Pacific Northwest
NATIONAL LABORATORY

PI: Susannah Burrows
DOE Early Career project
(2018-2023)

ASR
Atmospheric System Research

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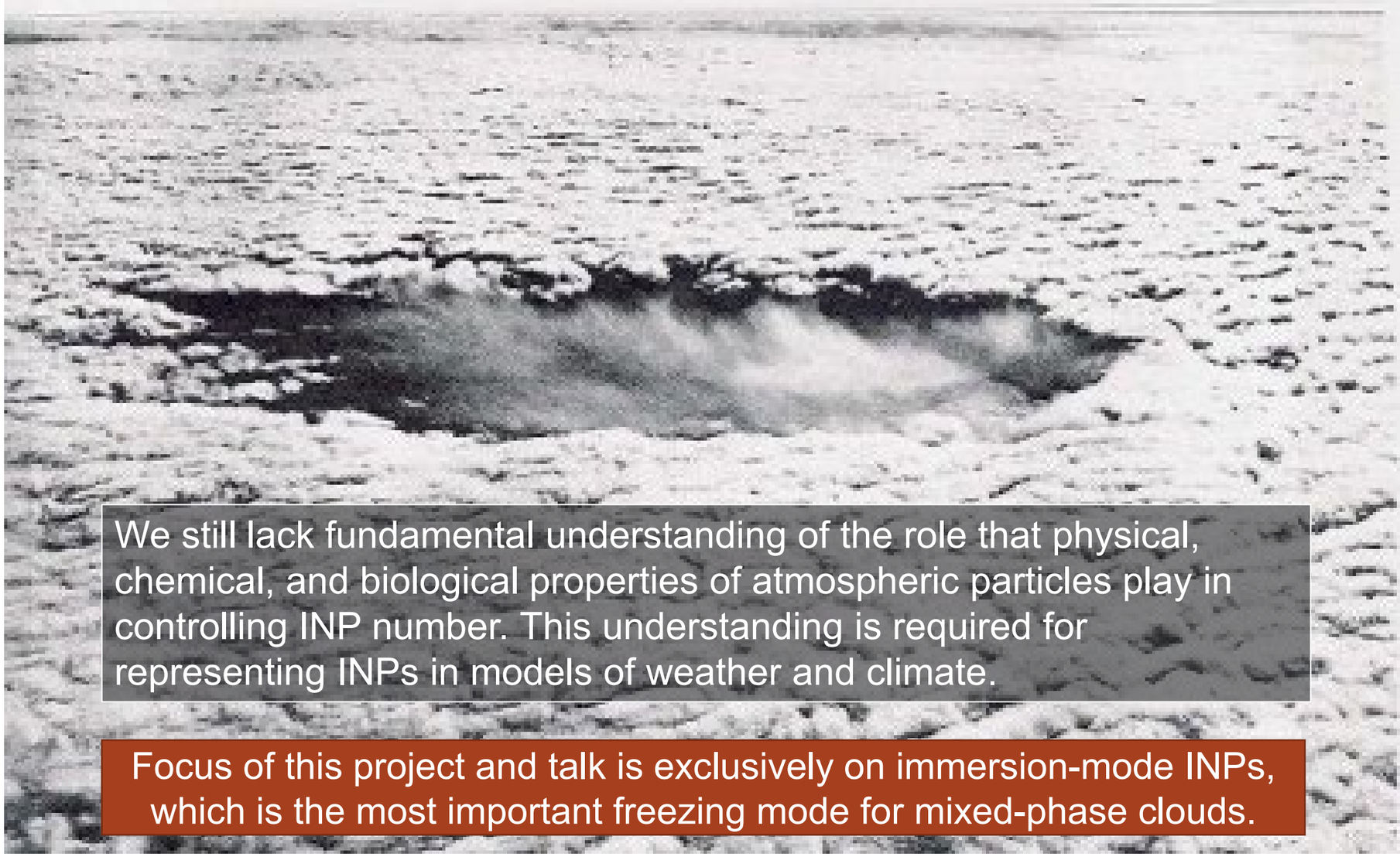
Ice-nucleating particles (INPs) that impact clouds and climate: progress and research needs

- INPs facilitate formation of cloud ice
- Important impacts for precipitation and climate



We still lack fundamental understanding of the role that physical, chemical, and biological properties of atmospheric particles play in controlling INP number. This understanding is required for representing INPs in models of weather and climate.

Focus of this project and talk is exclusively on immersion-mode INPs, which is the most important freezing mode for mixed-phase clouds.

Cloud seeding image from Sewell, W.R.D., et. al., 1973: Modifying the Weather

Acknowledgements

Project team:

- Gavin Cornwell, Isabelle Steinke (now at Uni Leipzig), Aishwarya Raman

Collaborators:

- **Pacific Northwest National Laboratory:** Alla Zelenyuk, Gourihar Kulkarni, Mikhail Pekour, Swarup China, Nurun Nahar Lata, Gregory Vandergrift
- **Colorado State University:** Paul DeMott, Tom Hill, Russell Perkins, Jessie Creamean, Carson Hume
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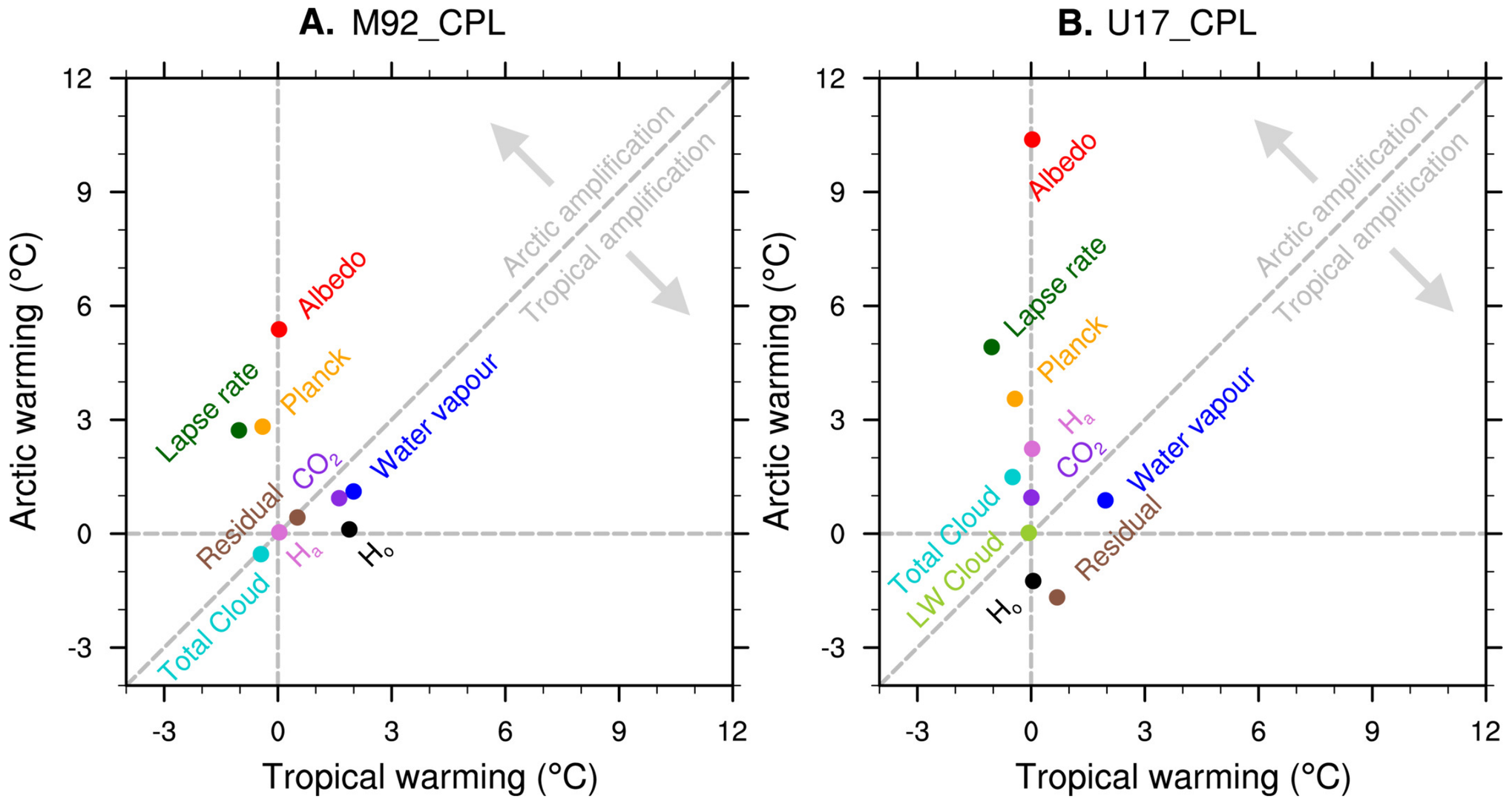
- **University of Denver:** Alex Huffman, Alex Volkova, Dorian Schwartz
- **Sandia National Laboratory:** Dari Dexheimer
- **Purdue University:** Alex Laskin
- And many others…

Ice nucleation schemes contribute to climate model spread in Arctic Amplification (AA)



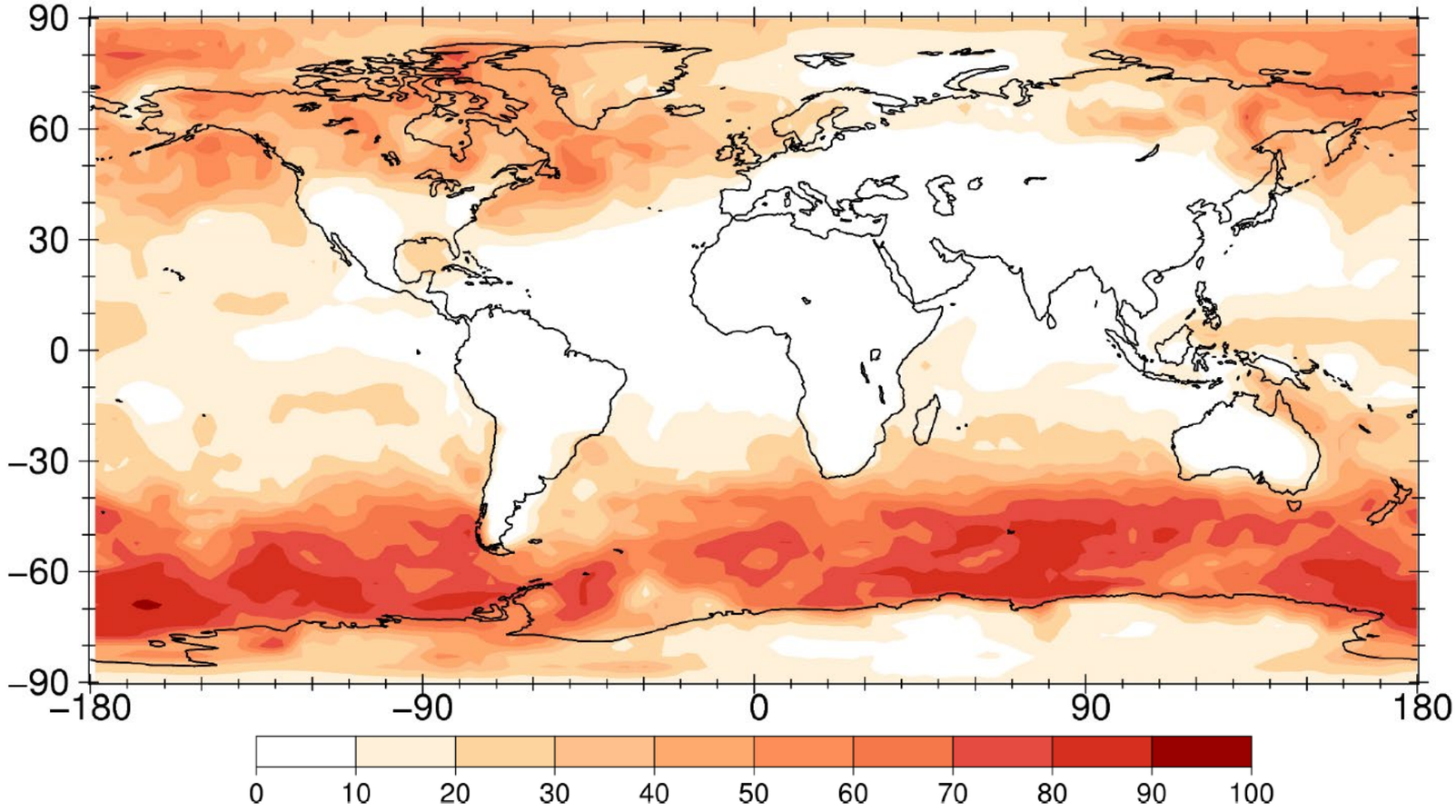
Tan, Barahona, and Coopman (2022)

Sea spray aerosol is an important source of INPs where dust is scarce.

Major sources of INPs:

1. **Mineral dust:** efficient INPs, especially at colder temperatures
2. **Sea spray:** Abundant in marine air but inefficient INPs
3. **Biological and biogenic primary particles:** Important source of warm-temperature INPs

Less well-understood: biologically-influenced sea spray and dust

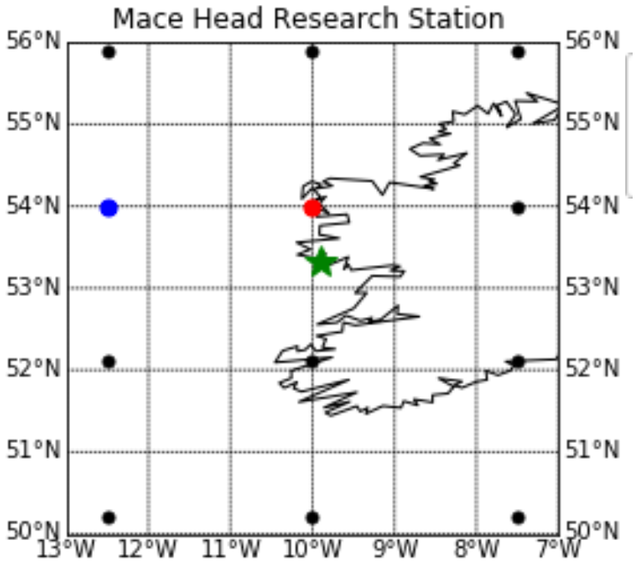


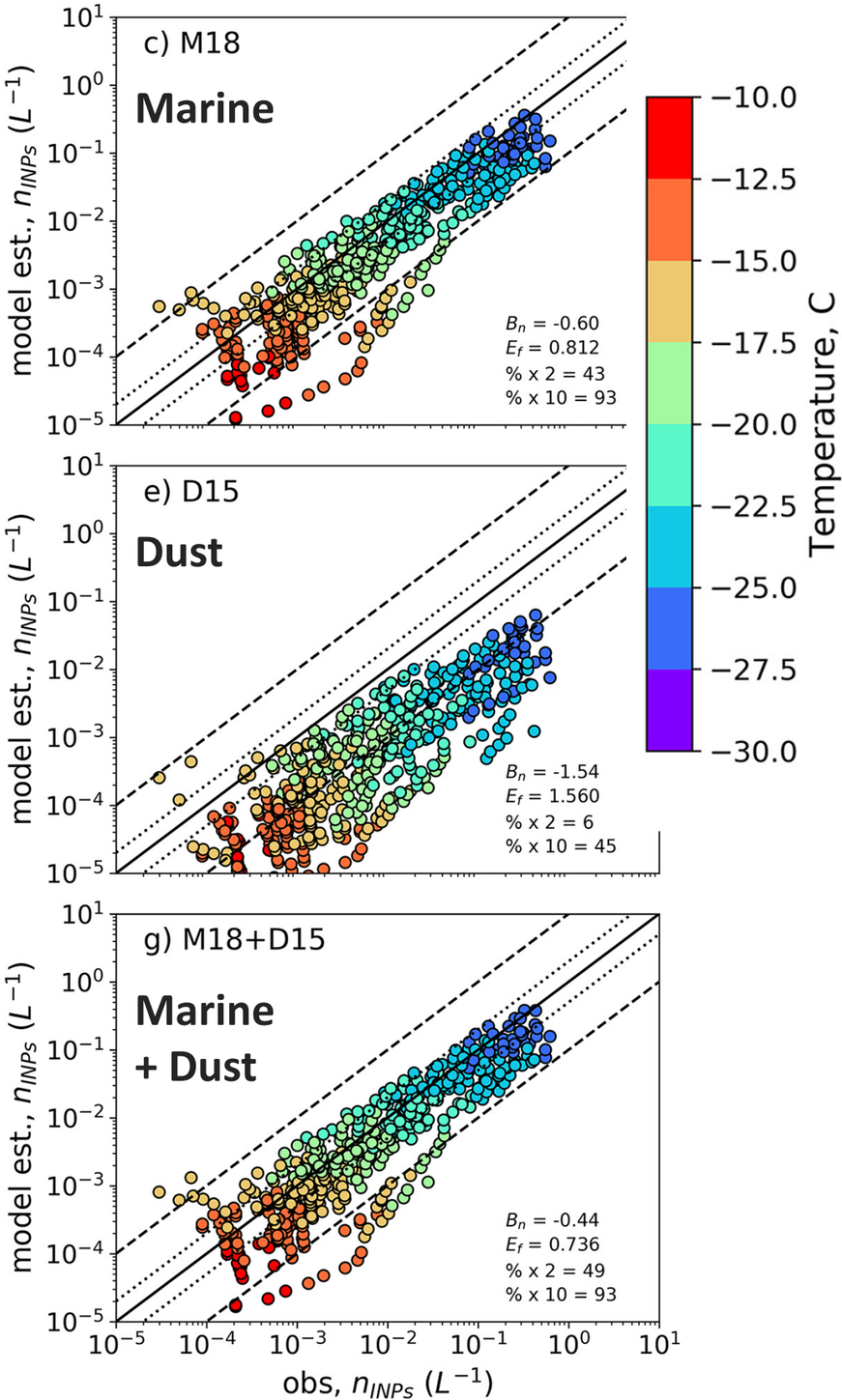
Percentage contribution of sea spray aerosol (versus dust) to annual mean boundary-layer INPs (T=-15°C).

Burrows, S.M., Hoose, C., Pöschl, U. and Lawrence, M.G., 2013. Ice nuclei in marine air: Biogenic particles or dust?. *Atmospheric Chemistry and Physics*, *13*(1), pp.245-267.

Including marine INP improves model agreement with observed INP number in short-term field experiments

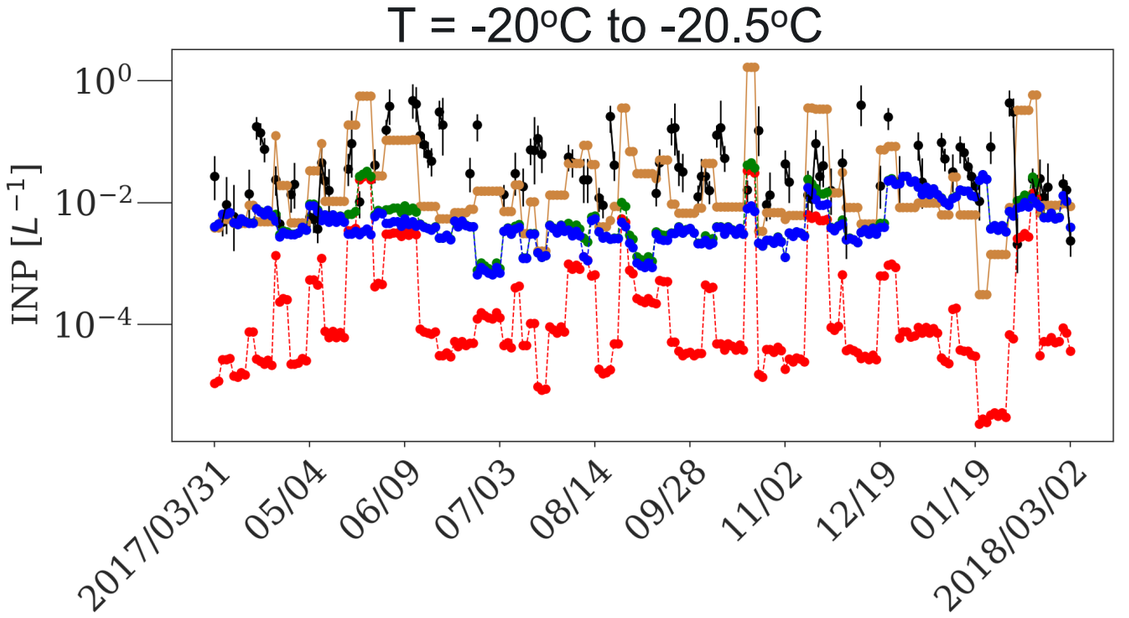
Mace Head, Ireland: August 2015





McCluskey, C. S., DeMott, P. J., Ma, P.-L., and **Burrows, S. M**. Numerical representations of marine ice-nucleating particles in remote marine environments evaluated against observations. *Geophysical Research Letters*, 46, 7838– 7847, 2019.

First long-term surface observations of INPs at Macquarie Island (MICRE) reveal challenges for model simulation of Southern Ocean INPs



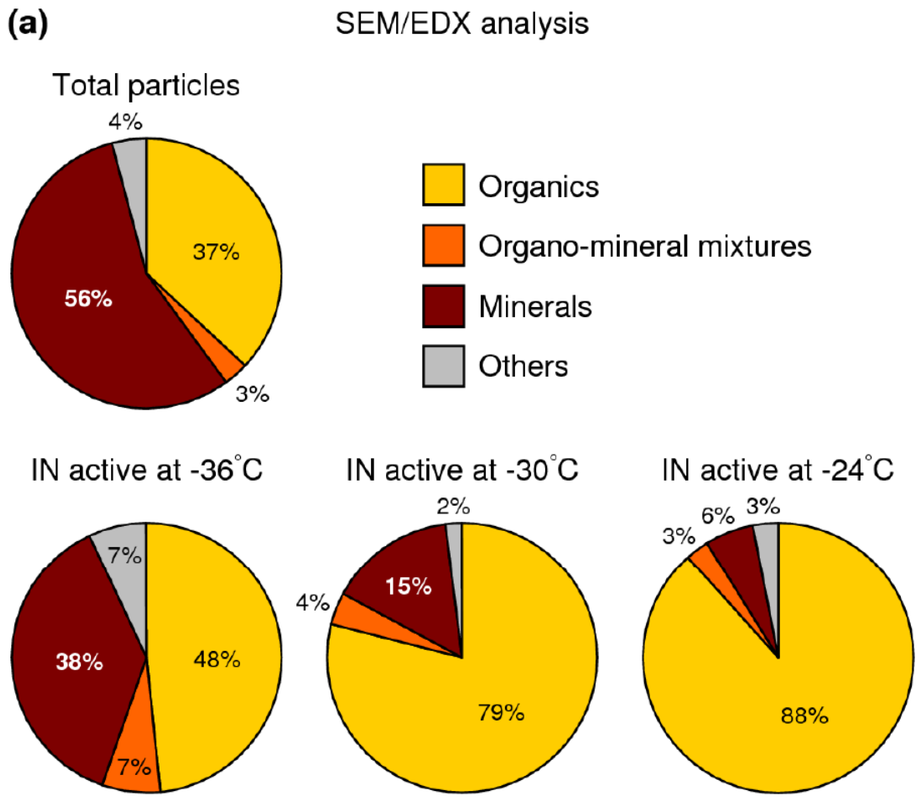
INPs at -20°C:
- Observed
- Dust (native CNT)
- Dust (empirical D15)
- Sea spray (M18)
- Dust + sea spray (M18+D15)

- **Observed INP concentrations span roughly three orders of magnitude.**
- Model captures background concentrations reasonably well, which are driven by sea spray.
- High-latitude dust is underpredicted by E3SMv1 (Wu et al., 2020); E3SM's native CNT parameterization likely overpredicts dust INP effectiveness (compensating errors).
- These issues are **not revealed well by short-term field campaigns** such as CAPRICORN (McCluskey et al., 2019, GRL), SOCRATES, or MARCUS – highlighting the value of long-term INP observations.

Raman, A., DeMott, P. J., Hill, T. C., Zhang, K., Ma, P. L., Singh, B., and **Burrows, S.M.** Investigating seasonal variability in marine ice nucleating particles from climate model simulations and observations in the Southern Ocean. *Atmospheric Chemistry and Physics Discussions [preprint; in revision].*

Prior work shows that agricultural soil dusts containing organic matter are effective INPs

INPs in agricultural soil contained a larger fraction of organic matter

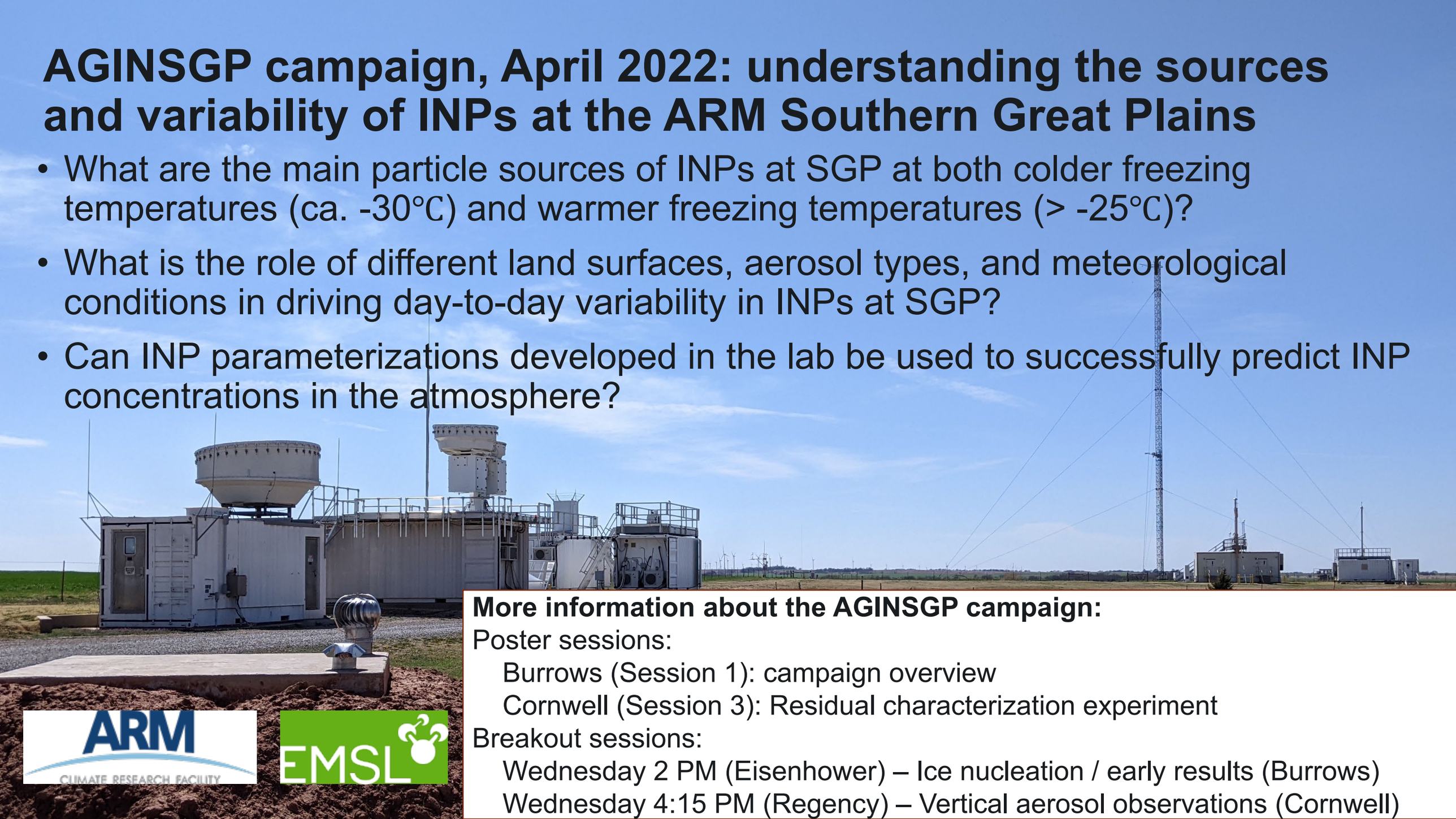


Can we identify enhanced organic or biological signatures in ambient sampling of INPs?

Tobo et al. (2014)

AGINSGP campaign, April 2022: understanding the sources and variability of INPs at the ARM Southern Great Plains

- What are the main particle sources of INPs at SGP at both colder freezing temperatures (ca. -30℃) and warmer freezing temperatures (> -25℃)?
- What is the role of different land surfaces, aerosol types, and meteorological conditions in driving day-to-day variability in INPs at SGP?
- Can INP parameterizations developed in the lab be used to successfully predict INP concentrations in the atmosphere?



More information about the AGINSGP campaign:

Poster sessions:

Burrows (Session 1): campaign overview

Cornwell (Session 3): Residual characterization experiment

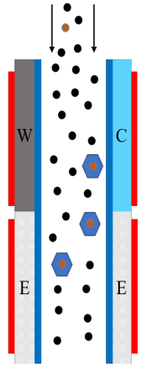
Breakout sessions:

Wednesday 2 PM (Eisenhower) – Ice nucleation / early results (Burrows)

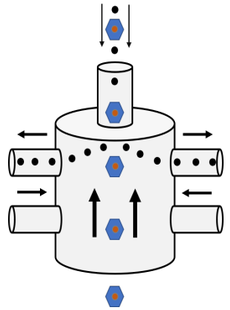
Wednesday 4:15 PM (Regency) – Vertical aerosol observations (Cornwell)

We performed a “residual characterization experiment” to characterize the composition of individual INPs

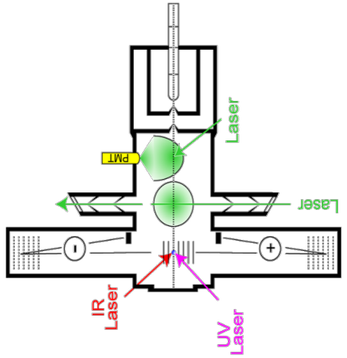
This technically challenging experiment gives us a “smoking” gun for the identity and distinguishing properties of INPs.



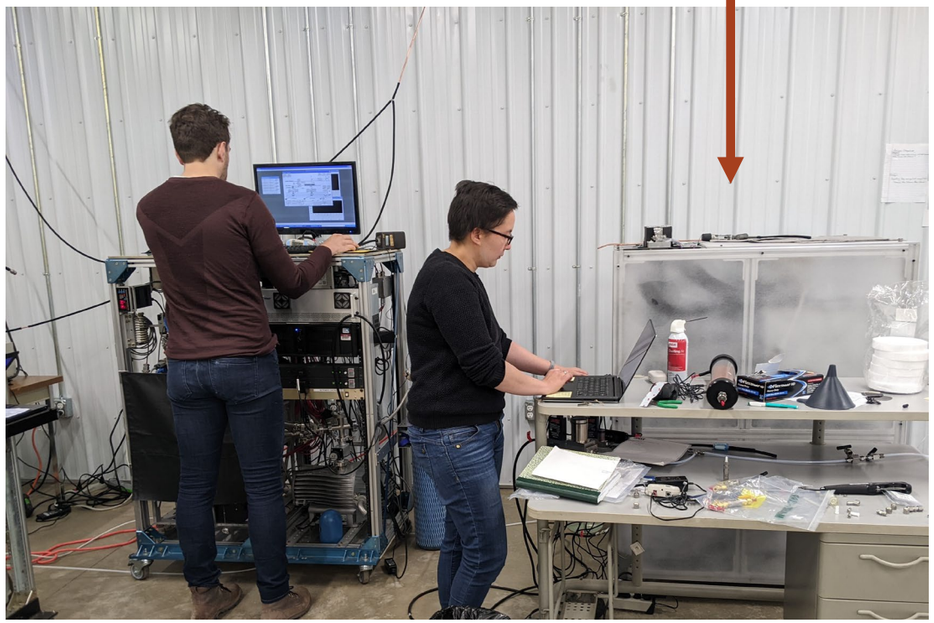
PNNL ice nucleation chamber: Activate INPs into ice crystals



Pumped counterflow virtual impactor: Separate large ice crystals



miniSPLAT: Measure particle composition



Schematic figure: Gavin Cornwell

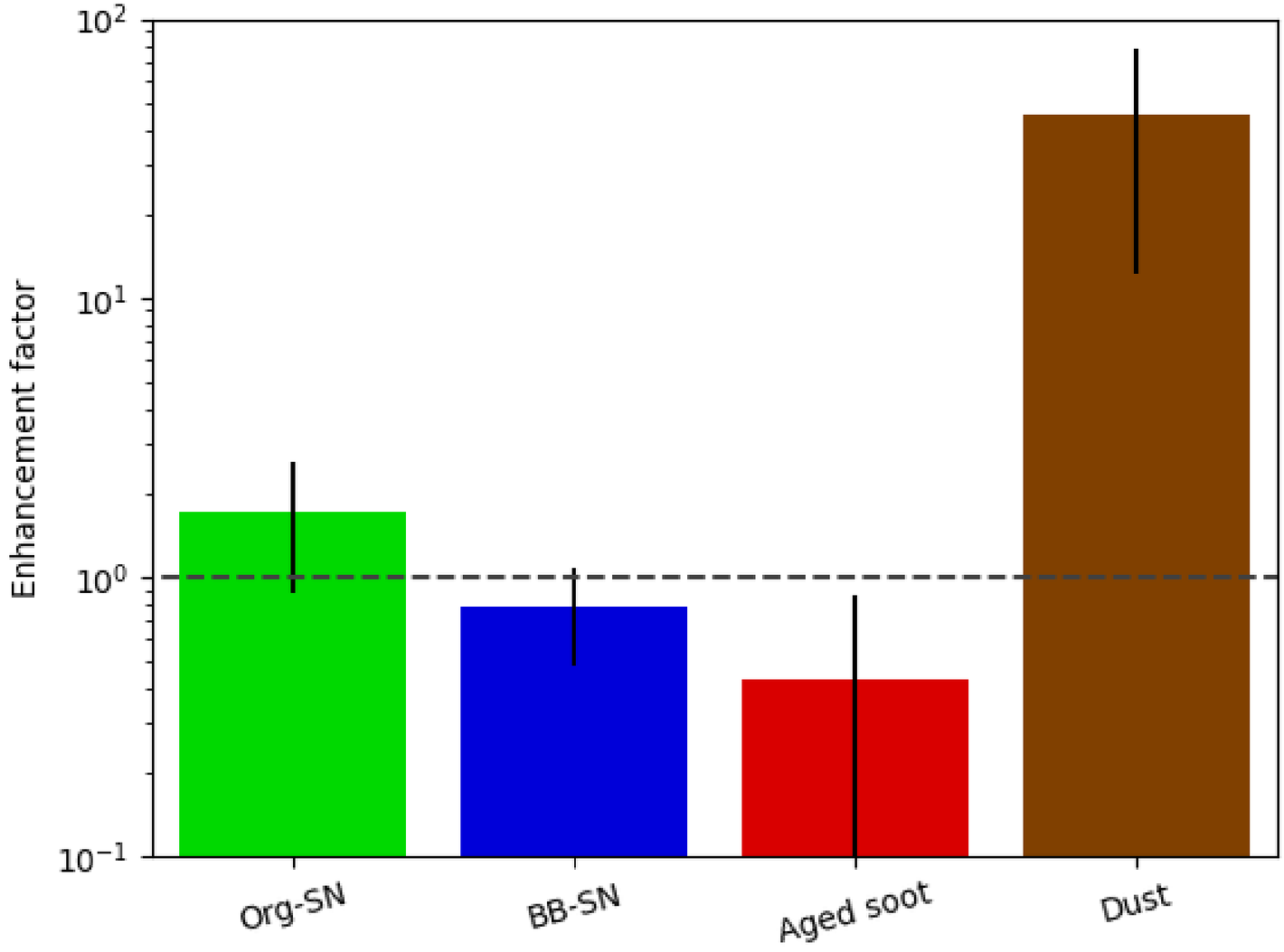
Are dust particles more likely to be INPs?

YES: dust is enhanced by more than an order of magnitude in ice residuals [T = ca. -30℃]

Enhancement factors for particle types classified from the miniSPLAT single-particle mass spectrometer.

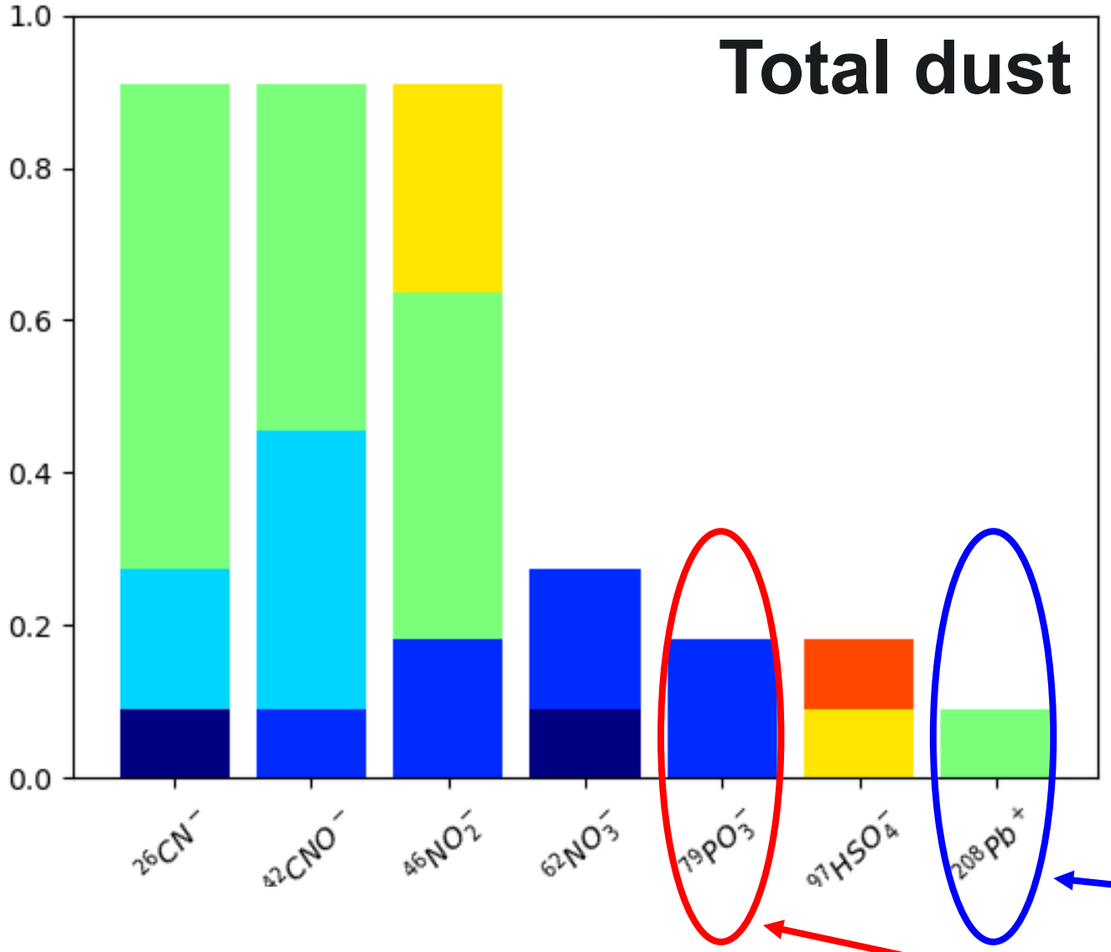
Enhancement factor = Fraction of INPs / Fraction of all particles

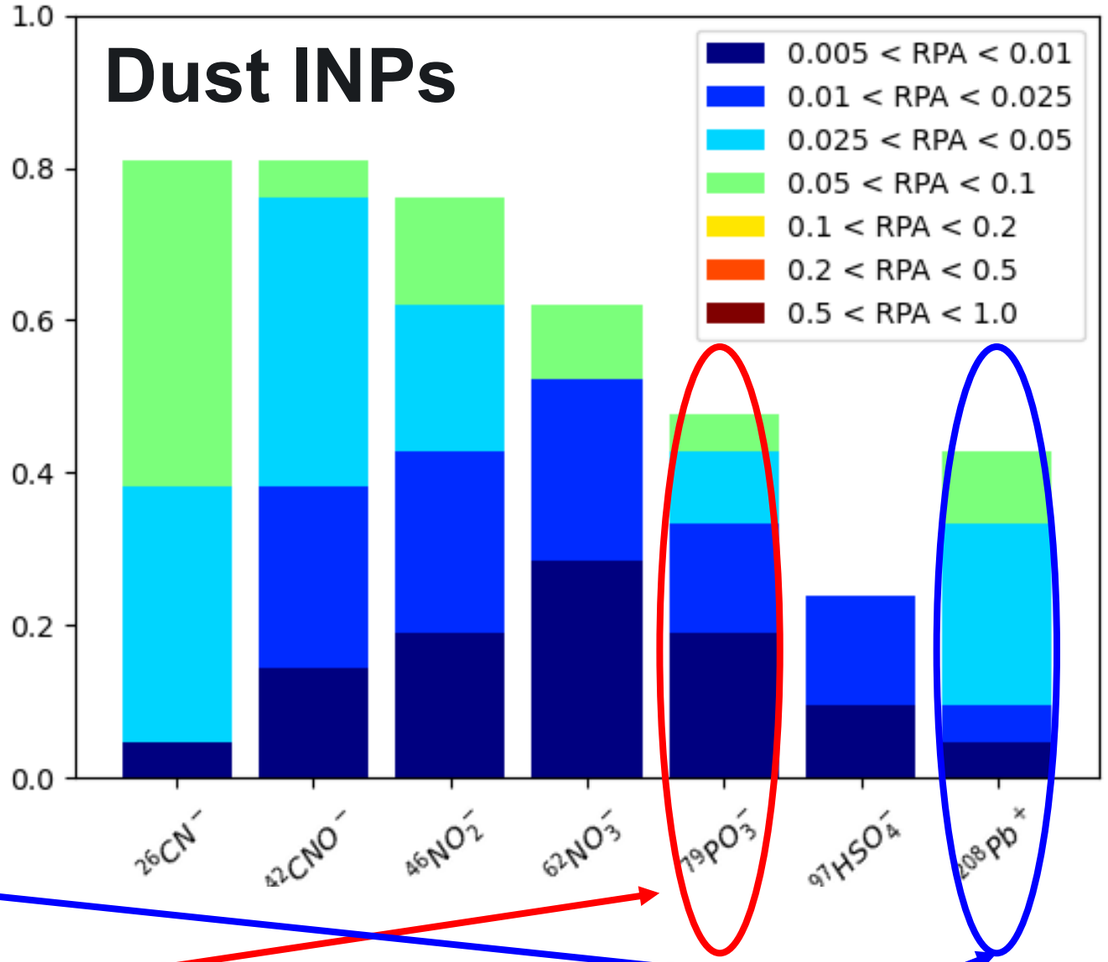
(per particle type)



Cornwell et al., in prep.

Are dust particles that contain more "biological" material more likely to be INPs? YES





Dust INPs contain more $^{79}PO_3^-$ (marker for bioaerosol) and $^{208}Pb^+$

Cornwell et al., in prep.

Research needs to bridge the model-observation gap for INPs

- Where do we need more process and fundamental understanding?
  - **Ambient biological/biogenic INPs (emissions, INP effectiveness)**
  - **Vertical particle transport processes**
  - **Loss processes, especially for supermicron particles**
  - **Additional closure studies (e.g., AEROICESTUDY led by Daniel Knopf)**
- Which observations are needed to further improve and evaluate model simulation of INPs?
  - **Long-term measurements**
  - **INP measurements with parallel measurements of the required aerosol properties**
    - ✓ **Refractory species composition – dust, sea spray, and biological**
    - ✓ **Size distribution and size-resolved composition, including supermicron**
  - **Observational constraints on vertical profiles**

Burrows, S. M., McCluskey, C. S., **Cornwell, G.**, **Steinke, I.**, Zhang, K., Zhao, B., Zawadowicz, M., **Raman, A.**, Kulkarni, G., China, S., Zelenyuk, A., and Demott, P. J. (2022). Ice-nucleating particles that impact clouds and climate: Observational and modeling research needs. *Reviews of Geophysics*, 60, e2021RG000745. https://doi.org/10.1029/2021RG000745

More information – any questions?

Recent publications:

- **Burrows, S. M.**, McCluskey, C. S., **Cornwell, G.**, **Steinke, I.**, Zhang, K., Zhao, B., Zawadowicz, M., **Raman, A.**, Kulkarni, G., China, S., Zelenyuk, A., and Demott, P. J., 2022. Ice-nucleating particles that impact clouds and climate: Observational and modeling research needs. *Reviews of Geophysics*, 60, e2021RG000745. https://doi.org/10.1029/2021RG000745
- **Cornwell, G. C.**, McCluskey, C. S., DeMott, P. J., Prather, K. A., **Burrows, S. M.**, 2021. Development of heterogeneous ice nucleation rate coefficient parameterizations from ambient measurements. *Geophys. Res. Lett.*, 48, e2021GL095359. https://doi.org/10.1029/2021GL095359
- **Steinke, I.**, DeMott, P. J., Deane, G. B., Hill, T. C. J., Maltrud, M., **Raman, A.**, **Burrows, S. M.**, 2022. A numerical framework for simulating the atmospheric variability of supermicron marine biogenic ice nucleating particles, *Atmos. Chem. Phys.*, 22, 847–859. https://doi.org/10.5194/acp-22-847-2022
- **Steinke, I.** and **Burrows, S. M.**, 2022. Using synthetic experiments to investigate the impact of heterogeneous ice nucleation rate distributions on predicted frozen fractions, *Environ. Sci., 2022.*
- **Raman, A.,** DeMott, P. J., Hill, T. C., Zhang, K., Ma, P. L., Singh, B., and **Burrows, S.M.** Investigating seasonal variability in marine ice nucleating particles from climate model simulations and observations in the Southern Ocean. *Atmospheric Chemistry and Physics Discussions [preprint; in revision].*

More information about early results from the AGINSGP campaign:

Poster sessions:

Burrows: AGINSGP campaign overview

Cornwell: Residual characterization experiment

Breakout sessions:

Wednesday PM (breakout 5) – Ice nucleation / early results (Burrows)

Wednesday PM (breakout 6) – Vertical aerosol observations (Cornwell)

Campaign data coming soon to the ARM data archive.

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Thank you