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Acronyms and Abbreviations

AGINSGP	Agricultural Ice Nuclei at SGP
ARM	Atmospheric Radiation Measurement
CFDC	Continuous Flow Diffusion Chamber
CSU	Colorado State University
DU	Denver University
EMSL	Environmental Molecular Sciences Laboratory
FICUS	Facilities Integrating Collaborations for User Science
INP	ice-nucleating particle
KIT	Karlsruhe Institute of Technology
PINE	Portable Ice Nucleation Experiment
PNNL	Pacific Northwest National Laboratory
SGP	Southern Great Plains
TBS	tethered balloon system
UTC	Coordinated Universal Time
WIBS	Wideband Integrated Bioaerosol Sensor

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1.0 Summary

The Agricultural Ice Nuclei at Southern Great Plains (AGINSGP) field campaign was conducted from April 4 to April 29, 2022, at the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) SGP site in Oklahoma. The goal of this campaign was to improve understanding of the sources and variability of ice-nucleating particles (INPs) at the SGP site. To this end, the key objectives of the campaign were (1) to produce a high-quality data set including measurements of atmospheric INP concentrations and aerosol particle properties relevant to the sources of INPs; and (2) to conduct a residual characterization experiment including offline and online analysis of the physical and chemical characteristics of INPs sampled in ambient air at SGP.

The campaign timing during the month of April was intended to enable sampling of dusty conditions associated with tillage of agricultural soils. Windy conditions and strong dust events occurred frequently during the first week of the campaign, while the latter portion was characterized by largely calm conditions, with frequent biomass burning influence.

A highlight of this campaign was the deployment of an integrated residual characterization experiment, where an ice-nucleation chamber was combined with a pumped counterflow virtual impactor to isolate individual INPs for analysis with a single-particle mass spectrometer, miniSPLAT. Additionally, INPs were collected on substrates for further offline analysis. For our case study day, April 11, 2022, a total of 151 INPs were successfully analyzed by either the miniSPLAT or offline methods, which we believe is unprecedented for a single day of ambient sampling.

Deployment of the PNNL ice-nucleation chamber and miniSPLAT, as well as offline aerosol analysis of samples collected during the campaign, were enabled through PNNL's Environmental Molecular Sciences Laboratory (EMSL) under a related User Proposal. Collaborations with Colorado State University (CSU) and the Karlsruhe Institute of Technology (KIT) supported the deployment of two additional real-time INP counters, and a Wideband Integrated Bioaerosol Sensor (WIBS) was deployed by the University of Denver (UD). Vertical sampling of aerosols aboard ARM's tethered balloon system (TBS) was supported under a related FICUS (Facilities Integrating Collaborations for User Science) proposal. Additional ground-based and vertical sampling of INPs for offline analysis with the ARM ice-nucleation spectrometer was supported under a related small ARM field campaign, the AGINSGP Supplemental Sampling.

The deployment lasted from April 4 to April 29, 2022. While the instruments largely operated successfully during the campaign, those measurements that required manual operation were not collected on scheduled rest days, and most instruments experienced occasional problems that were resolved through troubleshooting but led to some potential data gaps.

Instrument availability and status for all instruments throughout the campaign is summarized in Table 1.

Table 1. Summary of instrument status during campaign.

Date	PNNL CFDC	CSU CFDC	KIT-PINE	miniSPLAT	APS Status	WIBS Status	Off-line sampling	TBS sampling
4/6/2022	–	–	✓	✓	✓	✓	–	–
4/7/2022			✓	✓	✓	✓	–	–
4/8/2022	●	✓	✓	✓	✓	✓	–	–
4/9/2022	–	–	✓	■	✓	✓	–	–
4/10/2022	–	–	✓	■	✓	✓	–	–
4/11/2022	✓	✓	✓	✓	✓	✓	✓	✓
4/12/2022	●	✓	✓	✓	✓	✓	✓	–
4/13/2022	●	■	●	✓	✓	●	✓	–
4/14/2022	●	■	✓	✓	✓	✓	✓	✓
4/15/2022	✓	■	✓	✓	✓	✓	✓	✓
4/16/2022	✓	✓	✓	✓	✓	●	✓	–
4/17/2022	–	–	✓	✓	✓	✓	–	✓
4/18/2022	✓	✓	✓	●	✓	✓	✓	✓
4/19/2022	✓	✓	✓	✓	✓	✓	✓	–
4/20/2022	●	●	✓	●	✓	✓	✓	●
4/21/2022	✓	✓	✓	●	✓	✓	✓	–
4/22/2022	✓	✓	✓	✓	✓	✓	✓	–
4/23/2022	–	–	✓	✓	✓	✓	–	–
4/24/2022	–	–	✓	✓	✓	✓	–	–
4/25/2022	●	✓	✓	●	✓	✓	✓	●
4/26/2022	✓	✓	✓	✓	✓	✓	✓	✓

Date	PNNL CFDC	CSU CFDC	KIT-PINE	miniSPLAT	APS Status	WIBS Status	Off-line sampling	TBS sampling
4/27/2022	✓	✓	●	✓	✓	✓	✓	–
4/28/2022	✓	✓	●	✓	●	✓	✓	–

✓ = normal operations; ● = partially operational or showing measurement artifacts; ■ = not operational; – = scheduled rest day.

In Table 1, green indicates normal operations, red indicates that the instrument was not operational, and orange indicates that the instrument was operational but with some potential problems (e.g., instrument was offline for part of the day due to maintenance or a power outage, or some measurement artifacts were observed that will require further investigation during quality control). Note that both Continuous Flow Diffusion Chambers (CFDCs) and the offline sampling required manual operation, so data were not collected by these capabilities on scheduled rest days; additionally, these instruments were brought online a few days later.

2.0 Results

We selected April 11, 2022, as a case study day for more detailed analysis. This was one of only two days during the campaign during which a substantial number of INPs (82) were successfully characterized by the miniSPLAT, and an additional 69 INPs were sampled on substrates and analyzed offline via scanning electron microscopy with energy dispersive X-ray analysis. Additionally, all of the campaign instruments were operational on April 11.

As shown in Figure 1, pink shaded regions indicate residual characterization sampling. The horizontal extent indicates time periods during which INP residuals were successfully characterized by the miniSPLAT, and the vertical extent is proportional to the number of residuals collected during the sampling period. Colored dots indicate the INP concentrations measured by the CSU CFDC, at operating temperatures similar to the operating temperature of the residual experiment (and as indicated by coloration of the points).

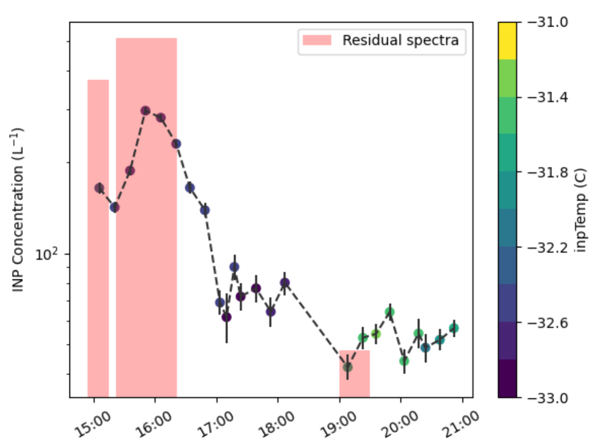

Figure 1. Overview of INP measurements from the AGINSGP campaign case study day, April 11, 2022 (preliminary results).

High INP concentrations were observed in the morning on April 11. Most of the INP residuals were sampled between 9:00 a.m. and 11:00 a.m. local time; during this time, the CSU CFDC measured INP concentrations ranging from 150–300 L^{-1} at temperatures around -33°C. These high INP concentrations were associated with dusty, dry, windy conditions, with southerly winds ranging from 10–17 m s^{-1} throughout the day. A shift in conditions occurred between 11:00 a.m. and noon local time, with morning clouds dissipating during this period and INP concentrations dropping.

Preliminary analysis of differences between the miniSPLAT spectra for ice crystal residuals and for ambient particles indicates that INPs were enriched in markers for dust, relative to ambient particles (not shown). Since locally windy conditions aerosolize substantial amounts of dust from nearby fields and roads, these INPs may be primarily sourced from local dusts, which may contain mixtures of mineral, organic, and biological components. We also collected soil samples from several nearby locations and plan to perform analysis of their physicochemical properties to compare with the windblown dust.

Initial findings from the residual characterization experiment indicate that dust was enhanced by more than one order of magnitude in INP residuals, compared to the total particle population. Additionally, INP dust residuals contained enhanced concentrations of phosphate ions (a proxy for biological material) and lead. Similar enhancements have been observed in laboratory analysis of soil dust samples, but have not previously been confirmed in ambient sampling.

A precipitation event occurred during the night preceding the AGINSGP case study day, which was followed by a strong peak in INP concentrations (Figure 2). Previous field experiments have observed similar post-rainfall peaks in INP concentrations, which were attributed to biological INPs sources (Huffman et al. 2013).

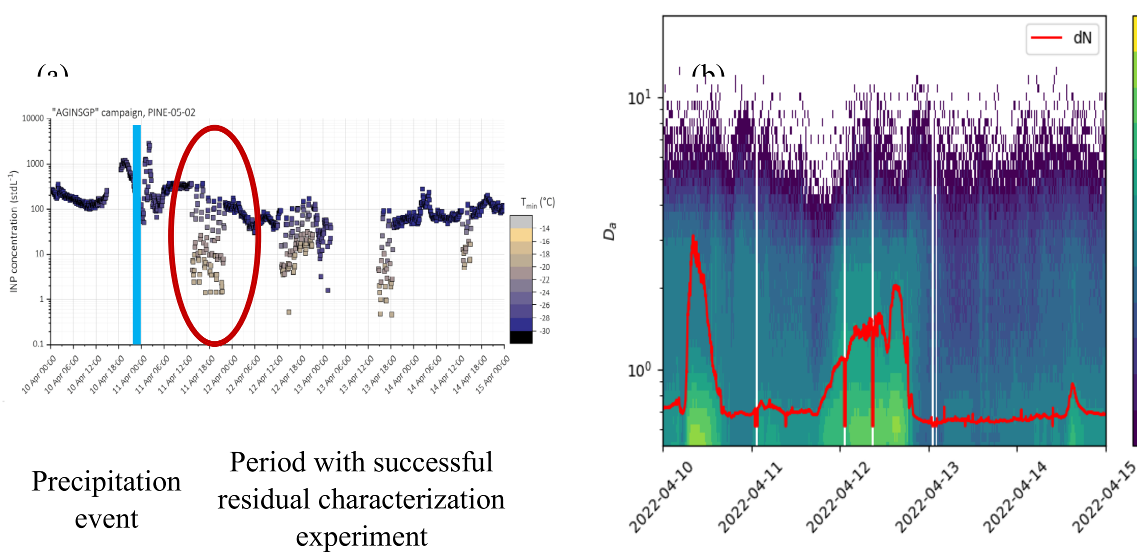

Figure 2. Time series measurements of INP concentrations and aerosol size distributions show no clear correlation when observed during the case study period. (a) Real-time measurements of INP concentrations from the Portable Ice Nucleation Experiment (PINE). During the preceding night, a precipitation event occurred, with the approximate timing indicated by a vertical blue line. This precipitation event was followed by a strong peak in INP number concentrations that was recorded by the PINE instrument during overnight operations. The daytime period with the successful residual characterization experiment is also indicated. (b). All times are in Coordinated Universal Time (UTC).

Finally, measurements of the particle size distribution showed no obvious correlation with INP concentrations during the focus period, which is consistent with an interpretation that the particle sources of INPs differ from the sources controlling total particle number at SGP.

The AGINSGP campaign team is currently analyzing data and writing publications describing the key campaign results. Our initial focus is the development of an overview paper highlighting key results from the campaign, and a paper focused on aerosol-INP closure calculations, including a description of key results from the residual characterization experiment.

Ample opportunities exist to leverage the AGINSGP campaign data in future research. For example, additional insights could be gained from a more detailed analysis of the upwind particle sources and meteorological conditions impacting INP measurements during the campaign, and from comparisons with previous and upcoming studies at SGP that observed INPs during different conditions or seasons. Additionally, while not the focus of the AGINSGP campaign, biomass burning events occurred frequently, and the physical-chemical measurements that were collected of these particles (for example, by the miniSPLAT) might be of value to future studies on biomass burning aerosol.

3.0 Publications and References

3.1 Publications

We expect to submit at least two publications focusing on results from the campaign within the next year, including an invited article providing an overview of the campaign in the journal *Environmental Science: Atmospheres*. Data from most of the real-time instruments participating in the campaign have been published to the ARM Data Center. Data from offline aerosol analyses performed at EMSL will be published at a later date, following the EMSL data policy.

3.2 Presentations

Results from this campaign have been or will be shared in the following presentations (team member names bolded):

Invited talks

1. **Burrows, SM. (invited)**. Title TBD. Gordon Research Conference in Atmospheric Chemistry, Newry, Maine, July, 2023.
2. **Steinke, I**, V Bailey, **SM Burrows, G Cornwell,** R Fösig, Y Hu, **O Möhler,** KF Patel, NS Umo, R Wagner, J Yao, **A Zelenyuk,** and Z Zhu. Synthetic aerosol systems − a new experimental platform for investigating heterogeneous ice formation in the lab? Chalmers University, departmental seminar, December, 2022.
3. **Burrows, SM**. Ice-nucleating particles (INPs) that impact clouds and climate: progress and research needs. Texas A&M University, departmental seminar, November, 2022.

4. **Steinke, I**, V Bailey, **SM Burrows, G Cornwell,** R Fösig, Y Hu, **O Möhler,** KF Patel, NS Umo, R Wagner, J Yao, **A Zelenyuk,** and Z Zhu. Synthetic aerosol systems − a new experimental platform for investigating heterogeneous ice formation in the lab? Karlsruhe Institute of Technology, departmental seminar, November, 2022.
5. **Burrows, SM. (plenary presentation)**. Ice-nucleating particles that impact clouds and climate: progress and research needs. 2022 Joint ARM User Facility and ASR PI Meeting, Rockville, Maryland, October, 2022.
6. **Burrows, SM**. Catching soil INPs on the fly: early results from the AGINSGP campaign. 2022 Joint ARM User Facility and ASR PI Meeting, Rockville, Maryland, October, 2022.

Contributed oral presentations

1. **Burrows, SM**. The Agricultural Ice Nuclei at SGP (AGINSGP) experiment: Understanding sources and variability of ice-nucleating particles in the Great Plains. American Meteorological Society Annual Meeting, Denver, Colorado, January 2023.
2. **Burrows, SM**. The Agricultural Ice Nuclei at SGP (AGINSGP) experiment: Understanding sources and variability of ice-nucleating particles in the Great Plains. American Geophysical Union Annual Meeting, Chicago, Illinois, December 2022.

Poster presentations

1. **Burrows, SM**. The Agricultural Ice Nuclei at SGP (AGINSGP) experiment: Understanding sources and variability of ice-nucleating particles in the Great Plains. 2022 Joint ARM User Facility and ASR PI Meeting, Rockville, Maryland, October, 2022.
2. **Cornwell, GC**. (poster presentation). Single-particle measurements of ice crystal residuals at the Southern Great Plains site during the AGINSGP experiment. 2022 Joint ARM User Facility and ASR PI Meeting, Rockville, Maryland, October, 2022.
3. **Cornwell, GC**. (poster presentation). Single particle measurements of ice crystal residuals at the Southern Great Plains site during the AGINSGP experiment. American Geophysical Union Annual Meeting, Chicago, Illinois, December 2022.

3.3 References

Huffman, JA, AJ Prenni, PJ DeMott, C Pöhlker, RH Mason, NH Robinson, J Fröhlich-Nowoisky, Y Tobo, VR Després, E Garcia, DJ Gochis, E Harris, I Müller-Germann, C Ruzene, B Schmer, B Sinha, DA Day, MO Andreae, JL Jimenez, M Gallagher, SM Kreidenweis, AK Bertram, and U Pöschl. 2013. "High concentrations of biological aerosol particles and ice nuclei during and after rain." *Atmospheric Chemistry and Physics* 13(13): 6151−6164, https://doi.org/10.5194/acp-13-6151-2013

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