



Reaching new heights: Profiling Upper altitudes For Ice Nucleation (PUFIN) on the Atmospheric Radiation Measurement (ARM) tethered balloon systems

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Abstract. Ice nucleating particles (INPs) are a rare yet climatically relevant subset of aerosols that initiate ice formation in mixed-phase clouds, strongly influencing cloud microphysics, precipitation, and Earth's radiative balance. Despite their significance, ground-based measurements of INPs may not always be representative of those at cloud level, yet vertically-resolved INP measurements remain limited. Here, we introduce PUFIN (Profiling Upper altitudes For Ice Nucleation), a robust, lightweight INP sampler designed for routine deployment on the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's tethered balloon system (TBS). PUFIN collects multiple filter samples per flight at up to three altitudes, integrating real-time monitoring of flow, power consumption, and atmospheric conditions, while remaining fully operable from the ground. Multiple deployments at two ARM observatories in Maryland and Alabama demonstrate that PUFIN achieves sufficient aerosol loading to detect INPs down to $\sim 10^{-3} \text{ L}^{-1}$ within as little as 28 min of sampling, but typically within an hour. Data from recent deployments reveal altitude-dependent variability in INP concentrations, indicative of boundary layer stratification and contributions from both local and transported aerosol sources. All resulting TBSINP data are publicly available via the ARM Data Center, and researchers may request PUFIN for future TBS campaigns or access archived filters for additional analyses. Looking forward, routine PUFIN deployments can be used to enhance understanding of the vertical distribution and sea-

sonal variability of INPs, enabling improved representation of aerosol–cloud interactions in Earth system models and advancing predictive capabilities for weather and climate.

1 Introduction

Ice nucleating particles (INPs) are a rare, but critical subset of atmospheric aerosols that catalyze the formation of cloud ice through heterogeneous nucleation, i.e., freezing supercooled liquid water at temperatures above the homogenous threshold at roughly -38°C (Pruppacher and Klett, 2010). Despite existing at concentrations orders of magnitude lower than cloud condensation nuclei (CCN) that facilitate the formation of cloud droplets, INPs exert an outsized influence on cloud microphysics, lifetime, and radiative properties (Kanji et al., 2017), especially in mixed-phase clouds, which are arguably the most prominent type of cloud globally (Mülmenstädt et al., 2015). By initiating the glaciation of such clouds, INPs can accelerate precipitation processes, alter cloud reflectivity, and modulate the hydrological cycle. Their role in determining cloud phase is especially consequential for Earth's energy balance, as ice-containing clouds differ strongly from liquid-only clouds in albedo and longwave emissivity (Storelvmo, 2017). Therefore, understanding INP abundance, composition, and variability is essential for improving the representation of aerosol–cloud interactions in weather and Earth system models (Burrows et al., 2022).

INPs connect boundary layer processes to terrestrial, oceanic, and cryospheric sources, linking biogeochemical systems to climate feedbacks on regional to global scales (Creamean et al., 2026; Murray et al., 2021; Schnell and Vali, 1976; Steiner, 2020). However, INP measurements are often made at ground level, which may not accurately represent the concentrations or composition of INP populations at cloud level where ice nucleation processes occur (Burrows et al., 2022), and are only directly relevant when clouds are coupled to the surface (e.g., Griesche et al., 2021). Furthermore, the types of INPs often vary with altitude. A recent modeling study suggests that, on a global average, biological and marine organic INPs are more prevalent at lower altitudes depending on hemisphere and freezing temperature, whereas dust INPs dominate at higher altitudes (Chatziparaschos et al., 2025). While crewed aircraft have a long history of conducting airborne INP measurements, they typically provide only brief snapshots and often cannot sample close enough to the surface to capture the full vertical structure from the ground to cloud base.

Smaller platforms such as uncrewed aerial and tethered balloon systems (UASs and TBSs, respectively) help fill this gap. Although these systems cannot accommodate the larger payloads of crewed aircraft, advances in lightweight instrumentation now enable vertically-resolved comprehensive measurements of meteorology and aerosol properties (Dexheimer et al., 2024; Mei et al., 2025; Pohorsky et al., 2024; Pilz et al., 2022). TBSs are particularly valuable because they can provide routine profiling or sustained sampling of aerosols at targeted altitudes up to several hours, reaching up to 1–2 km a.g.l., below, into, and above clouds (e.g., Creamean et al., 2021). These capabilities offer certain advantages over UASs, which are frequently limited by line-of-sight or altitude regulations, payload weight restrictions depending on aircraft design, and relatively short flight times at often an hour or less. Recent studies such as Pilz et al. (2023, 2024) and Lonardi et al. (2022) reported aerosol observations from TBS platforms during summer of the 2019–2020 Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAIC) expedition. Their results revealed substantial complexity in aerosol vertical structure, which varied by day and airmass origin, though most profiles indicated new particle formation above low-level clouds. Similarly, Guy et al. (2024) measured aerosol size distributions from the surface to cloud base over the central Greenland Ice Sheet using TBS and found distinct stratification, concluding that surface measurements alone failed to represent cloud-relevant aerosol conditions roughly half of the time. Pohorsky et al. (2025) also observed distinct aerosol layering using TBS in a high-latitude urban environment, where heavy pollution was trapped beneath a strong temperature inversion and overlain by typical Arctic haze aerosols. In another study, Zinke et al. (2021) developed a cloud water sampler they deployed on a TBS, enabling measurements of bulk cloud residual chemical composition and INP concentrations

in the high Arctic from an icebreaker, although these were not vertically-resolved.

Only a limited number of studies have reported on vertically-resolved INP measurements from balloon or UAS platforms. Creamean et al. (2018) quantified INPs in both immersion and deposition modes across six altitude ranges during three test flights in Colorado, using launched balloons rather than a TBS. This approach was challenging, as launched balloons can be entrained in low-level jets carrying them long distances, and physical retrieval is required to collect filters for offline INP analysis. Bieber et al. (2020) and Seifried et al. (2021) describe a developed system, the DAPSI (Drone-based Aerosol Particle Sampling Impinger/Impactor), for collecting INP samples using UAS. To date, results have been limited to test flights and a short (3 d) campaign conducted near a lake in Austria during summer. Porter et al. (2020) developed a size-resolved sampling payload for offline INP analysis, the SHARK (Selective Height Aerosol Research Kit), for deployment on a TBS. This system has been tested at several locations, including in the high Arctic (Porter et al., 2022); however, it collects samples at only one altitude above ground level per flight. More recently, Böhmmländer et al. (2025) developed an INP sampler capable of collecting filters at multiple altitudes for offline analysis. The system was initially tested on a UAS in Finland, with plans to test it for TBS applications. While these previous studies mark important progress toward resolving the vertical distribution of INPs, substantial effort is still needed to establish reliable, routine measurements. Such advancements are essential for improving the representation of INPs in models and, consequently, the simulation of aerosol–cloud interactions across vertical scales.

Here, we present a robust INP sampling system designed to address this gap, called PUFIN: Profiling Upper altitudes For Ice Nucleation. The instrument collects filters at up to three distinct altitudes plus a blank during each TBS flight and can be fully controlled from the ground. Developed collaboratively by the INP and TBS instrument teams under the U.S. Department of Energy's Atmospheric Radiation Measurement (DOE ARM) user facility, the system is intended for routine deployment at ARM sites in response to user requests. Resulting data products are publicly released on the ARM Data Center (<https://www.arm.gov/data>, last access: 4 June 2026) within six months of each TBS campaign. In this paper, we describe the system design and flight operations, outline the offline sample processing and data production, summarize the data that are currently available and how to access them, and guide users how to request deployment of PUFIN for their own research needs.

2 Instrument description

2.1 DOE ARM TBS and INP initiatives

The ARM TBS program has evolved into a critical observational capability for capturing high-resolution, vertically-stratified atmospheric data, operating at ARM observatories using helium-filled Skydoc balloons capable of ascending to approximately 1.5 km a.g.l. Typically, ARM conducts six to eight two-week TBS missions each year, with flights deploying baseline instrumentation suites, including aerosol, thermodynamic, and turbulence sensors, tailored to research objectives across clear-air and, occasionally, in-cloud conditions. More details on the TBS system and standard instrument payload can be found in Dexheimer et al. (2024) and up-to-date information on the ARM TBS website (<https://www.arm.gov/capabilities/instruments/tbs>, last access: 4 June 2026).

Since 2020, ARM has provided routine, publicly-available INP measurements at select sites. Prior to that, INP sampling was considered a guest instrument activity and required proposals by researchers for targeted campaigns and locations. Demand for such measurements has since grown, and as of 2025 INP data are available from seven ARM sites. These data are generated by collecting filters at ARM fixed observatories and mobile facilities, followed by offline processing with the Ice Nucleation Spectrometer (INS) at Colorado State University (CSU), as described briefly below and in detail in Creamean et al. (2024, 2025). Data products can be accessed through the ARM Data Center by searching for “INP.” Up-to-date information, including deployment details and data availability from TBS operations, is provided on the ARM INS website (<https://www.arm.gov/capabilities/instruments/ins>, last access: 4 June 2026), where a routinely updated field log is also available for community reference.

2.2 Design and integration of PUFIN with the TBS

PUFIN operates similarly to the standard ARM INP sampling system, but on a smaller scale and with multiple filters attached. A detailed parts list and design schematic are publicly available on GitHub at <https://github.com/ARM-Development/TBS-INP-Design> (last access: 4 June 2026) to enable researchers to build and deploy their own PUFIN replicas for their independent or collaborative studies. Figure 1 illustrates PUFIN’s flow diagram, which includes a dry floating scroll pump (SVF-E0-50P, ScrollLabs®), a multi-gas flow sensor (SFM4300, Sensirion AG), four stainless steel solenoid valves (PL-220101, Plum Garden), and four ports for reusable 47 mm in-line polycarbonate filter holders (Pall Life Sciences). The pump features a brushless motor powered by 24 VDC, achieves an ultimate vacuum of < 1 mbar, and provides flow rates up to 50 sL min⁻¹ (liters per minute at standard temperature and pressure (STP): 0 °C and 101.32 kPa) without a filter at-

tached. The flow sensor operates over a 0–50 sL min⁻¹ range. Each solenoid valve, with 1/4-inch threaded inlet connections, requires 12 VDC and is controlled via a motor driver controller board (L298N, HiLetGo). The filter holders, with an effective filtration area of 9.6 cm², are prepared as outlined in Sect. 2.4.1. With prepared filter holders attached, the pump can pull a maximum of roughly 11 sL min⁻¹ through the standard 0.2 µm pore size filters used for the ARM INP measurements. Connections at both ends consist of 1/4-inch hose barb adapters, linking to 1/4-inch tubing inside PUFIN and opening directly to the air on the exterior (Fig. 2). PUFIN does not incorporate a wind vane or active orientation system to maintain the inlet facing into the wind. Consequently, the inlet orientation relative to the ambient airflow can vary during TBS operations, which may introduce some uncertainty in sampling efficiency. However, each filter is sampled at flow rates of up to 11 L min⁻¹, corresponding to an inlet velocity of approximately 6 m s⁻¹ for the 1/4-inch inlet used in PUFIN. This active aspiration facilitates aerosol collection even when the inlet is not optimally aligned with the wind, especially given the wind speeds under which ARM TBS deployments are typically conducted. PUFIN’s components are protected by a 3D-printed enclosure, which is equipped with a ventilation fan for in-flight cooling and backed with a 0.32 cm thick aluminum electrical ground distribution board that also provides structural integrity for the mounting point to the tether. The enclosure and all other 3D-printed parts are fabricated from white ASA (acrylonitrile styrene acrylate) polymer (Bambu Lab) due to its exceptional UV and temperature resistance, high impact strength, durability, and suitability for long-term outdoor use. The total flight-ready weight of the instrument is 6.1 kg.

Figure 3 illustrates the primary components and features of both the interior and immediate exterior of PUFIN. It is powered by a 28.8 V, 14 000 mAh lithium ion battery pack (8S4P, MaxAmps), housed within a 3D-printed enclosure for protection and secure mounting. The battery pack typically powers PUFIN for approximately 3.5 h depending on the target flow rate, ambient temperature, and air density. A 30 W DC/DC converter (PYB30-U, Bel Power Solutions) steps down the battery voltage to 12 V to supply the pump, valves, and sensors. System power consumption is monitored using a current, voltage, and power monitor (INA260, Adafruit Industries LLC), providing measurements of electrical load and enabling safe operation during flight. PUFIN’s control system is built around a TEENSY 4.1 microcontroller (iMXRT1062, SparkFun Electronics), which serves as the central processing unit for all sensor operations. Onboard sensors communicate digitally with the microcontroller, and analog pump command signals are generated using a digital-to-analog converter (MCP4725, SparkFun Electronics), enabling the microcontroller and other computational components to interpret and respond to sensor inputs accurately. This configuration allows precise regulation of flow rates, valve actuation, and system monitoring dur-

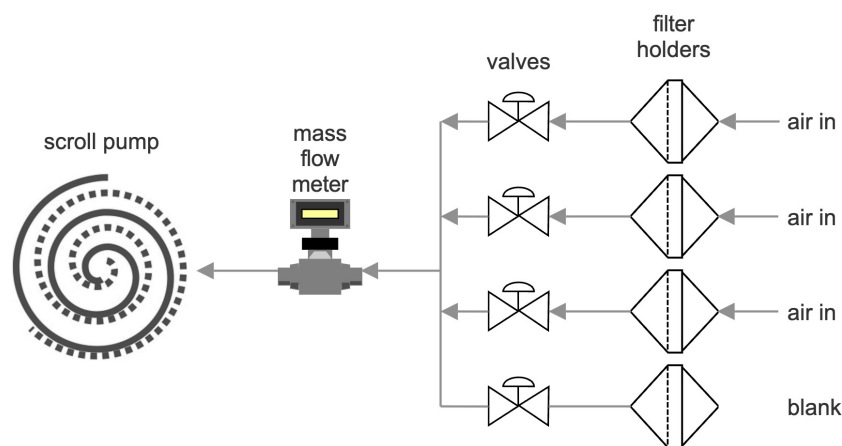


Figure 1. Schematic of PUFIN airflow. Main components are labeled. Valves are sequentially triggered to direct airflow through one filter at a time, while the fourth filter serves as a field blank and remains closed to airflow. Arrows indicate direction of airflow. The schematic was generated with <https://smartdraw.com> (last access: 4 June 2026).

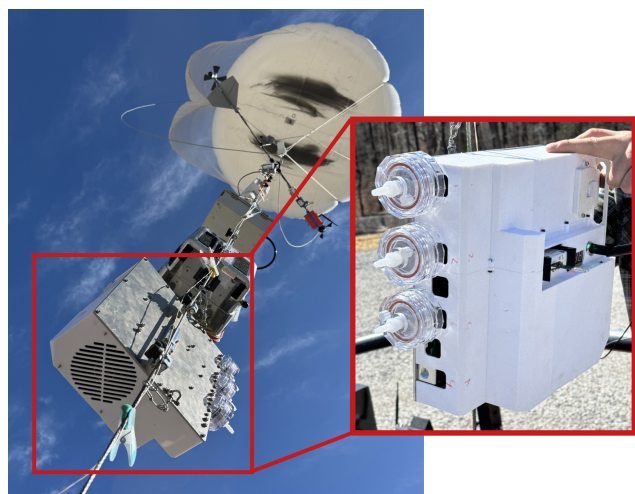


Figure 2. Exterior views of PUFIN mounted on the ARM TBS tether during a field deployment, shown in flight alongside other instrument payloads. The inset on the right displays a frontal view of PUFIN with filter holders attached. This flight required collection of INPs at two designated altitudes plus one field blank.

ing flight. PUFIN's communications system integrates atmospheric sensing, data transmission, and user interface components to enable real-time monitoring during flight. An iMet-XQ2 sensor measures atmospheric pressure, temperature, and humidity, and includes a GPS receiver, rechargeable battery, and onboard data logger. However, these measurements are only accurate to approximately ± 20 m; therefore, data are taken from the TBS iMet payload, available as the "TBSIMET" datastream from the ARM Data Center (Dexheimer et al., 2024). The sensor is mounted in a custom 3D-printed holder bracket. Wireless data transmission is achieved via a 2.4 GHz radio frequency transceiver

module with antenna (NRF24L01P + PA + LNA, HiLetgo), allowing real-time communication between PUFIN and the ground station. A 9 dBi omni-directional antenna is used with the transceiver to increase range (ANT-WS-A-NF-09-150, ATOP Technologies). System status and measurements are displayed locally on a 2.8 in. (7 cm) LCD touch panel (ILI9341, HiLetgo) and a digital LED tube clock module. All remote electronics, including the transceiver, display, and sensor assemblies, are housed in a series of 3D-printed enclosures to protect components while maintaining accessibility and visibility during deployment.

2.3 INP sample collection during deployments

2.3.1 Filter material and holder preparation

In preparation for aerosol collection, $0.2\ \mu\text{m}$ polycarbonate filters (47 mm diameter Whatman® Nuclepore™ Track-Etched Membranes) are loaded into the reusable 47 mm polycarbonate in-line filter holder, pre-cleaned with cycles of methanol and deionized water. These filters are identical in preparation to those used at ARM fixed and mobile sites (Creamean et al., 2025). All components, including filters, forceps, and workspaces are pre-cleaned following the procedure described in Barry et al. (2021). Filter holders are disassembled and reassembled under ultraclean conditions inside a laminar flow cabinet with near-zero ambient particle concentrations, wrapped in foil, then sealed and stored individually in clean airtight bags until deployment. Filter holders are thoroughly cleaned following each use and before reuse by immersion in 5 % hydrogen peroxide for 1 h, followed by 10 min of ultra sonication in deionized water and Windex® Original Glass Cleaner to remove any remaining particles.

The $0.2\ \mu\text{m}$ filters used in PUFIN provide a simple, robust, and widely adopted approach for INP sampling, enabling bulk-integrated collection across particle sizes and fa-

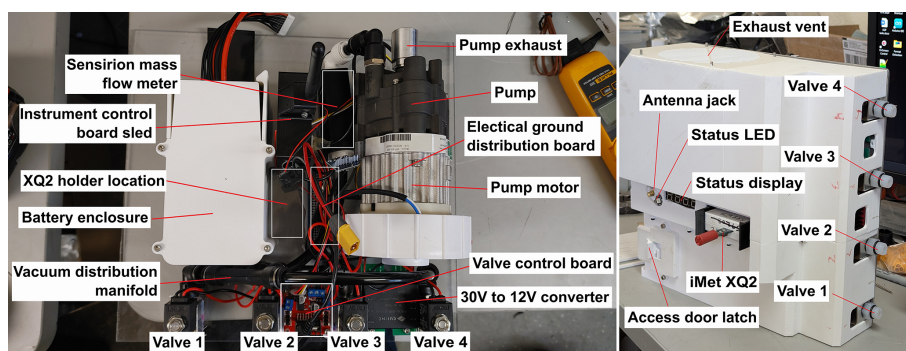


Figure 3. Photos of the interior (left) and immediate exterior (right) of PUFIN. The main components and features are labeled. The exterior housing shown in the right image is 3D printed.

cilitating intercomparability across studies. Compared to impingers, filters do not require liquid handling, are less sensitive to environmental conditions, and allow for more stable storage of INPs when frozen (e.g., Beall et al., 2020). Compared to impactors, they provide a bulk-integrated sample rather than size-segregated fractions, simplifying analysis and reducing uncertainties associated with particle bounce and stage-specific collection efficiencies. Based on calculations from Spurny and Lodge (1972), these filters exhibit relatively high collection efficiencies across PUFIN's operating flow rate range ($4\text{--}11\text{ L min}^{-1}$), with a decrease near 150 nm but still maintaining efficiencies on the order of $78\text{--}91\%$. Based on a measured pressure drop of 64 kPa at 11 L min^{-1} across the filter in PUFIN's in-line holder, estimated pressure drops are approximately $40\text{--}50\text{ kPa}$ for typical PUFIN flow rates ($7\text{--}9\text{ L min}^{-1}$) and $50\text{--}65\text{ kPa}$ for the flow rates of the ground-based filters measured at ARM sites where PUFIN has operated, on average. These values indicate that the pressure differentials from both systems are broadly comparable despite differences in sampling configuration. In principle, the filters sample total suspended particulates. However, inlet-related biases, particularly for coarse particles, may arise due to wind speed-dependent inertial and gravitational losses (e.g., governed by Stokes number and settling velocity), such that the largest particles may be underrepresented, although this has not yet been empirically quantified for this system.

2.3.2 Operation of PUFIN during flight

PUFIN is typically operated manually unless used in environments with elevated electromagnetic interference. During setup, the blank filter remains installed as the instrument is mounted onto the tether. It is then removed using latex gloves, wrapped in aluminum foil, labeled, and stored in a -80°C ultracold freezer. The pump is activated, and the first solenoid valve is manually opened to begin sampling (Fig. 4). The instrument makes multiple passes through the first target altitude over a $30\text{--}60\text{ min}$ interval. Before transitioning to the

next altitude range, the valve is closed, and the next solenoid valve is opened. This process is repeated for the third valve at the highest altitude.

PUFIN sampling is often conducted in coordination with concurrent airborne measurements, including aerosol size distributions and multimodal micro-spectroscopy, to enable complementary characterization of aerosol properties across altitudes. Sampling is performed within predefined altitude ranges to facilitate comparison across flights, seasons, and locations, targeting roughly $0\text{--}250$, $250\text{--}500$, and $> 500\text{ m a.g.l.}$ These altitude bins are adjusted as needed based on flight duration and atmospheric conditions. They can be modified in real time to target layers of interest identified from on-site aerosol and meteorological measurements.

After the flight, the instrument is removed from the tether and placed on a workspace lined with clean aluminum foil. Filters are removed using latex gloves, wrapped in foil, labeled, and stored in the same plastic bag as the blank filter in the -80°C freezer. The operation log is retrieved from the onboard SD card. Once all flights are completed, the collected filters are shipped overnight to CSU for analysis in a hard-sided 7 kg -capacity cooler with 2.2 kg of dry ice.

3 Filter processing for INP data

3.1 INS sample processing

The INS, similar to the CSU Ice Spectrometer, simulates immersion freezing of cloud droplets by measuring heterogeneous ice nucleation initiated by ambient aerosol particles acting as INPs (Creamean et al., 2024, 2025). This technique provides quantitative insight into the population of ambient aerosols capable of initiating cloud ice formation across a broad range of subzero temperatures, thereby determining INP concentrations spanning up to six orders of magnitude. The INS is supported by robust experimental protocols and has been widely applied across diverse atmospheric contexts (e.g., Barry et al., 2023; Beall et al., 2017; DeMott et al.,

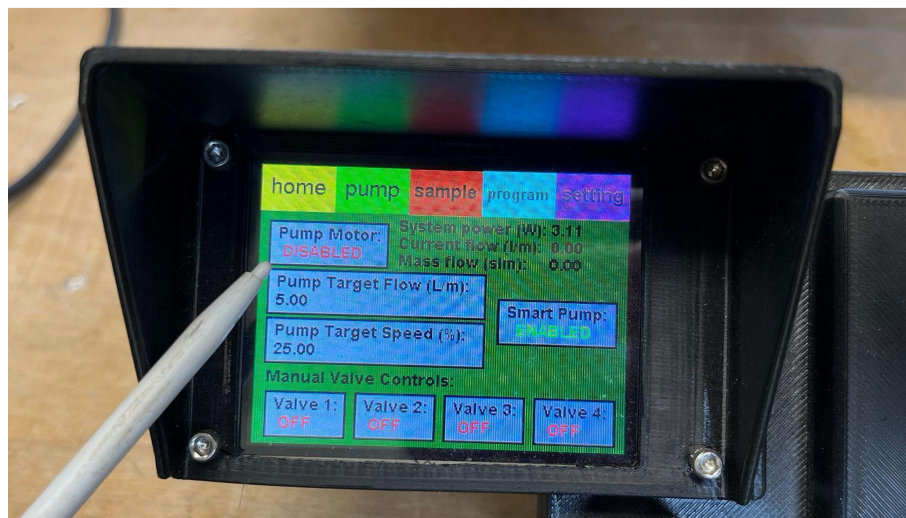


Figure 4. Photo of the PUFIN ground station undergoing manual operation. The image depicts the pump motor in an inactive state (“DISABLED”) with all four valves closed and 0 sL min^{-1} of flow. The target flow upon activation is 5.00 sL min^{-1} .

2017; Hill et al., 2016; Hiranuma et al., 2015; Lacher et al., 2024; McCluskey et al., 2017; Suski et al., 2018).

The INS contains two units that operate simultaneously to increase processing throughput. Each unit consists of two 96-well aluminum incubation blocks designed for polymerase chain reaction (PCR) plates, arranged end-to-end and thermally regulated via cold plates on the sides and base. The instrument measures freezing across a temperature range of 0°C to approximately -27 to -30°C . For analysis, filters are carefully removed from the in-line holders under ultraclean conditions inside a laminar flow cabinet. Each filter is placed in a sterile 50 mL polypropylene tube with 7–10 mL of $0.1 \mu\text{m}$ -filtered deionized (DI) water, with the volume adjusted based on expected aerosol loading; lower volumes are used for cleaner environments to enhance sensitivity. Samples are re-suspended by end-over-end rotation for 20 min. Serial dilutions are prepared using the suspensions and $0.1 \mu\text{m}$ -filtered DI water, typically including 11-fold dilution steps. Each suspension and its dilutions are aliquoted into sets of 32 wells ($50 \mu\text{L}$ per well) of single-use 96-well PCR trays (Optimum Ultra), along with a 32-well negative control containing only filtered DI water. Trays are placed into the INS blocks and cooled at a controlled rate of $0.33^\circ\text{C min}^{-1}$. Uncertainty of the thermocouple is $\pm 0.2^\circ\text{C}$. Freezing is monitored optically using a CCD camera with a 1 s resolution. A continuous flow of HEPA-filtered N_2 , pre-cooled just above block temperature, purges the headspace to minimize condensation and prevent warming of the samples. Field blanks are processed in an identical manner as sampled filters.

3.2 INP concentration and uncertainty calculations

INP concentrations, blank corrections, and uncertainties were generated using the Open-source Library for Automating Freezing Data acQuisition from Ice Nucleation Spectrometer (OLAF DaQ INS; <https://github.com/SiGran/OLAF>, last access: 4 June 2026). Details are described in Creamean et al. (2025). The program calculates INP concentrations at each temperature interval using the fraction of frozen droplets and the known total volume of air that passed through each filter, following Eq. (1) (Vali, 1971):

$$K(\theta) (\text{L}^{-1}) = -\frac{\ln(1-f)}{V_{\text{drop}}} \times \frac{V_{\text{suspension}}}{V_{\text{air}}} \quad (1)$$

where f is the fraction of frozen droplets, V_{drop} is the volume of each droplet, $V_{\text{suspension}}$ is the volume of the suspension, and V_{air} is the volume of air sampled (liters at STP of 0°C and 101.32 kPa). The primary variable of the INS is the freezing temperature spectrum of cumulative immersion mode INP number concentration, $K(\theta)$, from aerosols re-suspended from individual filters. INP spectra are corrected using DI negative controls and subsequently blank-subtracted. Specifically, each run includes a 32-well DI negative control. For each 0.5°C temperature bin, the number of frozen wells in the DI control is subtracted from the number of frozen wells in each dilution. The corrected freezing counts are then converted to frozen fraction for each dilution and subsequently to INP concentration as a combined spectrum. Sample blanks are processed in a similar manner as filter samples, with INP concentrations calculated per blank filter for each 0.5°C temperature bin. All blanks from a given campaign are averaged to generate a representative blank spectrum (expressed as INP per blank filter; see Fig. S1 in the Supplement full complete field blank and DI background

spectra). For each sample, concentrations are first converted to INP per filter, the average blank spectrum is subtracted, and the corrected values are then converted back to INPL^{-1} . Binomial 95 % confidence intervals are calculated following Agresti and Coull (1998), varying with the proportion of wells frozen. For example, freezing in 1 of 32 wells yields a confidence interval range of approximately 0.2–5.0 times the estimated concentration, while 16 of 32 yields approximately 0.7–1.3 times the estimated concentration. $K(\theta)$ and upper and lower confidence intervals are derived per every 0.5 °C interval.

4 Accessibility of PUFIN and resulting TBSINP data

4.1 Availability of TBSINP data and filters

INP data collected with PUFIN on the ARM TBS and processed using the INS are available through the ARM Data Center by searching for “TBSINP”. Not all TBS deployments included PUFIN and resulted in TBSINP data, but this section summarizes those that have. Table 1 provides an overview of TBS campaign details through the end of 2025, which occurred at four main ARM sites: (1) Southern Great Plains (314 m a.m.s.l., 36.607° N, 97.488° E), (2) Gunnison, Colorado (2886 m a.m.s.l., 38.956° N, 106.988° W) during the SAIL (Surface Atmosphere Integrated field Laboratory) campaign, (3) Bankhead National Forest, Alabama (293 m a.m.s.l., 34.342° N, 87.338° W), and (4) Baltimore, Maryland (158 m a.m.s.l., 39.422° N, 77.21° W) during the CouRAGE (Coastal-urban-Rural Atmospheric Gradient Experiment) campaign. While not all datasets are available, those pending release as of the publication date of this paper are indicated in the table. Campaigns that used an earlier INP collection method predating PUFIN (called the IcePuck), as described in Creamean et al. (2024), are also identified. Limitations of the IcePuck in collecting sufficient air volumes to capture the higher freezing temperature range of the cumulative INP spectrum, along with challenges in ease of use, prompted the development of PUFIN. Exact start and end dates and times, altitude range, sample duration, and volume of air sampled for each sample and each flight can be found in the field log link on the INS website (<https://www.arm.gov/capabilities/instruments/ins>, last access: 4 June 2026). For deployments in which data are not or only partially available, researchers interested in accessing or analyzing these samples may submit a request to ARM (<https://www.arm.gov/guidance/campaign-guidelines/small-campaigns>, last access: 4 June 2026). User-requested data from additional INP processing will also be made accessible to the broader research community through the ARM Data Center.

The SGP site is located in the midst of agricultural fields in north-central Oklahoma, United States, which often produce high concentrations of INPs from soil dust lofted dur-

ing farming activities such as harvesting and plowing (Knopf et al., 2021). The TBS deployment at SGP was part of an intensive observational period (IOP) aimed at investigating the drivers of variability in INP concentrations from regional emissions of fertile, organic-rich agricultural soils, as well as intermittent contributions from other sources, including aerosols from controlled burns or wildfires, long-range transported desert dust, cellulose-containing plant matter, fungal spores, and microbial particles. Cornwell et al. (2024) reported enrichments of phosphate, lead, and soil organics in dust particles acting as INPs from surface measurements, while non-ice-nucleating aerosols were primarily carbonaceous or secondary in origin. TBSINP data from this deployment are still under analysis for a forthcoming publication, but several noteworthy case days have already emerged, including instances with elevated particle concentration layers within the boundary layer. The GUC site, part of the SAIL campaign, is located high in the Colorado Rocky Mountains. SAIL aimed to develop a quantitative understanding of atmospheric and land–atmosphere interaction processes, across relevant scales, that influence mountain hydrology in the midlatitude continental interior of the United States (Feldman et al., 2023). TBS flights at GUC were conducted in all seasons except autumn and sampled both within the mountain valley and above ridgelines, capturing cases influenced by local valley sources as well as more regional aerosol below cloud level.

In this paper, we focus on the TBS deployments at CRG and BNF where PUFIN was included, and consequently, larger air volumes were collected (Table 1). These conditions produced relatively complete cumulative INP spectra over much shorter collection times (~ 30 to 60 min) compared with previous IcePuck deployments at SGP and GUC, which often required more than an hour to obtain sufficient sample loading for INP detection, given the low flow rate of IcePuck. The shorter collection time is advantageous because it allows sampling at more altitude ranges per flight given constraints on flight duration imposed by battery life and staffing limitations.

At CRG, TBS operations took place in both winter and summer as part of the CoURAGE campaign, which investigates how spatial gradients in land–atmosphere interactions across coastal, urban, and rural environments influence atmospheric processes such as aerosols, clouds, radiation, precipitation, and boundary-layer dynamics in the Baltimore region. A central objective of CoURAGE is to improve representation of coastal urban climates in Earth system models by leveraging observations from a four-node regional observatory network to test and refine model simulations of urban atmospheric environments. The BNF observatory, a long-term ARM mobile facility (AMF) located in northwest Alabama, United States, is designed to advance understanding of the coupled interactions among aerosols, clouds, and land–atmosphere processes, particularly within forested environments, to strengthen their representation in Earth sys-

Table 1. Details on ARM TBS deployments with INP sampling. Information includes ARM sampling site, flight dates during each deployment, altitude range of the flights (m a.m.s.l.), the range of sample duration (min), value or range of flow rates during sample collection (L min^{-1}), range of volume of air collected per sample (liters), if the data are available on the ARM Data Center (ADC), and the sampling method used. For the site, SGP = Southern Great Plains, GUC = Gunnison, Colorado, BNF = Bankhead National Forest, Alabama, and CRG = Baltimore, Maryland. Sampling method indicates whether the older INP sampler (IcePuck) or PUFIN were used. For data availability, yes = all data are posted, partial = some data are available within the dates indicated, queued = samples will be processed/data will be available in the future, and no = samples are archived for possible future processing/no data are available.

ARM site	Flight dates	Altitude range (m a.g.l.)	Sample duration (min)	Flow rate (L min^{-1})	Vol air sampled (L)	Data on ADC	Sampling method
SGP	10–26 Apr 2022	0–1000	30–150	0.3–0.9	34–133	Yes	IcePuck
GUC	6–16 May 2022	0–500	74–149	0.6	40–90	Yes	IcePuck
GUC	23–28 Jul 2022	0–750	21–119	0.6	27–71	Partial	IcePuck
GUC	21–24 Jan 2023	0–560	33–74	0.4–0.5	30–37	No	IcePuck
GUC	6–11 Apr 2023	0–1150	70–120	0.1–0.5	34–133	Partial	IcePuck
GUC	9–13 May 2023	0–500	119–120	0.3–0.5	30–41	No	IcePuck
GUC	9–15 Jun 2023	0–1000	60–120	0.3–0.5	16–47	No	IcePuck
CRG	14–23 Feb 2025	0–900	59–119	7.1–11.0	447–1456	Yes	PUFIN
CRG	15–28 Jul 2025	0–1050	4–30	4.6–8.2	31–245	Yes	PUFIN
BNF	21–27 Mar 2025	0–1100	60–91	6.9–7.2	416–1157	Yes	PUFIN
BNF	17–27 Apr 2025	0–850	46–62	6.9–7.3	350–438	Yes	PUFIN
BNF	29 May–6 Jun 2025	0–700	28–44	7.3–8.9	204–394	Yes	PUFIN
BNF	9–24 Aug 2025	0–850	30–89	7.7–8.9	254–713	Yes	PUFIN

tem models. In addition, BNF is envisioned to serve as a testbed for applying artificial intelligence and machine learning methods to enhance predictability in atmospheric science, while supporting detailed studies of land–atmosphere feedbacks and aerosol–cloud interactions. To date, four TBS deployments have been conducted at BNF during spring and summer, with additional campaigns anticipated in the future.

4.2 INP profile data from recent ARM TBS campaigns

The objective of this section is to provide an initial presentation of the temperature spectra, demonstrating the capabilities of the dataset and highlighting its potential for future scientific investigation. A more in-depth scientific interpretation of these data falls beyond the primary scope of this manuscript; however, we encourage the community to further explore these observations in combination with complementary meteorological and aerosol measurements. Figure 5 shows cumulative INP spectra from CRG during February and July 2025, with darker shades of each color representing the lower altitude sampled each day. We also evaluated equivalent potential temperature (θ_e) during flight days using data collected from the TBS to assess whether the boundary layer in the PUFIN sampling region was well mixed, where INP concentrations would be expected to be similar across altitudes, or stratified, which can promote aerosol layering (Creamean et al., 2021; Griesche et al., 2021, 2026). Details of the θ_e calculations are provided in the Supporting Information.

In February, multiple flights were conducted, with two altitudes sampled per day, revealing substantial variability

both in overall INP concentrations and in the vertical structure. For example, on 14 and 22 February (red and green shades, respectively), higher altitudes (loitering at 600 and 300–575 m, respectively) consistently exhibited significant elevated INP concentrations (i.e., spectra varied beyond the 95 % confidence intervals) across all temperatures compared with lower altitudes (200 and 0–300 m, respectively). These days also corresponded to a fairly stratified part of the boundary layer during the flights, since θ_e varied vertically by ~ 2 to 4 K (Fig. S2). In contrast, on 19 and 23 February (orange and blue shades, respectively), no significant differences were observed between upper and lower altitude levels (0–300 m vs. 300–740 m and 0–300 m vs. 250–900 m, respectively), as concentrations overlapped within the 95 % confidence intervals. The boundary layer during the flights appeared to be well mixed on 19 February (θ_e varied by only ~ 1 K vertically) but stratified on 23 February (Fig. S2); therefore, the observed differences in INP spectra are unlikely to be driven solely by distinct aerosol layers. In July, INP concentrations averaged an order of magnitude lower (19 L^{-1}) than in February (145 L^{-1}) at -25°C , but were an order of magnitude higher at -15°C (3 vs. 0.6 L^{-1}). Interestingly, even the sample collected over just 4 min (31 L of air) yielded detectable INP concentrations and was among the higher values observed at CRG at all temperatures. The spectral shapes also differed: February spectra were more log-linear, whereas July spectra exhibited a sharp increase in concentration below -15°C followed by a plateau, consistent with the influence of biological INPs (Creamean et al., 2019). This is notable given that Baltimore is an urban

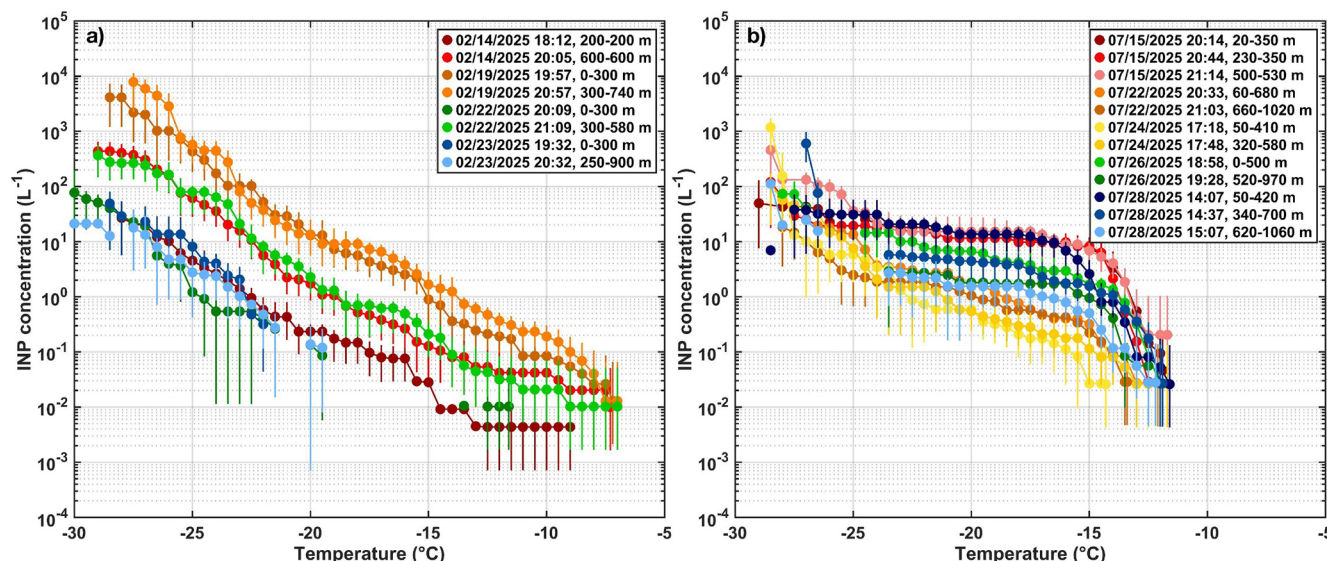


Figure 5. Cumulative INP spectra from CRG TBS flights in (a) February and (b) July 2025. Two altitudes or altitude ranges were sampled per day. PUFIN loitered at a single altitude if the range is the same value; if a range with different values is listed, PUFIN profiled within that range to collect the sample. Date (mm/dd/yyyy) and time (hh:mm:ss) indicate the sampling (flight) start in UTC. Each day is a different color, with each altitude (range, in m a.g.l.) a different shade of that color. Error bars indicate 95 % confidence intervals.

environment, yet it may still be influenced by biological activity linked to ice nucleation activity, which has been observed in other urban environments (Cabrera-Segoviano et al., 2022; Tobo et al., 2020; Yadav et al., 2019). However, the Baltimore region is bordered by farmland to the east where the dominant crops are grains, oilseeds, dry beans, and dry peas (USDA and NASS, 2024), which may have influenced the sampled INP population. Higher freezing temperatures were reached in February due to larger sampling volumes (Table 1), with detection up to -7°C compared to -11°C in July. In July, the flights on 22, 26 July, and the lowest (53–423 m) and highest (618–1062 m) altitude ranges on 28 July had significant differences. During all three cases, higher INP concentrations were observed at the lower altitude ranges than the upper ranges, which was the opposite of the February observations. These dates also coincided with a stratified vertical structure based on θ_e profiles (Fig. S2).

Figure 6, similar to Fig. 5, presents results from BNF flights across four months in 2025. In March, INPs were limited to relatively lower temperatures ($\leq -14^{\circ}\text{C}$), despite the highest sampled air volumes at BNF compared to other months (Table 1), and no significant differences were observed between altitude levels on any day. The boundary layer during the 27 March flight was highly stratified, but was well mixed on the 21 and 22 March flights (Fig. S3). In April, only one day included two altitude levels, which again showed no significant difference. Generally, April exhibited average concentrations comparable to those observed in March (13 and 10 L^{-1} at -25°C , respectively). By the end of April, a single sample was collected over the full

flight from ground level to 850 m, and concentrations began to increase toward the warmer end of the spectrum. May involved one flight towards the end of the month at two altitude levels with no difference in INP concentration, likely due to the well-mixed boundary layer (Fig. S3), and were similar in concentration to March and April on average (12 L^{-1} at -25°C). Although the 1 June samples did not show a significant difference, likely due to the generally well-mixed boundary layer aside from a near-surface inversion, the higher altitude range exhibited an order of magnitude higher INP concentration than the lower range (42 vs. 4 L^{-1} at -25°C). Later in June, concentrations increased at higher freezing temperatures, and a significant difference was observed during the 15 June flight, with the lower altitude range showing higher INP concentrations (41 vs. 5 L^{-1} at -25°C), opposite to the pattern observed earlier in the month. Again, this is consistent with the boundary layer structure, which was well mixed on 6 June and stratified on 15 June (Fig. S3). The increase towards the end of June suggests that as summer approaches, biological activity in the forest likely intensifies, producing biological INPs active at higher freezing temperatures as evidenced by the spectral shape (Creamean et al., 2019). This is also consistent with observations of increased INPs and bioaerosols during summer in other forested regions (Petersson Sjögren et al., 2023; Schneider et al., 2021; Schumacher et al., 2013). Combined with CRG, these results highlight highly variable vertical and seasonal trends in INP concentrations at a single location, as captured by PUFIN and processed offline with the INS, yielding publicly available data for further exploration by the research community.

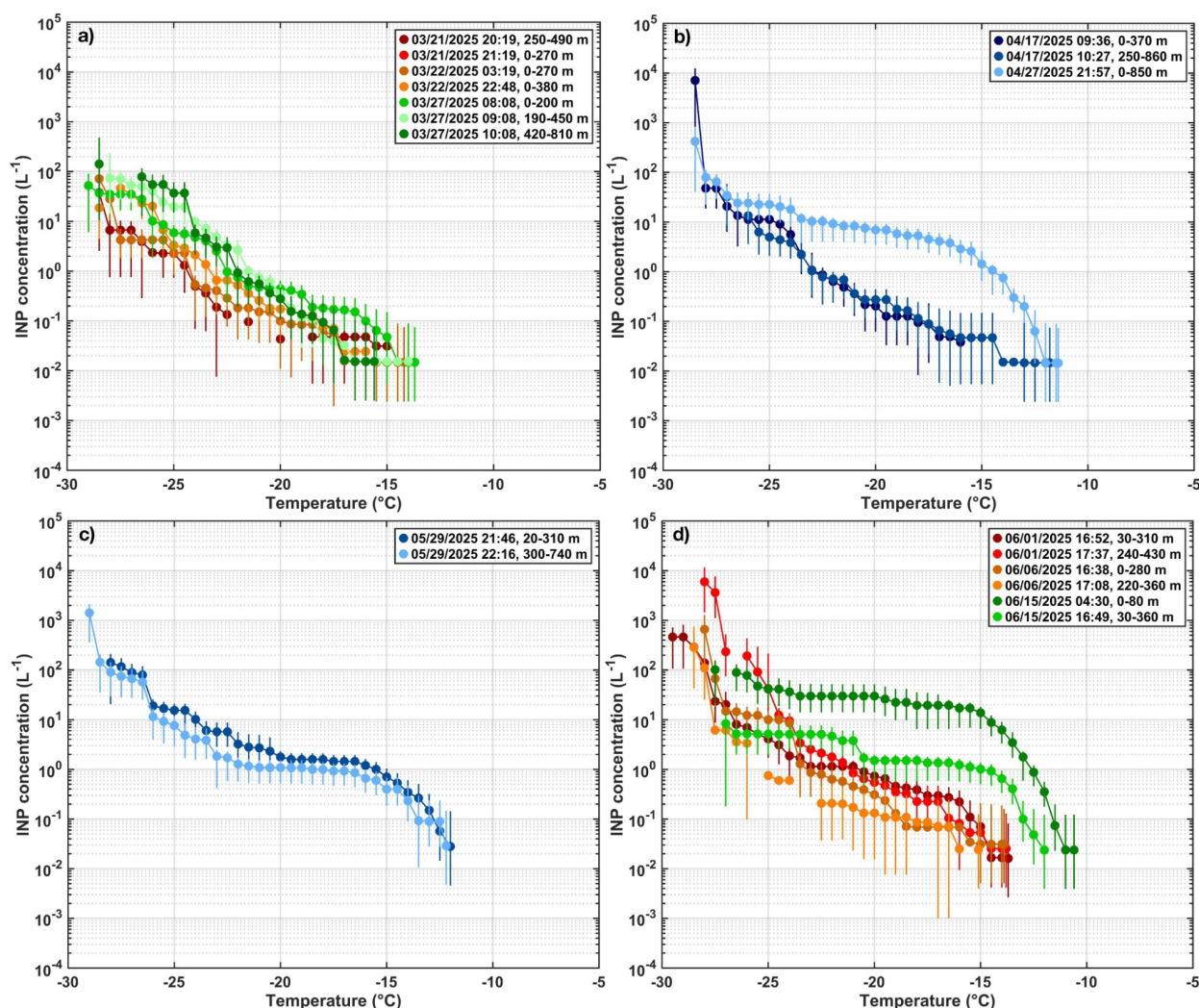


Figure 6. Same as Fig. 5, but for BNF in (a) March, (b) April, (c) May, and (d) June 2025.

At -20°C , the INP concentrations observed at CRG ($0.01\text{--}1\text{ L}^{-1}$ in winter; $0.01\text{--}12\text{ L}^{-1}$ in summer) and BNF ($0.01\text{--}1\text{ L}^{-1}$ in spring; $0.02\text{--}11\text{ L}^{-1}$ in summer) fall within the broad range reported in recent studies. For example, Creamean et al. (2018) reported $1\text{--}11\text{ L}^{-1}$ in springtime agricultural regions in Colorado from vertically-resolved filters via a launched and retrieved balloon system, while similar concentrations ($\sim 0.02\text{--}12\text{ L}^{-1}$) were observed by Bieber et al. (2020) and Seifried et al. (2021) near a lake in Austria in summer via UAS. Böhmmländer et al. (2025) reported lower values of $\sim 0.2\text{--}0.5\text{ L}^{-1}$ during spring and autumn UAS test flights in a boreal environment in Finland. In April in Cyprus, Marinou et al. (2019) reported $\sim 3\text{ L}^{-1}$ from UAS measurements. Values ranging from $\sim 0.2\text{--}10\text{ L}^{-1}$ from size-resolved measurements have been reported by Porter et al. (2020) across multiple sites in Europe and the Arctic using balloon-based sampling. Overall, the concentrations reported here are consistent with the range of environments sampled in the lit-

erature, spanning relatively clean to more biologically or terrestrially influenced regions.

Overall, the flights conducted to date demonstrate that PUFIN can collect sufficient aerosol loadings to capture concentrations as low as 10^{-2} INPL^{-1} in as little as 28 min (equivalent to $\sim 250\text{ L}$ of air; 4 min at 31 L of air is achievable but at a higher detection limit of 10^{-1} INPL^{-1}). For comparison, INP spectra from SGP and GUC TBS flights are shown in Figs. S4 and S5, respectively, in which the same detection limit is achieved but from a longer sampling duration as discussed in Sect. 4.1. By comparison, ground-based ARM INP measurements are typically collected over 24 h ($\sim 10\,000$ to $30\,000\text{ L}$ of air), enabling lower detection limits of 10^{-4} INPL^{-1} (Creamean et al., 2025). Although PUFIN cannot yet achieve such low concentrations, it provides valuable vertically-resolved INP measurements detectable at temperatures as high as -7°C from measurements

thus far. Longer collection durations may further extend detection toward higher temperatures, potentially above -7°C .

4.3 Requesting PUFIN for future ARM TBS campaigns and beyond

Researchers interested in deploying PUFIN on an ARM TBS mission should first consider contacting the INP and TBS mentors (co-authors of this manuscript, Jessie Creamean and Darielle Dexheimer) to discuss the feasibility, timing, and logistical considerations of potential campaigns. Two identical PUFIN units are currently available, including the original system and a newly constructed duplicate. An intercomparison test was conducted using standard ARM ground-based INP filters (Creamean et al., 2025), in which ambient samples were collected outside CSU for 30 min, using the first sample valves on both PUFIN systems. The resulting INP spectra show good agreement between the two units, and the ground-based INP filters deployed routinely at ARM sites, demonstrating reproducibility and consistency in sampling and analysis (Fig. S6).

Formal requests for PUFIN deployment are submitted through the ARM TBS proposal process, following the guidelines provided on the TBS campaign website (<https://www.arm.gov/guidance/campaign-guidelines/tbs>, last access: 4 June 2026). PUFIN is currently configured for deployment on the ARM user facility TBS system, but the design is flexible and could be adapted for use on other balloon platforms or UASs, contingent on community interest. Users may also request sample collection for total INP concentrations, as well as the application of thermal and peroxide treatments to infer INP types, including heat-labile (likely biological), heat-stable (likely organic), and inorganic (likely mineral) INPs (Barry et al., 2023, 2025; DeMott et al., 2025; Hill et al., 2016; McCluskey et al., 2018; Schiebel et al., 2016; Suski et al., 2018; Testa et al., 2021; Tobo et al., 2019). Proposals must target existing ARM observatories, adhere to specific submission deadlines, and include sufficient detail on desired sampling locations, altitudes, and measurement objectives. Both ARM-only and collaborative campaigns are supported. For example, researchers may propose joint ARM–EMSL FICUS (Facilities Integrating Collaborations for User Science) missions to deploy guest instruments, leverage specialized laboratory capabilities, and access additional resources to enhance the scientific output of the campaign (<https://www.emsl.pnnl.gov/proposals/type/ficus-program>, last access: 4 June 2026). Detailed information on proposal requirements, timelines, and eligible instruments is provided on the ARM TBS guidance webpage.

5 Summary

This paper introduces PUFIN (Profiling Upper altitudes For Ice Nucleation), a robust INP sampling system developed for

routine deployment on the DOE ARM TBS platform. INPs, though present at concentrations orders of magnitude lower than CCN, exert a strong influence on cloud microphysics, lifetime, and radiative properties, particularly in mixed-phase clouds. Accurate representation of INPs in weather and climate models requires knowledge of their vertical distribution, which is often not captured by surface-based measurements or short-duration crewed aircraft observations. Small, flexible platforms such as TBS allow multi-hour, vertically-resolved sampling at targeted altitudes below, within, and above clouds.

PUFIN collects filters at up to three altitudes plus a field blank per flight, and all operations are fully ground-controlled. The collected samples are processed offline using the INS at Colorado State University, producing cumulative INP spectra across subzero temperatures. Recent deployments in Baltimore, Maryland (CRG) and Bankhead National Forest, Alabama (BNF) demonstrate that PUFIN can detect INP concentrations as low as $\sim 10^{-3} \text{ L}^{-1}$ in as little as 28 min, a substantial improvement over the older ARM TBS INP sampling system and enabling multiple altitude profiles per flight. CRG data revealed notable vertical variability in INP concentrations likely linked to boundary layer stratification and aerosol transport, while BNF exhibited generally lower INP concentrations with limited vertical dependence. All PUFIN-generated INP data are publicly available via the ARM Data Center, and researchers can request PUFIN deployment for future TBS campaigns, including collaborative missions at existing and future proposed ARM observatories.

As PUFIN has only been deployed a limited number of times to date, we are still actively identifying best practices. While we have not yet fully evaluated performance under extreme environmental conditions, future deployments will require careful consideration of such factors. Initial experience highlights the importance of maximizing sampling volume for robust INP detection and the value of sending test samples from new or unfamiliar environments for immediate analysis to inform subsequent sampling strategies. We also note that inlet components (e.g., hose barbs) may introduce minor collection efficiency losses, though further testing is needed to assess potential trade-offs with background contamination during ascent and descent. Maintaining consistent altitude ranges where possible improves comparability, and future dedicated flights are planned to include longer-duration sampling at fixed “loitering” altitudes to better resolve vertical structure and potentially achieve even lower detection limits.

Future improvements to PUFIN will focus on enhancing altitude accuracy, overall system robustness, and evaluating particle removal methodologies to ensure the most effective approach is used. Planned upgrades include the incorporation of pressure-based altitude measurements and higher-accuracy GPS sensors, as well as standardized reporting of altitude relative to surface elevation (a.g.l.) to facilitate inter-site comparisons. In addition, improvements to power man-

agement, particularly more reliable charging and distribution for onboard sensors, are anticipated to ensure stable operation during extended deployments. Future iterations of the system may incorporate a wind-alignment mechanism to further characterize and optimize sampling efficiency under varying flight conditions. For particle removal from the filters, this approach has been intercompared with other techniques employing different extraction methods and showed good agreement (DeMott et al., 2017, 2025; Lacher et al., 2024). Future work will evaluate a range of rotation times to ensure that the current 20-minute extraction is sufficient across filters with varying particle loadings.

Looking forward, expanding the use of PUFIN and similar systems as TBS operations become more routine would not only provide more comprehensive assessments of vertical INP distributions but also capture seasonal variability in these profiles. By providing high-resolution, vertically-stratified INP measurements, PUFIN enhances understanding of aerosol–cloud interactions, informs representation of INPs in models, and supports studies of regional to global climate processes.

Code and data availability. TBSINP data are available from the DOE ARM Data Center (<https://www.arm.gov/data>, last access: 4 June 2026) or Data Discovery portal (<https://adc.arm.gov/discovery/>, last access: 4 June 2026) under <https://doi.org/10.5439/2001041> (Creamean et al., 2024). PUFIN design drawing and parts list are available at <https://github.com/ARM-Development/TBS-INP-Design> and <https://doi.org/10.5281/zenodo.21258036> (Creamean and Sherman, 2026). OLAF code is available at <https://github.com/SiGran/OLAF/tree/v.0.3.0> (last access: 9 July 2026) and <https://doi.org/10.5281/zenodo.17509699> (Grannetia and Hume, 2025).

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Author contributions. JMC and AT conceptualised the INP mentor program. JMC, CCH, DD, and BTMH designed the TBSINP sampler, while BTMH built it. DD, CL, and CR were responsible for TBS deployments at ARM sites. CCH and MV conducted the sample and data analysis for the TBSINP data that are publicly-available for download from the DOE ARM Data Center. All authors contributed to the writing of this manuscript.

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