



GloPINE dataset: model-ready measurements of INP concentrations using PINE instruments

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Abstract. Ice-nucleating particles (INPs) are a subset of aerosol particles that facilitate the freezing of supercooled cloud droplets heterogeneously and influence the radiative properties of supercooled clouds. The role of INPs in the Earth system remains unquantified in part due to poorly constrained representations of their spatial distributions and properties in global and regional models. In this study, we present a quality controlled dataset, called GloPINE, comprising 70,000 hours of INP concentrations measured using Portable Ice Nucleation Experiment (PINE) instruments that use an expansion chamber to



make automated long-term (months to years) and high temporal resolution (< 10 mins). We collate measurements from 20 recent ground-based PINE field campaigns in the Northern Hemisphere conducted between January 2018 and December 2023, totaling more than 400,000 expansions performed under conditions relevant for mixed-phase clouds. In the GloPINE dataset, we subset and average the PINE measurements across synoptically relevant time intervals of 6 h and 2 K temperature bins, providing 36,000 INP measurements. Combining PINE expansions over these intervals enhances counting statistics at higher freezing temperatures, decreases the lower limit of measurable INP concentrations, and provides an INP dataset readily applicable to model simulation data and meteorological reanalysis products. The frequency and duration of measurements combined with the lack of instrument or methodological variability provides a means to robustly evaluate and constrain global models on a scale that has not previously been possible.

15 1 Introduction

Aerosol particles play an important role in the Earth System. On relatively short timescales, they influence fluxes of radiation directly via aerosol extinction and indirectly via modification to cloud radiative properties (Carslaw, 2022). Aerosol particles can directly influence cloud properties by acting as cloud condensation nuclei (CCN), thus influencing the cloud droplet size distribution (e.g., Fanourgakis et al., 2019), and/or ice-nucleating particles (INPs), which induce primary ice production at supercooled temperatures (e.g., Murray et al., 2012). Anthropogenic activity has changed the concentrations and spatial distribution of aerosols, thereby modifying the properties of clouds and fluxes of radiation (Szopa et al., 2021). The radiative forcing associated with anthropogenic aerosols over the industrial era is estimated to be negative on the global scale (thus partially counteracting the warming due to greenhouse gases), but there is considerable uncertainty. The latest Intergovernmental Panel on Climate Change (IPCC) assessment report (Forster et al., 2021, AR6) estimates an effective radiative forcing of -1.3 W m^{-2} due to aerosol changes with an uncertainty range between -2.0 and -0.6 W m^{-2} ; Bellouin et al. (2020) estimate a similar range between -2.0 and -0.4 W m^{-2} (for the same confidence interval). The uncertainty range increases when viewed on regional scales (Szopa et al., 2021).

An important source of this uncertainty is associated with the physiochemical properties of each aerosol species that define its ability to act as a CCN or INP. INPs are a relatively rare subset of aerosols in the atmosphere (Murray et al., 2012; Kanji et al., 2017), yet they can have substantial impacts on cloud radiative properties over widespread regions (e.g., Murray et al., 2021; Vergara-Temprado et al., 2018; Hawker et al., 2021; Liu et al., 2012; Shi and Liu, 2019; Huang et al., 2025). Our current understanding from laboratory and modelling studies demonstrates that there are likely key aerosol species that drive the global distribution of INP availability. This includes mineral dust, organically enriched sea spray aerosol, primary biological aerosol particles (PBAPs; including pollen, fungal spores and bacteria), volcanic ash, and carbonaceous aerosol (Murray et al., 2012; Kanji et al., 2017; Hoose and Möhler, 2012). Due to the short-lived nature of these aerosol species and spatially and temporally variable emission fluxes, it is necessary to use global climate models to quantify the role of aerosols and INPs in the climate.

In situ INP observations are vital for testing the representation of INPs in global models. These are used to evaluate the model and identify biases in aerosol distributions and/or their ice-nucleating activity. For example, Chatziparaschos et al.



(2025) used the BACCHUS (Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic Under Standing) global INP observational dataset to evaluate their INP model and found evidence that PBAPs may play a more important role than previously thought. Herbert et al. (2025) used an alternative collection of observations to evaluate their INP model and identified a potential missing INP source from biogenic material associated with dust.

These datasets provide unequivocally important observational constraints, but have associated limitations. INP measurements have been made using a wide variety of instruments and methods, each with their own uncertainties and biases. This is well demonstrated by intercomparison studies for ambient air samples (DeMott et al., 2025; Lacher et al., 2024) and in laboratory based studies (DeMott et al., 2018; Wex et al., 2015; Hiranuma et al., 2015, 2019) that regularly report a variation of around an order of magnitude (or more) in measured INP concentrations. Field campaigns are also often restricted in the duration and temporal resolution of INP measurements, either due to methodological constraints (e.g., filter samples taken on daily timescales) or physical constraints (e.g., 2 h time series taken during a daytime research flight). In addition, in many campaigns, the duration of the deployment is typically on the order of days to weeks. This restricts model evaluation to daily or monthly mean comparisons, which is likely an inadequate test for a variable that is known to vary by several orders of magnitude during a single diurnal cycle (e.g., Canzi et al., 2025, Fig. 5a).

Recently, instruments for automated and continuous operation have been developed, including the Continuous Flow Diffusion Chamber - Ice Activation Spectrometer (CFDC-IAS; Bi et al., 2019), the automated Horizontal Ice Nucleation Chamber (HINC-Auto; Brunner and Kanji, 2021), and the Portable Ice Nucleation Experiment chamber (PINE; Möhler et al., 2021). These build upon previous instruments designed to make online in-situ measurements (e.g., Rogers et al., 2001; Kanji and Abbatt, 2009; Stetzer et al., 2008) with the additional capability of operating autonomously on long time scales (months to years) at relatively high temporal resolution (< 15 min).

In this study, we present a new INP measurement dataset designed for model evaluation using one of these new instruments. We collate ground-based INP measurements made using PINE instruments that reproduce mixed-phase cloud conditions from 20 recent field campaigns, providing over 400,000 individual measurements sampled over 70,000 hours. The measurements span a range of concentrations from less than 0.01 L^{-1} to more than 1000 L^{-1} and temperatures between 240 K and 263 K. We subset these PINE measurements into regular 6 h time intervals (consistent with synoptic scale changes in meteorology) and 2 K temperature bins to provide a model-ready dataset. The new dataset includes around 36,000 INP measurements above the lower limit of measurable concentration (non-zero) from across the Northern Hemisphere, with a mean campaign duration of 172 days (ranging from 16 to 804 days). In Section 2 we provide a brief description of the PINE instrument and relevant information for each of the 20 field campaigns. In Section 3, we describe and demonstrate the methodology for subsetting and averaging each time series. In Section 4, we introduce the PINE INP dataset and provide an outline of the data format and public access, and in Section 5 we conclude the study.

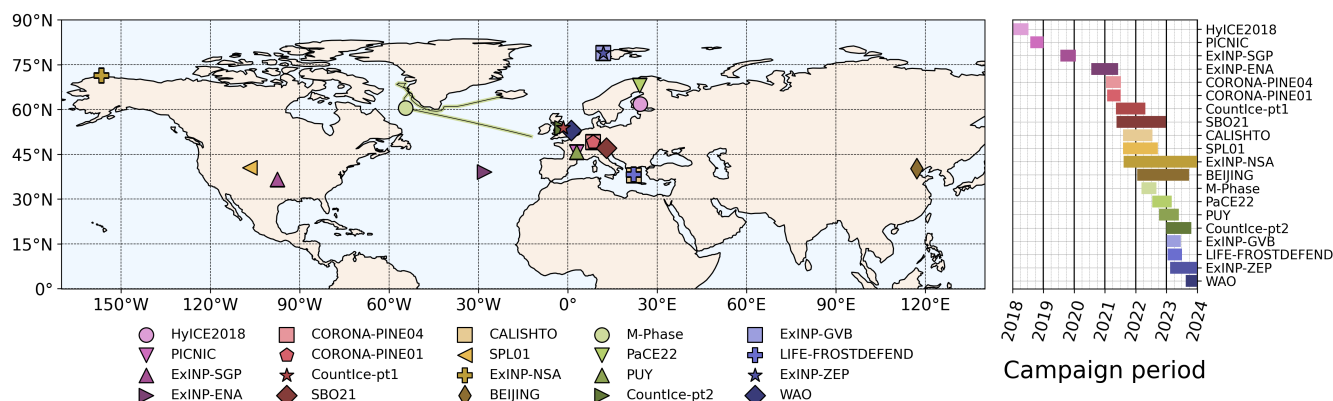


Figure 1. Location and duration of the PINE campaigns included in this dataset. All campaigns remained at the same location for the duration except for M-Phase, which was onboard a research ship. The ship trajectory (green line in the North Atlantic) is shown for the period when PINE measurements were being made.

70 2 PINE measurements

2.1 The PINE instrument

The mobile PINE cloud simulation chamber, described in full by Möhler et al. (2021), was designed to reproduce the conditions of an ascending air parcel cooling adiabatically. This is achieved through expansion cooling of a chamber using a mechanical pump thus reducing pressure, reducing temperature, and increasing relative humidity. The temperature of the walls of the chamber is controlled by a cooling system that is used to set the starting temperature of the chamber walls and thus the air temperature within the chamber (to a minimum of about 213 K) prior to expansion. Each PINE run includes three stages or modes: flush, expansion, and refill. In the flush mode, ambient air is drawn through the vessel at a flow rate around 2 L min^{-1} . In the expansion mode, the inlet valve to the chamber is closed and the air flow bypasses the chamber at a rate of 3 to 4 L min^{-1} . Note that all flows and concentrations reported are at standard temperature and pressure. The expansion flow acts to reduce the temperature inside the chamber and increase relative humidity and continues to a predefined minimum pressure. The instrument is capable of reproducing conditions appropriate for homogeneous freezing and heterogeneous freezing through immersion, pore-condensation, and deposition modes. In this dataset, we focus on freezing via the immersion mode, which is the dominant pathway for primary ice production in mixed-phase clouds (Murray et al., 2012; de Boer et al., 2010; Westbrook and Illingworth, 2013). Aerosols in the chamber can activate to cloud droplets once water saturation is exceeded, after which the droplets may freeze heterogeneously upon INPs present in the chamber. The particle size distribution (both liquid and ice) is measured with an optical particle counter (OPC) positioned downstream of the chamber in the pump line establishing the expansion flow. The PINE-01-A instrument uses a Palas GmbH welas 2500 OPC sensor, whilst all other instruments use a Palas GmbH fidas-pine OPC (see Table 1 for a list of instruments used in each campaign). Ice crystals are optically larger than cloud droplets and are distinguished using a size threshold that is determined by post-processing software (see Sect. 2.3). In



the refill mode, the chamber is re-pressurized to the starting pressure at a controlled rate. The total time for each run is around 5 to 15 min and primarily determined by the time for the flush mode.

The temperature dependence of INP concentrations is measured by changing the wall temperature of PINE, controlled by the cooling system. In this study, typical temperature scans are performed between 240 K and 263 K. Post-processing software is used to extract INP concentrations and associated temperatures during each run and is discussed further in Sect. 2.3. Möhler et al. (2021) estimate a temperature uncertainty of ± 1 K, primarily due to the inhomogeneous temperature distribution within the chamber. The uncertainty in ice crystal number concentration is dependent on the OPC. For the PINE-01-A instrument using the welas OPC, Möhler et al. (2021) estimate a conservative value of ± 20 %; for all other instruments that use the fidas-pine OPC, Böhmländer et al. (2025) estimate a conservative value of ± 10 %. In our dataset, we use counting statistics that can be used to flag the most uncertain data. This is discussed further in Sect. 3. Möhler et al. (2021) assessed the aerosol loss rate between air inlet and introduction to the PINE chamber and reported a loss of less than 20 % of particles with diameter $D < 2 \mu\text{m}$ and about 50 % for $D = 4 \mu\text{m}$. Knopf et al. (2021) and Wilbourn et al. (2024) also evaluated the loss rate in PINE during two field campaigns and report losses of 50 % at $D = 9.4 \mu\text{m}$ and $D = 8.0 \mu\text{m}$. Adams (2020, Fig. 24) assessed the transmission efficiency of size-resolved ambient air samples during the HyICE-2018 campaign (Vogel et al., 2024; Brasseur et al., 2022) and report a drop in efficiency for $D > 5 \mu\text{m}$. This upper size limit will not greatly affect the measured INP concentration, but will have implications for reproducing the INP measurements from modelling studies. Following Adams (2020), we recommend that the upper size limit of $D = 5 \mu\text{m}$ is applied to simulated aerosol size distributions when comparing to the measured INP concentrations. We plan to assess the impact of this upper limit on modeled INP concentrations in a follow-up study.

2.2 Campaigns

In this dataset, we collate INP measurements made with PINE instruments from 20 campaigns that took place between 2018 and 2024. The locations and durations of the campaigns are shown in Fig. 1 and details of the campaigns and instruments are presented in Table 1. The campaigns include locations in the Arctic, Europe, North America, the North Atlantic Ocean, and East Asia. These locations are influenced by a range of important INP sources including arid environments (Central Africa, the Middle East, and Central Asia), marine environments, remote regions (the Arctic), and biologically rich environments (Europe and North America). The collated datasets provide INP concentrations on monthly, seasonal, and annual timescales. The shortest campaign duration is 16 days, the longest is 804 days, and the mean is 172 days. A brief characterization of each campaign is provided below.

HyICE-2018: INP measurements were conducted at the SMEAR II (Station for Measuring Ecosystem-Atmosphere Relations) station (Hari and Kulmala, 2005) located in the boreal forest in Hyytiälä, Finland. Aerosols were sampled through a heated total aerosol inlet 6 m above ground level. PINE was set to the following operation parameters: (1) Flush at 3 L min^{-1} for 4 min, (2) Expansion at 4 L min^{-1} to 700 mbar, (3) Refill at 3 L min^{-1} . More details on the campaign can be found in Brasseur et al. (2022) and Vogel et al. (2024).



PICNIC: INP measurements were conducted at the Site d’Observations Atmosphériques Puy de Dôme, a mountain-top site in France. It is an observational facility of the ACTRIS (Aerosol, Clouds, and Trace Gases Research Infrastructure) and the
 125 Global Atmosphere Watch (GAW) measurement programs. Sampling was performed via a heated whole-air inlet situated 2 m above the laboratory roof. PINE measurements were conducted with the following program: (1) Flush for 5 min at 2 L min⁻¹, (2) Expansion at 3 L min⁻¹ to 650 mbar (ambient pressure 850 mbar), (3) Refill at 2 L min⁻¹. More details on the campaign can be found in Lacher et al. (2024).

ExINP-SGP: PINE measurements were made at the US Department of Energy (DOE) Southern Great Plains (SGP) Atmospheric
 130 Radiation Measurement (ARM) site in Oklahoma, US. The site is surrounded by farmland. The PINE instrument was housed within the Guest User Facility, with ambient air sampled through a 0.15 m diameter quasi-laminar sampling inlet with a total suspended particulate (TSP) sampling head at 5.5 m above the ground. The measurement program was the following: (1) Flush for 5 min at 2 L min⁻¹, (2) Expansion at 3 L min⁻¹ to 750 mbar, (3) Refill at 2 L min⁻¹ to ambient pressure. More details on this campaign can be found in Wilbourn et al. (2024).

ExINP-ENA: PINE measurements were made at the US DOE Eastern North Atlantic (ENA) ARM site on Graciosa Island, Azores. The PINE instrument was housed in an air-conditioned container on the site, with ambient air sampled through a 0.1 m diameter quasi-laminar sampling inlet with a TSP sampling head at 5.5 m above the ground. The measurement program was the following: (1) Flush for 10 min at 2 L min⁻¹, (2) Expansion at 3 L min⁻¹ to 800 mbar, (3) Refill at 2 L min⁻¹ to ambient pressure. More details on this campaign can be found in Wilbourn et al. (2024).
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CORONA-PINE04 and CORONA-PINE01: The CORONA campaign was conducted at the AIDA (Aerosol Interaction and Dynamics in the Atmosphere) facility at the Karlsruhe Institute of Technology (KIT), Campus North in Germany. PINE was installed at a PM₁₀ non-heated aerosol inlet, as icing during winter was not expected. The inlet was installed 1 m above the laboratory roof and 9 m above ground. INP measurements were alternately conducted with the PINE models PINE-01-A and PINE-04-01. The measurement program was the following: (1) Flush for 3 min (PINE-1A) or 4 min (PINE-04) at 2 L min⁻¹,
 145 (2) Expansion at 3 L min⁻¹ to 820 mbar, (3) Refill at 2 L min⁻¹. The datasets are published (Lacher, 2025a; Vogel, 2025a), but no accompanying papers are available.

CountIce-pt1 and CountIce-pt2: PINE measurements were made within the Leeds IcePod mobile laboratory (O’Sullivan et al., 2018) located on the University of Leeds campus, UK. The site was characterized as an urban environment with low-rise buildings. Ambient air was sampled through a heated TSP sampling head (DTSP03/00/16, Digitel, Switzerland) on a 2 m
 150 sampling tube. A flow splitter was used to direct part of the air flow into PINE. Each expansion was operated with the following program: (1) Flush for 5 min at 2 L min⁻¹, (2) Expansion at 3 L min⁻¹ down to 840 mbar, (3) Refill at 2 L min⁻¹. A year gap between the two campaigns occurred due to the deployment of the PINE instrument on the M-Phase campaign. The datasets are published (Tarn and Murray, 2025a, b), but no accompanying papers are available.

SBO21: PINE measurements were made at the Sonnblick Observatory (SBO), which is located in Austria on the summit
 155 of the mount “Hoher Sonnblick”. Ambient air was sampled through a heated total aerosol inlet designed according to GAW guidelines, with an upper cut-off size of 20 μm at a wind speed of 20 m s⁻¹. The inlet was located at the rooftop of the station.



Each expansion in PINE was operated with the following program: (1) Flush for 4 min at 1.5 L min^{-1} , (2) Expansion at 3 L min^{-1} down to 575–600 mbar, (3) Refill at 1.5 L min^{-1} . More information can be found in Bogert (2024).

SPL01: PINE measured INP concentrations at Storm Peak Laboratory, a mountain-top site in the Rocky Mountains (Hallar et al., 2025), US. The site is operated by the University of Utah and supported by the National Science Foundation (NSF). The instrument was connected to one of the facility's heated inlets, (Petersen et al., 2019) with the following measurement program: (1) Flush for 5 min at 1 L min^{-1} , (2) Expansion at 3 L min^{-1} to 530 mbar (ambient pressure 685 mbar), (3) Refill at 1 L min^{-1} . The dataset is published (Lacher, 2025b), but no accompanying paper is available.

CALISHTO: INP measurements were performed at the (HAC)² (Helmos Hellenic Atmospheric Aerosol and Climate Change) station at the top of Mount Helmos, Greece. Sampling was performed through an omnidirectional total inlet installed on the rooftop of the observatory. PINE was operated with the following program: (1) Flush for 5 min at 1 L min^{-1} , (2) Expansion at 3 L min^{-1} to 650 mbar, (3) Refill at 1 L min^{-1} . Information on the measurement campaign can be found in Gao et al. (2025).

ExINP-NSA: PINE measurements were made at the Barrow Atmospheric Baseline Observatory, next to the US DOE North Slope of Alaska (NSA) ARM site, located close to the town of Utqiagvik, Alaska. The PINE instrument was located inside the observatory and sampled ambient air through stainless steel sampling pickup inlets (19 mm diameter) connected to a polyvinyl chloride vertical sampling stack (0.1 m diameter) 12 m above the ground. A 9.5 mm conductive tube bridged the pickup port to the instruments in the observatory. The measurement program was the following: (1) Flush for 10 min at 2 L min^{-1} , (2) Expansion at 3 L min^{-1} to 800 mbar, (3) Refill at 2 L min^{-1} to ambient pressure. More information can be found in Pantoya et al. (2025).

BEIJING. INP measurements were made at the Beijing Cloud Laboratory and Observational Utilities Deployment Base (CLOUD Base, CB). The site is located in Pinggu District, Beijing, China, and is situated on a plain surrounded by farmland and low-rise buildings. The instrument was installed at a PM_{10} non-heated aerosol inlet as icing was not expected during winter. The inlet was installed 1 m above the laboratory roof and 12 m above ground. The measurement program was the following: (1) Flush for 3 min at 1.5 L min^{-1} , (2) Expansion at 3 L min^{-1} to 850 mbar, (3) Refill at 1.5 L min^{-1} . Note that measurements below the lower limit of measurable concentration (see Sect. 3) were not included in the Level 1 data for this campaign; therefore, we omit all data above a temperature threshold of 252.15 K. This removes expansions within a temperature regime where we would expect to encounter low concentrations with poor counting statistics (see Fig. 5). The dataset is published (Herbert, 2025), but no accompanying paper is available.

M-Phase: PINE measurements were made within the Leeds IcePod mobile laboratory (O'Sullivan et al., 2018) onboard the RRS Discovery during the joint M-Phase/SEANA research cruise in the Labrador Sea. The IcePod was located on the foredeck, forward of the ship stack. Ambient air was sampled through a heated TSP sampling head (DTSP03/00/16, Digitel, Switzerland) on a 2 m sampling tube. A flow splitter was used to direct part of the air flow into PINE. Each expansion was operated with the following program: (1) Flush for 5 min at 2 L min^{-1} , (2) Expansion at 3 L min^{-1} down to 840 mbar, (3) Refill at 2 L min^{-1} . The dataset is published (Tarn et al., 2025), but no accompanying paper is available.



PaCE22: PINE measurements were conducted at the Pallas Sammallunturi station in northern Finland around 170 km north of the Arctic Circle, representing sub-Arctic conditions. The site is within the Pallas-Yllästunturi National Park on top of a hill above the boreal forest tree line. PINE was connected to the heated whole air inlet of the station. Each expansion was operated with the following program: (1) Flush for 4 min at 1 L min⁻¹, (2) Expansion at 3 L min⁻¹ from around 950 mbar to 800 mbar, (3) Refill at 1 L min⁻¹. An overview of the PaCE22 (Pallas Cloud Experiment 2022) campaign is given by Brus et al. (2025), whilst more information on the PINE measurements can be found in Böhmländer et al. (2025).

PUY: PINE measurements were made at the Puy de Dôme station, located at the highest point of the Chaîne des Puys, a volcanic mountain range in central France. PINE was connected to the whole air inlet of the station (50% loss of particles at 30 µm). Ambient aerosol particles sampled through the inlet are passively dried to approximately 40% relative humidity with respect to water (RH_w) before being sampled by the instrument. Each expansion was operated with the following program: (1) Flush for 7.5 min at 2 L min⁻¹, (2) Expansion at 3 L min⁻¹ from around 850 mbar to 700 mbar, (3) Refill at 2 L min⁻¹. More information on this campaign can be found in Canzi et al. (2025).

ExINP-GVB: INP concentration measurements during this campaign were performed at Gruebadet Atmosphere Laboratory in the high Arctic, in close proximity of the Ny-Alesund Research Station (Lupi et al., 2016) on Svalbard. PINE was attached to the heated whole air inlet and the following measurement program was used: (1) Flush for 5 min at 2 L min⁻¹, (2) Expansion at 3 L min⁻¹ from around 1000 mbar to 850 mbar, (3) Refill at 2 L min⁻¹. The dataset is published (Böhmländer, 2023), but no accompanying paper is available.

LIFE-FROSTDEFEND: INP measurements during the LIFE-FROSTDEFEND campaign were conducted in a mobile container, placed in a lemon orchard near Aigio, Greece. Aerosol sampling was performed via a PM₁₀ inlet, about 1 m above the container roof. PINE was operated with the following program: (1) Flush for 4 min at 1 L min⁻¹, (2) Expansion with 3 L min⁻¹ to 880 mbar, (3) Refill at 1 L min⁻¹. The dataset is published (Vogel, 2025b), but no accompanying paper is available.

ExINP-ZEP: PINE measurements were performed at the Zeppelin observatory at Mt. Zeppelin (Platt et al., 2022), located in the high Arctic on Svalbard. The station is located south of Ny-Alesund Research Station, however, due to frequent temperature inversions the site is typically shielded from anthropogenic emission from the village. PINE was connected to a ground-based counterflow virtual impactor for measurements of cloud residuals, and a heated whole air inlet (see Karlsson et al. (2021) for more details). In this study we only present measurements from the whole air inlet. The following program was used: (1) Flush for 5 min at 2 L min⁻¹, (2) Expansion at 3 L min⁻¹ from around 930 mbar to 790 mbar, (3) Refill at 2 L min⁻¹. The dataset is published (Böhmländer, 2025), but no accompanying paper is available.

WAO: PINE measurements were made within the Leeds IcePod mobile laboratory (O'Sullivan et al., 2018) located at the Weybourne Atmospheric Observatory (WAO), a GAW Regional station on the Norfolk coast of the UK. Ambient air was sampled through a heated TSP sampling head (DTSP03/00/16, Digitel, Switzerland) on a 2 m sampling tube. A flow splitter was used to direct part of the air flow into PINE. Each expansion was operated with the following program: (1) Flush for 5 min at 2 L min⁻¹, (2) Expansion at 3 L min⁻¹ down to 840 mbar, (3) Refill at 2 L min⁻¹. The dataset is published (Herbert, 2025), but no accompanying paper is available.



Table 1. Details of PINE measurement campaigns collated in this dataset. The location is provided in decimal degrees, altitude in m above sea level, and dates in the format dd-mm-yy.

Name of campaign	Location	Altitude	Dates	Software	Instrument
HyICE-2018	Hyytiälä, Finland (61.85 °N, 24.29 °E)	118 m	22-03-18 – 29-04-18	PIA 2.0.0	PINE-01-A
PICNIC	Puy de Dôme, France (45.77 °N, 2.96 °E)	1465 m	09-10-18 – 25-10-18	PIA 2.0.0	PINE-01-A
ExINP-SGP	SGP site OK, US (36.61 °N, -97.49 °E)	314 m	01-10-19 – 14-11-19	WTAMU	PINE-03
ExINP-ENA	Graciosa, Azores (39.09 °N, -28.03 °E)	30 m	01-10-20 – 28-03-21	WTAMU	PINE-03
CORONA-PINE04	Karlsruhe, Germany (49.10 °N, 8.43 °E)	114 m	25-03-21 – 02-05-21	PIA 2.1.0	PINE-04-01
CORONA-PINE01	Karlsruhe, Germany (49.10 °N, 8.43 °E)	114 m	09-04-21 – 29-04-21	PIA 2.1.0	PINE-01-A
CountIce-pt1	Leeds, UK (53.81 °N, -1.56 °E)	66 m	20-07-21 – 15-10-22	PIA 2.0.2	PINE-04-03
SBO21	Sonnblick Observatory, Austria (47.05 °N, 12.96 °E)	3106 m	28-07-21 – 15-10-22	PIA 2.1.0	PINE-04-02
SPL01	Storm Peak CO, US (40.46 °N, -106.74 °E)	3220 m	12-10-21 – 12-07-22	PIA 2022	PINE-01-A
CALISHTO	Helmos, Greece (37.9 °N, 22.2 °E)	2314 m	12-10-21 – 08-05-22	PIA 2.1.0	PINE-04-01
ExINP-NSA	North Slope, Alaska, US (71.32 °N, -156.62 °E)	8 m	19-10-21 – 01-01-24	WTAMU	PINE-03
BEIJING	Beijing CLOUD Base, China (40.17 °N, 117.12 °E)	100 m	28-03-22 – 17-07-23	PIA 1.0.1	PINE-05-03
M-Phase	Labrador Sea (various locations)	7 m	19-05-22 – 25-06-22	PIA 2.0.2	PINE-04-03
PaCE22	Pallas Sammaltunturi station, Finland (67.97 °N, 24.12 °E)	565 m	23-09-22 – 23-12-22	PIA 2.0.2	PINE-04-01
PUY	Puy de Dôme, France (45.77 °N, 2.96 °E)	1465 m	15-12-22 – 19-03-23	PIA 1.0.1	PINE-05-01
CountIce-pt2	Leeds, UK (53.81 °N, -1.56 °E)	66 m	09-03-23 – 15-08-23	PIA 2.0.2	PINE-04-03
ExINP-GVB	Gruvebadet, Svalbard (78.92 °N, 11.93 °E)	67 m	15-03-23 – 10-04-23	PIA 2.0.2	PINE-04-02
LIFE-FROSTDEFEND	Aigio, Greece (38.23 °N, 22.13 °E)	20 m	27-03-23 – 24-04-23	PIA 2.1.0	PINE-05-02
ExINP-ZEP	Zeppelin, Svalbard (78.9 °N, 11.88 °E)	474 m	26-04-23 – 23-10-23	PIA 2.0.2	PINE-04-02
WAO	Weybourne, UK (52.95 °N, 1.12 °E)	17 m	27-10-23 – 01-01-24	PIA 2.0.2	PINE-04-03

2.3 PINE analysis software

Post-processing software is used to convert the raw Level 0 data from each PINE run into relevant Level 1 data. The key information taken from the Level 0 data includes the minimum temperature during the expansion and the particle size distribution measured by the OPC, which the software uses to establish a size threshold that separates the smaller liquid droplets from the larger ice particles. With this threshold, an ice number concentration can be determined. The key Level 1 variables that are relevant for this dataset are the expansion time (UTC), the minimum temperature, and the number concentration of activated INPs per litre of sampled air under standard conditions (273.15 K and 1013.25 hPa). Seventeen of the campaign datasets (Table 1) use the publicly available PINE INP Analysis software (PIA Büttner and Fösig, 2025) developed at KIT and three use a variation developed by WTAMU, which differs in how the size threshold is determined: in the PIA software, the threshold is determined for each PINE expansion (each run), and in the WTAMU software, a single threshold is determined over an 'operation period' which may include anywhere between one run and more than 100 runs (Wilbourn et al., 2024, Sect. S8).



Both software packages include automatic quality control to flag the data, which is used by each campaign team to remove poor quality data. For some campaigns, upper or lower temperature ranges were used to manually flag data from temperature regimes that are deemed uncertain. In this dataset, we have removed all Level 1 flagged data.

3 Data subsetting

In our dataset, we subset the time series Level 1 data from each campaign (e.g., Fig. 2a) into regular 6 h intervals (daily 00, 06, 12, 18, 24 UTC) and 2 K temperature bins (e.g., Fig. 2b). We provide time series of the mean measured INP concentration from the subset data ($N_{\text{INP},ss}$, where ss denotes subset) and the associated mean minimum temperature measured during the subset of PINE expansions ($T_{\text{min},ss}$). We averaged the data for two reasons. The lowest measurable concentration in PINE during a single expansion is implicitly one ice crystal ($N_{\text{ice}} = 1$) per sampled volume (approximately 2 L); this corresponds to a lower limit of the measurable INP concentration ($\text{lim}N_{\text{INP}}$). In order to improve counting statistics and reduce $\text{lim}N_{\text{INP}}$, we use data collected from multiple expansions to increase the total volume of air that is being sampled and the statistical likelihood of measuring an ice crystal. $\text{lim}N_{\text{INP}}$ is inversely scaled with the number of expansions that are included in the subset of data, as demonstrated in Fig. 2. In this example, the Level 1 data for the ExINP-GVB campaign has a lower measurable concentration of $\text{lim}N_{\text{INP}} \approx 0.5 \text{ L}^{-1}$ (Fig. 2a) and includes many expansions below this value (shown as zero counts), whilst the lowest concentration from the subset data, $\text{lim}N_{\text{INP},ss}$ (Fig. 2b), is now regularly lower than the Level 1 limit, providing additional data primarily at higher freezing temperatures where INPs are rarer. The number of zero counts has been reduced from 639 in the Level 1 data to 10 in the subset data, which demonstrates how the zero counts can still provide useful information. Subsetting into regular time intervals also makes the dataset easy to apply to simulation studies, meteorological reanalysis products, and back-trajectory analyses. Global simulation studies generally restrict the frequency of output to synoptic timescales, which will range from hours to days. Similarly, reanalysis products such as ERA5 (Hersbach et al., 2020) and MERRA2 (Gelaro et al., 2017) are available at regular intervals. Back-trajectory analysis packages, such as HYSPLIT (Stein et al., 2015) and FLEXPART (Bakels et al., 2024) can be driven by reanalysis products. A time period of 6 h was chosen to maximize the number of expansions within the interval, whilst maintaining a time scale that is appropriate for synoptic scale meteorology and the applications discussed above. The subsetting method applied to the Level 1 data from the 20 campaigns takes N_{INP} measurements from 423,678 expansions (367,487 at or above $\text{lim}N_{\text{INP}}$) and results in 35,997 non-zero $N_{\text{INP},ss}$ measurements in the dataset.

Some portions of the data sets suffer from poor counting statistics, hence for each collection of subset data we determine a coefficient of variation, $\text{CV}_{ss} = \sigma_{N_{\text{ice},ss}} / \mu_{N_{\text{ice},ss}}$, where σ and μ are the standard deviation and mean of $N_{\text{ice},ss}$, the total number of ice crystals measured in the subset of expansions. The particle detections will follow a Poisson distribution, and thus the equation can be written as $\text{CV}_{ss} = 1 / (\sqrt{N_{\text{ice},ss}})$. $N_{\text{ice},ss}$ is calculated from N_{INP} using $\text{lim}N_{\text{INP}}$ from the the Level 1 data (see Fig. 2a), which corresponds to the situation when $N_{\text{ice}} = 1$ in the PINE instrument. $\text{lim}N_{\text{INP}}$ is a function of the PINE instrument setup and may vary during the campaign duration; therefore, a 3 d moving time window is applied to the Level 1 data to allow small variations throughout the time series of each campaign. N_{ice} as a function of time (t) for each expansion is

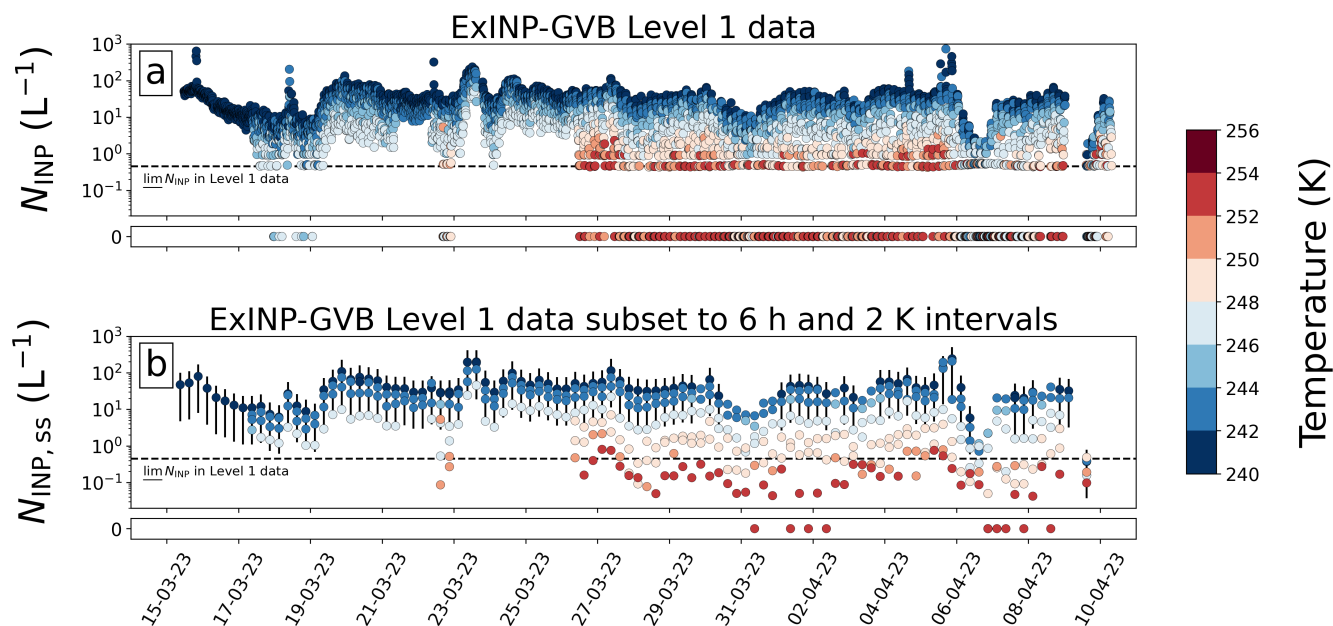


Figure 2. Time series of INP measurements from the ExINP-GVB campaign demonstrating the subsetting method. Panel (a) shows the Level 1 N_{INP} time series as a function of temperature (colors), with each marker showing the measurements from a single PINE expansion. Concentrations are per standard liter of measured air at 273.15 K and 1013.25 hPa. Expansions where N_{INP} is below $\lim N_{\text{INP}}$ (shown as the grey dashed line) are shown at the bottom of the panel. Panel (b) shows $N_{\text{INP,ss}}$ averaged over intervals of 6 h and 2 K and includes $\lim N_{\text{INP}}$ from the Level 1 data. Intervals where $N_{\text{INP,ss}} = 0$ are shown at the bottom of the panel. Error bars due to the uncertainty in the OPC (see Sect. 2.1) are included in panel (b) for data points below 240 K as an example.

calculated as $N_{\text{ice}}(t) = N_{\text{INP}}(t) / \lim N_{\text{INP}}(t)$ and summed for all expansions in the subset interval to give $N_{\text{ice,ss}}$. The value of CV_{ss} can be used along with a threshold value to statistically remove uncertain data. Figure 3 demonstrates the sensitivity of the threshold on the percentage of subset data that would be removed from each campaign.

4 The GloPINE INP dataset

In this section, we present an overview of the new GloPINE INP dataset (without application of a CV_{ss} threshold). Figure 4 shows the distributions of $T_{\text{min,ss}}$ for each PINE campaign in the dataset. There is a good coverage of freezing temperatures, ranging from 240 to 263 K. Some campaigns, such as BEIJING and ExINP-SGP, have a consistent and wide-ranging distribution of $T_{\text{min,ss}}$, while others, such as M-Phase and CALISHTO, have measurements weighted towards a smaller range of $T_{\text{min,ss}}$. This reflects the sampling method chosen by each team. Keeping the temperature relatively constant (see the initial period in Fig. 2a) provides a higher number of expansions to combine in the time interval, which increases the sensitivity of the measurements (see Sect. 3). This is a good method for measuring N_{INP} close to $\lim N_{\text{INP}}$. However, cycling through different

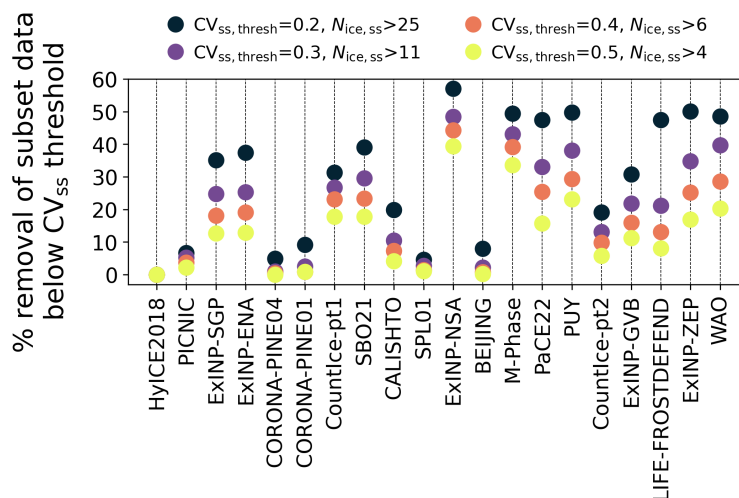


Figure 3. Figure demonstrating the application of different threshold CV_{ss} values (0.2, 0.3, 0.4, and 0.5) to the subset $N_{INP,ss}$ measurements in each campaign. Each threshold CV_{ss} value has a corresponding threshold of $N_{ice,ss}$ shown in the legend.

temperatures (see the latter period in Fig. 2a) provides a more complete picture of the INP spectrum, although without the increase in sensitivity. This method may be particularly advantageous when INP sources or concentrations are likely to vary on short timescales, such as in dust or biomass burning plumes. Figure 4 also shows the number of $N_{INP,ss}$ measurements from each campaign within the INP dataset, which totals 35,997 non-zero measurements. For comparison, Herbert et al. (2025) and Chatziparaschos et al. (2025) recently evaluated their global INP models with datasets that include 1000s of immersion-mode INP measurements.

Figure 5 shows the distributions and medians of non-zero $N_{INP,ss}$ as a function of temperature and campaign. $N_{INP,ss}$ measurements span a range from less than 0.01 L^{-1} to over 1000 L^{-1} over a temperature range from 240 to 263 K. Higher concentrations are observed at lower temperatures for all campaigns, and there is considerable variability between each location, with medians spanning two orders of magnitude at most temperatures. The highest $N_{INP,ss}$ measurements were observed in the BEIJING campaign, and the lowest are commonly observed in high-latitude environments, such as PaCE22 (northern Finland) and ExINP-ZEP (Svalbard). The PINE INP dataset provides a diverse range of $N_{INP,ss}$ measurements and is consistent with the spatial variability of INP sources and concentrations within the northern hemisphere (e.g., Kanji et al., 2017).

4.1 GloPINE dataset format

The GloPINE dataset (Herbert, 2025) is provided as individual NetCDF4 (.nc) files corresponding to each campaign. This permits the addition of further campaigns in the future. The file attributes are the campaign name, the PINE instrument used

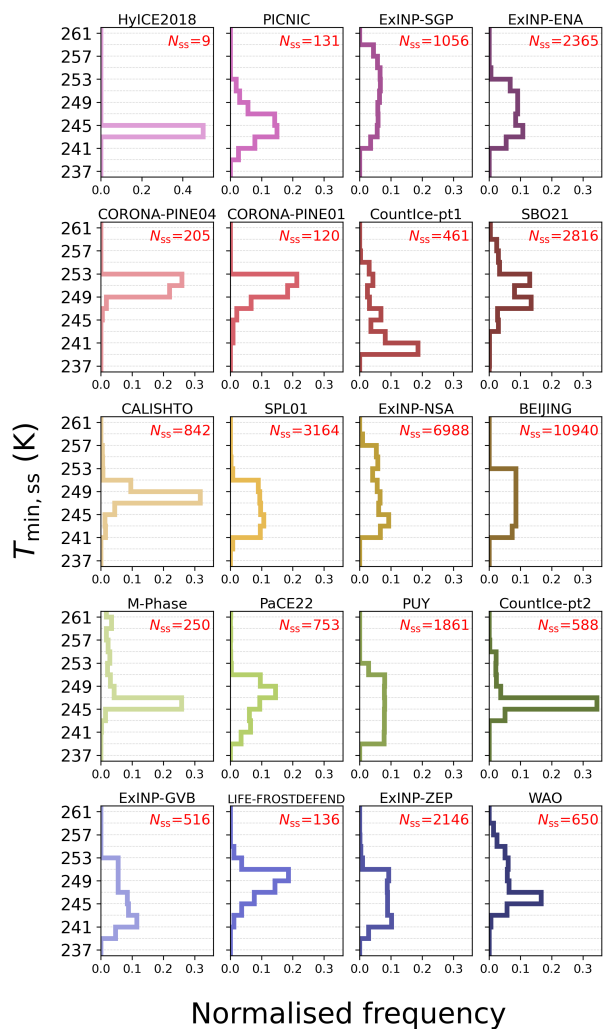


Figure 4. Normalized frequency distribution of temperatures from the 6 h subset data for each campaign. The number of non-zero $N_{INP,ss}$ measurements from each campaign in the dataset (N_{ss}) is shown in the top right corner of each plot. All campaigns use the same range on the x-axis except for HyICE2018.

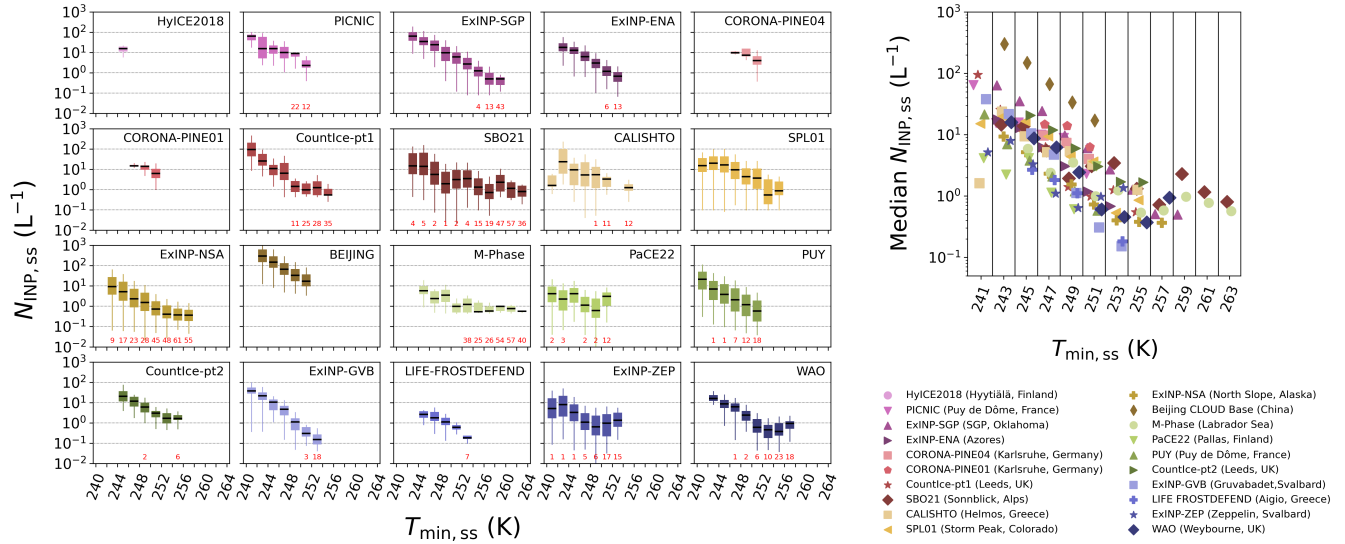


Figure 5. Distribution of non-zero $N_{\text{INP},ss}$ measurements as a function of $T_{\text{min},ss}$ from the 6 h subset data for each campaign in the dataset. Concentrations are per standard liter of sampled air at 273.15 K and 1013.25 hPa. The distributions are presented as box plots: the black line shows the median, the bar shows the inter-quartile range, and the whiskers extend to the farthest data point lying within 150 % of the inter-quartile range. The red figure below each bar is the percentage of subset data where $N_{\text{INP},ss} < \lim N_{\text{INP},ss}$. The larger plot on the right shows the median values of $N_{\text{INP},ss}$ as a function of $T_{\text{min},ss}$. The different colored symbols correspond to each campaign; symbols are offset in each temperature bin for clarity.

to make the measurements, and the duration of the campaign. Each variable is suffixed with "6h" or "6h2K" to denote the subsetting interval in time or time/temperature. The variables included in each file are:

- **latitude_6h**: mean latitude(s) of campaign (°N)
- **longitude_6h**: mean longitude(s) of campaign (°E)
- **altitude_6h**: mean altitude(s) of PINE inlet (m above sea level)
- **time_6h**: mean time of INP measurements in interval (fractional days since 1900-01-01)
- **INP_6h2K**: mean INP concentration in interval (m^{-3})
- **INP_uncertainty_6h2K**: mean INP concentration uncertainty in interval ($\pm \text{m}^{-3}$)
- **temperature_6h2K**: mean PINE minimum temperature in interval (K)
- **CV_6h2K**: coefficient of variability in interval, expressed as a decimal (-)



Note that concentrations of $N_{\text{INP,ss}}$ are converted from units of L^{-1} and provided in SI units of m^{-3} . Missing values are set to a value of -999 and represent binning intervals that did not include any PINE expansions. Values of zero in the variables **INP_6h2K** and **CV_6h2K** represent intervals when at least one PINE expansion was performed but no ice crystals were measured. All campaigns have geospatial variables (**latitude_6h**, **longitude_6h**, and **altitude_6h**) in dimensions of time. This permits a consistent format for campaigns that were either in a fixed location (e.g., ExINP-NSA) or a variable location (e.g., the M-Phase cruise campaign). For campaigns in a fixed location, the values are constant throughout the timeseries.

5 Data availability

The GloPINE INP dataset is publicly available at Zenodo under <https://doi.org/10.5281/zenodo.16745514> (Herbert, 2025). The repository contains the data as described in Sect. 4.1 with a summary overview of the dataset. We plan to continue building on this dataset by including new PINE measurement datasets when they become available. Table 2 provides access details to the Level 1 datasets collated in this study.

6 Code availability

The code used to take Level 1 data and subset into the Level 2 data is provided as a python script in the dataset repository. We also include a python script that provides examples of how to extract and use the Level 2 data.

7 Conclusions

Aerosols can influence the properties and evolution of mixed phase clouds by acting as INPs that facilitate the freezing of cloud droplets at supercooled temperatures as low as $\sim 235 \text{ K}$ (-38°C). INP measurements made under ambient conditions are necessary to constrain the representation of INPs and primary ice production in models and quantify the role of INPs in the climate system.

In this paper, we present GloPINE, a new INP measurement dataset that includes measurements made during 20 campaigns in the northern hemisphere, with plans to incorporate Southern Hemisphere campaigns in the future. All campaigns used PINE instruments to autonomously sample ambient air every 5 to 15 min over long periods of time (months to years) and over a wide range of temperatures (239 to 259 K). The collated PINE Level 1 data include measurements from $\sim 400,000$ expansions sampled over $\sim 70,000$ hours of operation. In the GloPINE dataset, we subset and average the Level 1 PINE data into 6 h time intervals and 2 K temperature intervals, resulting in $\sim 36,000$ INP measurements. Combining expansions within the intervals enhances the counting statistics and decreases the lower limit of measurable INP concentrations, primarily enhancing the number of non-zero INP measurements at relatively high freezing temperatures. All measurements include a coefficient of variability, based on counting statistics, which describes the associated uncertainty of the INP concentration. The GloPINE INP dataset is designed to be easily applied to modeling studies and other research that requires measurements made at regular time intervals, providing a means to robustly evaluate and constrain global models on a scale that has not previously been possible.



Table 2. Location of Level 1 data from each PINE measurement campaign collated in this dataset.

Name of campaign	Access location of Level 1 dataset
HyICE2018	doi: 10.5281/zenodo.10469663
PICNIC	doi: 10.35097/7gt99xqnh6k8sw42
ExINP-SGP	Access via http://www.arm.gov/research/campaigns/sgp2019exinpsgp
ExINP-ENA	Access via http://www.arm.gov/research/campaigns/ena2020exinpena
CORONA-PINE04	doi: 10.35097/j823gv823jbwy7b0
CORONA-PINE01	doi: 10.35097/m61r3c6tn0t3qk1y
CountIce-pt1	doi: 10.5281/zenodo.17451020
SBO21	doi: 10.35097/g828m8z2det94691, 10.35097/dxcsmnvfunkx76vx
SPL01	doi: 10.35097/rmfxfbr6jegua5cv
CALISHTO	doi: 10.35097/jxwbwycbyu64n2p0, 10.35097/4xawjaqwteyvx4fr
ExINP-NSA	Access via http://www.arm.gov/research/campaigns/nsa2021exinpnsa
BEIJING	doi: 10.5281/zenodo.16745514
M-Phase	doi: 10.5281/zenodo.17378346
PaCE22	doi: 10.5281/zenodo.13889647
PUY	https://www.opgc.fr/DOI/10.25519/sh8r-f866
CountIce-pt2	doi: 10.5281/zenodo.17451024
ExINP-GVB	doi: 10.35097/dc0vhg052pzx95wx
LIFE-FROSTDEFEND	doi: 10.35097/mdxcqd7p646cwc0u
ExINP-ZEP	doi: 10.35097/tdwrwzd5z7nakajv
WAO	doi: 10.5281/zenodo.16745514

A particular strength of this method is the use of a single instrument design and methodology, which removes the uncertainty that is usually introduced when combining measurements from different instruments and techniques. However, we note that there is inherent variability in the instrument versions (Sect. 2.1), the operation method for each campaign (Sect. 2.2), and the post-processing software used to produce the Level 1 data. Nonetheless, this is very likely to introduce considerably less uncertainty than between distinct instruments and methods. An important caveat to this rationale is that the dataset presented here is sensitive to instrument deficiencies associated with PINE that may introduce systematic biases. Schrod and Bingemer (2025) have recently shown that small temperature uncertainties can result in large discrepancies in the reported $N_{\text{INP}}(T)$ values. The authors identified the inhomogeneous distribution of temperature within the PINE chamber during expansion as a potentially important source of uncertainty. We aim to continue to build the PINE campaign database, and as such there is the possibility of updating previous entries in-line with new understanding or changes to the PIA software that act to reduce biases that may be discovered.



Author contributions. RJH, BJM, OM, NH, LL, AB, MDT, AC, AP, EF, KH, PB, CP and PT came up with the conceptual design of this dataset. LL, AB, MDT, AC, AP, EF, KH, PB, CP, PT, MA, SB, DB, NB, MD, KD, KE, GF, RF, DGG, MIG, AGH, RK, EL, MM, IBM, TK, JR, FV, PZ, NH, OM and BJM were involved in facilitating, obtaining, or analyzing the PINE data. RJH collated the datasets, wrote the code to subset the PINE data, and produced the GloPINE INP dataset. RJH prepared the original draft of the manuscript. All co-authors were involved in reviewing and editing the manuscript.

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