chamber temperature.

Ice Nucleation - III/IV

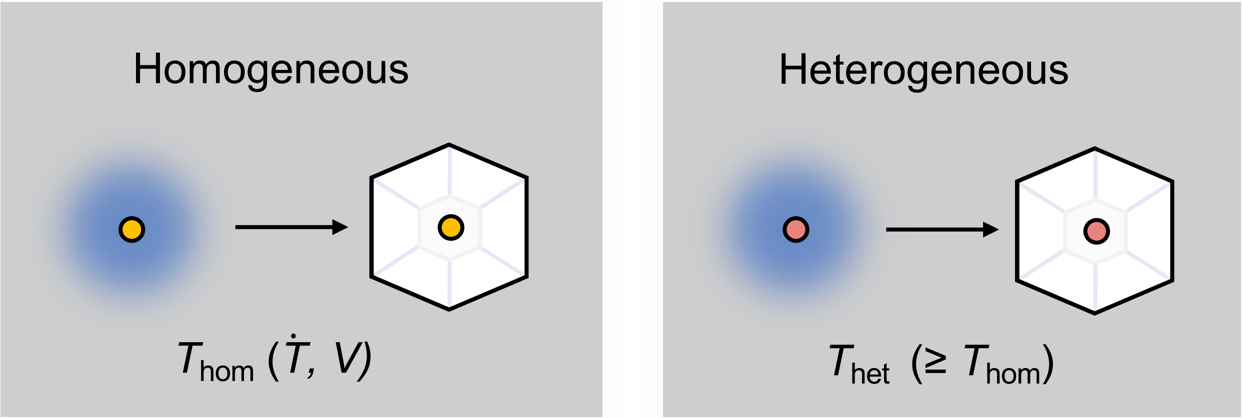
***Intermediate* chamber temperature:** T_c = 244.5 K (T_o = 240.0 K)





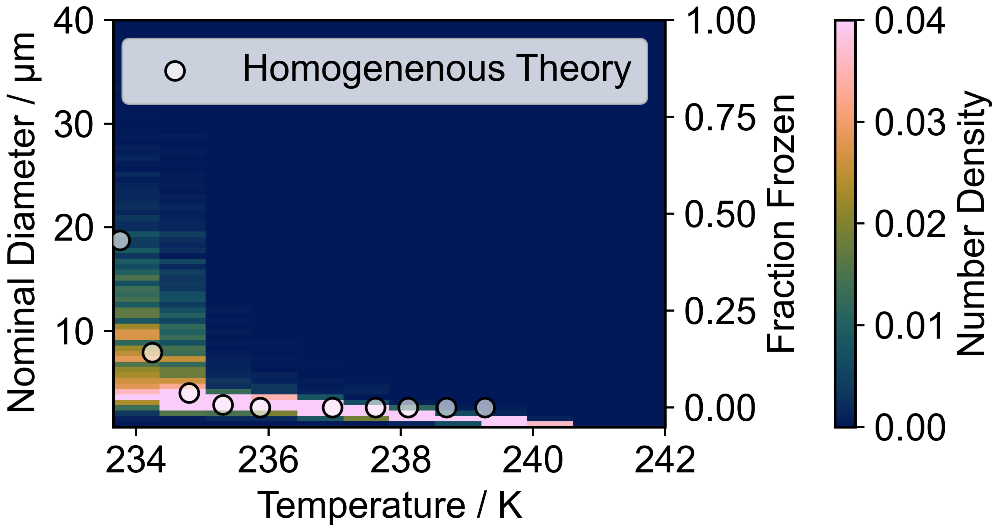
- Ice crystals nucleate from growing water droplets (activated lubrication oil droplets)
- This is **condensation followed by _____ freezing**

Freezing Mechanisms (from liquid phase)



Our results

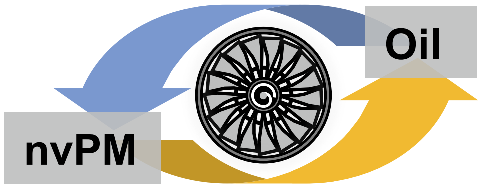
- Ice nucleation onset at T_{hom} ~ 235 K, consistent with **homogeneous** freezing [16]
- Lubrication oil droplets freeze by **condensation followed by <u>homogeneous</u> freezing**



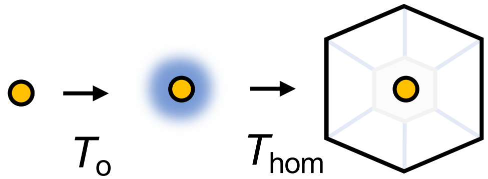
[16] B Murray et al., 2012

Summary

- Decrease in nvPM emissions will lead to an increase in relative lubrication oil emissions



- Nucleation of ice by **condensation** followed by **homogeneous freezing**



- Important in low-soot regime

Ongoing/Future Work

- Production of representative nvPM using a portable inverse diffusion flame combustor

- Explore ice nucleation for mixed populations of nvPM and lubrication oil droplets

Thank you, any questions?

Research Team

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