

## **Topical Centre for Cloud In Situ Measurements (CIS)**

### **Centre for Cloud Ice Nucleation (CCIce)**

#### **Measurement guidelines for ice-nucleating particle measurements**

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## 1. About this document

ACTRIS (Aerosol, Clouds and Trace gases Research Infrastructure) aims at generating high-class and quality-assured data by following harmonized and standardized operation procedures and fulfilling the FAIR (Findable, Accessible, Interoperable, Reusable) data principles. The data is generated by the National Facilities (NFs), while the quality control measures and tools are provided by the respective Central Facilities (CFs).

Within CIS, the Centre for Cloud Ice nucleation (CCIce) provides the service to measure ice nucleating particle number concentrations and ice nucleating particle temperature spectra for ACTRIS National Facilities.

This document describes the measurement guidelines and documentation needs for INP instruments, that are necessary to meet the ACTRIS QA/QC requirements and data inter-comparability amongst the NFs. In this way, it describes procedures such as checking the instrumental setup (e.g. leak tests), maintenance procedures (e.g. de-icing), background tests, and outlines standard procedures for experimental settings. Accordingly, this document serves as an addition to the existing instrument manuals.

The here described guidelines for sampling and measuring the CCIce variables are mandatory for observational platforms and the basis for the NF-specific Standard Operation Procedures (SOPs). ACTRIS exploratory platforms are expected to adhere to these requirements and guidelines as closely as possible, although specific platform characteristics may necessitate deviations. In this case, the PIs should contact the CCIce team to get support for developing customized measurement guidelines.

The technical requirements for new ACTRIS National Facilities (NFs), or for existing NFs upgrading to measure CCIce variables, are described separately (Höhler et al., 2026).

## 2. Measurement guidelines for online INP measurements

Instruments that provide near real-time information on the concentration of ice-nucleating particles (*INP<sub>cn</sub>*) in sampled air are referred to as online INP instruments. Those are stationed directly at the measuring site – usually in a dry indoor place – and sample ambient aerosol via exterior inlets and sample lines. As described in the document “Technical requirements for ice-nucleating particle measurements”, CCIce currently services two online INP instruments: The Portable Ice Nucleation Experiment (PINE) (Möhler et al., 2021) and the automated Horizontal Ice Nucleation Chamber (HINC-Auto) (Brunner and Kanji, 2021). Below, we describe the general measurement guideline for both instruments. As some procedures will differ between the NFs due to location, infrastructure, and meteorological conditions, NFs have to provide specific standard operation procedures (SOPs). Those SOPs will be based on the general measurement guidelines described below, but will possibly have to be adapted to the needs of the individual NFs. A draft for the NF-specific SOPs will be provided by CCIce.

## 2.1. Measurement guideline for the PINE instrument

Before installing and operating PINE, please consult the PINE manual, which is provided with the instrument. It outlines all the technical steps required for setting up the instrument (<https://www.bilfinger.com/de/pine/>).

The working principle of PINE (Möhler et al., 2021) is based on that of the AIDA (Aerosol Interaction and Dynamics in the Atmosphere) atmospheric simulation chamber and mimics cloud formation through expansion cooling. PINE measures *INP<sub>cn</sub>* in the immersion freezing mode. One operation in PINE consists of several runs, with each run representing a single cloud formation experiment from which *INP<sub>cn</sub>* is derived. Each run consists of three modes: The flush mode, expansion mode, and refill mode. During the flush mode, aerosol particles are directed through the instrument to replace the air volume in the chamber. Before entering the chamber, the sampled air is dried to suitable conditions to avoid the accumulation of ice on the cooled chamber wall. In the expansion mode, a valve upstream of the chamber is closed, and the sample air is continuously pumped out of the chamber, causing the air to expand. This results in a reduction in pressure and temperature, leading to the establishment of supersaturated humidity conditions. The cloud droplets formed on cloud condensation nuclei and ice crystals formed on INPs are counted by the Optical Particle Counter (OPC), located at the exit of the chamber, and are used to calculate *INP<sub>cn</sub>*, considering the volume analyzed during the expansion. Please note that the OPC is set up to fully detect the ice crystals and larger cloud droplets. Therefore, it does not measure the complete size distribution of droplets in the expansion mode and only detects larger aerosol particles in the flush mode. The lowest gas temperature measured during the expansion is the assigned reference temperature for the evaluated ice nucleating particle number concentration. In the following, it is called  $T_{min}$ . After completion of the expansion mode, PINE is set to the refill mode during which the chamber is filled with filtered sample air until restoration of ambient pressure conditions. Then another cycle of flush, expansion, and refill is initiated.

Below, we give guidelines to guarantee quality assurance for long-term INP data within ACTRIS. Table 1 lists these standard operations (SO) sorted by the execution frequency. Details on the different tasks are given below.

Table 1: Tasks for PINE operations and data.

|                   | Operations and checks                                                 |                                          |                             |                                                                                      | Data                               |                       |
|-------------------|-----------------------------------------------------------------------|------------------------------------------|-----------------------------|--------------------------------------------------------------------------------------|------------------------------------|-----------------------|
| Every day         | Check for visibility of cloud droplets during expansion (2.1.5,2.1.6) |                                          | Ice background test (2.1.7) | INP concentration measurement: Temperature scan (2.1.4) or fixed temperature (2.1.3) | Transfer of raw data (2.1.12)      | Documentation (2.1.2) |
| Every week        | Defrosting* (see 2.1.8)                                               |                                          |                             |                                                                                      |                                    |                       |
| Every month       | Chamber leak test (2.1.9)                                             |                                          |                             |                                                                                      |                                    |                       |
| Every year        |                                                                       |                                          |                             |                                                                                      | Manual data validation** (2.1.12)  |                       |
| Every three years | Validation experiments at AIDA facility (2.1.13)                      | Temperature validation** (2.1.13)        |                             |                                                                                      |                                    |                       |
| PINE set-up       | Chamber leak test (2.1.9)                                             | Inlet and sample line leak test (2.1.10) |                             |                                                                                      | Check database information (2.1.1) |                       |
| PINE restart      | Chamber leak test (2.1.9)                                             | Inlet and sample line leak test (2.1.10) | Ice background test (2.1.7) |                                                                                      | Check database information (2.1.1) |                       |

\*recommended (shorter or longer intervals may be chosen by experienced user due to environmental conditions at measurement site)

\*\*ACTRIS requirement: CCice recommends a more frequent manual data validation (e.g once per month)

### **2.1.1 Check instrumentation database information**

The ACTRIS instrument database (DB) is hosted at Sonnblick Observatory but maintained by CIS. Instruments in this database are assigned with a Persistent Identifier (PID), that is used for data reference (metadata). Instruments have to be registered in the DB before ACTRIS data can be uploaded. The database will also be used to note instrument downtimes for calibrations or repairs, so that the annual data coverage can be calculated automatically.

PINE implementation into this database is being finalized. NFs will get information how to include their instrumentation as soon as it is available.

Whenever PINE is re-started after maintenance, repairs, technical adaptations, or calibration, the information in the database has to be checked and updated when required. After major technical revisions, the assignment of a new PID might be necessary. Please contact CCIce if you see the need to update the information in the DB.

### **2.1.2 Documentation**

The documentation of PINE operation in the sense of a logbook is important metadata for ACTRIS variables and necessary for data quality control. The PINE LabVIEW software allows for the logging of recurring procedures and instrument settings. If alternative or additional lab books are used, those have to be stored in an electronic format. Logs and lab books do not have to be uploaded to ACTRIS DB but have to be stored at the NF and have to be made available for data quality control. CCIce recommends to use a recent version of the PINE LabVIEW software. For older PINE LabVIEW software versions, the procedures described in the following may deviate. For example, coupling PINE runs to different temperatures may not be supported.

The following tests need to be documented (date and time):

- Calibration, validation, and reference experiments (Section 2.1.13)
- Inlet and sample line leak test (Section 2.1.10)
- Chamber leak test (Section 2.1.9)
- Ice background test (Section 2.1.7)
- Defrosting (Section 2.1.8)
- Performance of fixed temperature runs and temperature scans (Sections 2.1.3, 2.1.4)

### 2.1.3 Fixed temperature runs

In order to compare INP data from different NFs and to be able to observe long-term trends in INP concentrations, a recurring ACTRIS PINE operation is defined and implemented in the PINE software. This is an operation at a fixed temperature of for example -25 °C, depending on the best setting for the individual NF. Please note that this is the minimum gas temperature reached during expansion ( $T_{min}$ ), thus the temperature that is set at the cryostat needs to be adjusted accordingly. This operation should be performed daily for at least one hour between 1 am and 5 am.

Several settings for each mode (flush, expansion, and refill) regarding the flow and the duration are possible (Table 2). These settings are also applicable for “temperature scan” (Section 2.1.4). In the flush mode, the aerosol particles are guided through the chamber with a certain flow that determines the inlet sample flow. At the same time, it impacts the dew point temperature, as the residence time of the air in the dryers is controlled by the flow. The flush mass flow can thus be varied in a range of 1 to 3 stdLPM (standard liter per minute, a liter at 1013 hPa and 0 °C). The flush mode aims to exchange the air inside the cloud chamber; therefore, the duration of the flush mode depends on the flush flow. Examples of the flush mode settings are given in Table 2. The actual cloud formation experiment occurs during the expansion mode when the pressure in the cloud chamber is reduced by typically 15% of the ambient pressure at an expansion volume flow of 3 LPM (liter per minute). The INP concentration ( $INP_{cn}$ ) is calculated as follows

$$INP_{cn} = \frac{\Delta N_{ice}}{\Delta V} = \frac{\Delta N_{ice}}{F \Delta t}$$

with total number of counter ice particles  $\Delta N_{ice}$ , measured volume at standard conditions  $\Delta V$ , mass flow  $F$  and duration of expansion mode  $\Delta t$  (Möhler et al., 2021). In the refill mode, the chamber is refilled with filtered sample air. The refill flow is equal to the flush flow to maintain a constant dew point temperature and a constant inlet flow. Examples of typical settings of the three modes are given in Table 2, which are valid for runs at constant  $T_{min}$  of -25 °C and -30 °C, and can also be applied to temperature scans (see Section 2.1.4).

Table 2: Example settings for PINE operation with constant flush volume of 10 L (numbers to be entered in the PINE LabVIEW software are highlighted in yellow).

|           |                                    | Setting #1              | Setting #2 | Setting #3 |
|-----------|------------------------------------|-------------------------|------------|------------|
| Total     | Total duration (s)                 | 689                     | 389        | 274        |
| Flush     | Flush volume (L)                   | 10                      |            |            |
|           | Flush mass flow (stdLPM)           | 1                       | 2          | 3          |
|           | Flush duration (s)                 | 600                     | 300        | 200        |
| Expansion | Expansion volume flow (LPM)        | 3                       |            |            |
|           | Expansion $\Delta$ pressure (mbar) | 15% of ambient pressure |            |            |
|           | Expansion time (s)                 | 33                      |            |            |
|           | Approximate volume analyzed (L)    | 2.2                     |            |            |
| Refill    | Refill mass flow (stdLPM)          | 1                       | 2          | 3          |
|           | Refill time (s)                    | 94                      | 47         | 31         |

#### 2.1.4 Temperature scan

PINE is able to perform INP concentration measurements at changing temperatures. Typical ambient measurements have shown that temperature scans are useful between  $T_{min}$  of -20 °C and -30 °C. At specific locations with high INP concentrations the upper temperature limit can also be set higher. For this, PINE is operated with the settings from Table 2, while the cryostat temperature is varied over a certain time. Typical settings for such a temperature scan are provided for a dynamic and constant number of runs in Table 3 and in Table 4, respectively.

Table 3: Typical temperature scan settings for PINE with dynamic number of runs.

| $T_{min}$      | Approximate duration (min) | Number of runs | Approximate volume of air analyzed (L) |
|----------------|----------------------------|----------------|----------------------------------------|
| -20            | 26                         | 4              | 8.8                                    |
| -22            | 26                         | 4              | 8.8                                    |
| -24            | 19.5                       | 3              | 6.6                                    |
| -26            | 19.5                       | 3              | 6.6                                    |
| -28            | 13                         | 2              | 4.4                                    |
| -30            | 26                         | 4              | 8.8                                    |
| -28            | 13                         | 2              | 4.4                                    |
| -26            | 19.5                       | 3              | 6.6                                    |
| -24            | 19.5                       | 3              | 6.6                                    |
| -22            | 26                         | 4              | 8.8                                    |
| -20            | 26                         | 4              | 8.8                                    |
| Total duration | 234                        |                |                                        |

Table 4: Typical temperature scan settings for PINE with a constant number of runs.

| $T_{min}$      | Duration (min) | Number of runs | Volume of air analyzed (L) |
|----------------|----------------|----------------|----------------------------|
| -20            | 26             | 4              | 8.8                        |
| -22            | 26             | 4              | 8.8                        |
| -24            | 26             | 4              | 8.8                        |
| -26            | 26             | 4              | 8.8                        |
| -28            | 26             | 4              | 8.8                        |
| -30            | 52             | 8              | 17.6                       |
| -28            | 26             | 4              | 8.8                        |
| -26            | 26             | 4              | 8.8                        |
| -24            | 26             | 4              | 8.8                        |
| -22            | 26             | 4              | 8.8                        |
| -20            | 26             | 4              | 8.8                        |
| Total duration | 312            |                |                            |

### 2.1.5 Dew point temperature check

For successful PINE operation, several conditions have to be met. First, the dew point temperature of the sampled air must be equal to or slightly higher than the chamber temperature at the start of a cloud formation experiment, ensuring that the sampled volume reaches sufficient supersaturation for the formation of cloud droplets and ice crystals. At the same time, the dew point temperature should not be significantly higher than the wall temperature, as excessively humid incoming air can lead to the formation of ice on the chamber inlet. Table 5 gives an overview of typical temperatures for the temperature in PINE during the flush mode (respectively, at the start of a cloud formation experiment), and corresponding ranges of dew point temperatures.

Table 5: Dewpoint temperature range for given flush mode temperature in PINE.

| Wall temperature (during flush mode) | -15 °C        | -20 °C        | -25 °C        | -30 °C        |
|--------------------------------------|---------------|---------------|---------------|---------------|
| Dewpoint temperature range           | -12 to -15 °C | -14 to -20 °C | -15 to -25 °C | -18 to -30 °C |

### 2.1.6 OPC settings

For the identification and quantification of ice crystals during expansion experiments in PINE, the upper size limit of the liquid cloud droplets has to be visible in the particle size spectrum recorded by the OPC attached downstream of PINE. During data analysis, optically larger ice crystals are distinguished from optically smaller liquid cloud droplets with the so-called ice threshold. An example is given in Figure 1.

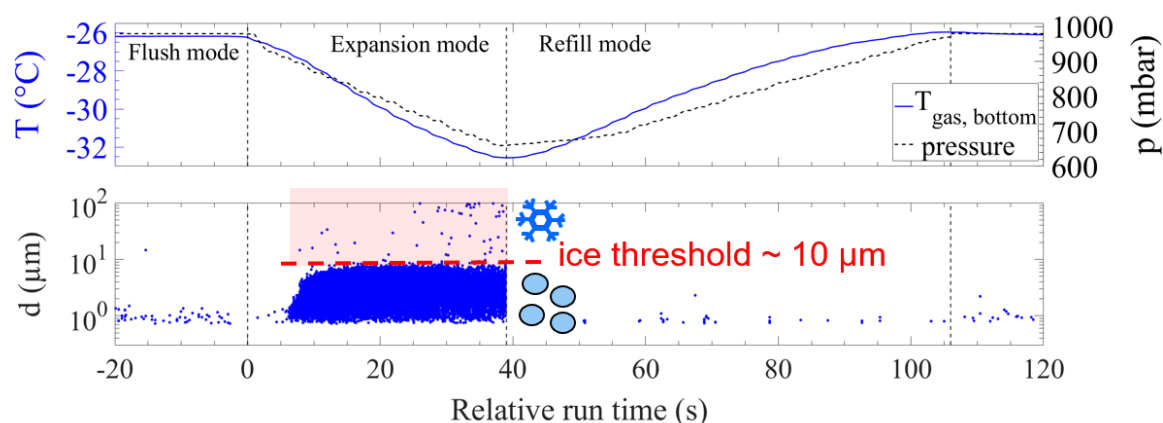


Figure 1: Timeseries of temperature  $T$  and pressure  $p$  (upper panel) and particle diameter  $d$  (lower panel) during flush mode, expansion mode, and refill mode; the forming cloud droplets are visible during the expansion mode as particles below about 10 μm, which determines the ice threshold.

Due to the sensitivity of the OPC, it is not possible to measure the complete size distribution of cloud droplets and aerosol particles as this would lead to an over-counting of the OPC. To avoid the over-counting of the OPC, a lower threshold for the detection size range needs to be set. This lower size threshold can be set with *min channel* in the settings section of the OPC tab of the PINE LabView software. The standard setting is a *min channel* of 80 (see Figure 2). If there is still an over-counting of the OPC, the *min channel* needs to be set to a higher value. An over-counting of the OPC can be identified by error messages of the OPC which appear in the Pine LabView software during the expansions. CIS recommends to use size calibrated OPCs with a fixed gain voltage (*PMV*, depends on OPC).



If the PINE instrument uses an older version of the LabView software, it may not be possible to set a lower threshold of the OPC size detection range. Then, the OPC gain voltage *PMV* needs to be lowered to avoid OPC over-counting. In this case, please contact CIS or Bilfinger SE to obtain the newest PINE software.

Figure 2: OPC settings in the Labview software.

### 2.1.7 Ice background test

The detection of artificial frost from the chamber walls or the inlet region needs to be avoided. To verify a zero-ice background, a daily background test needs to be conducted. This test should be denoted as a background operation in the logbook for future reference.

For testing the PINE background, the incoming sample air is guided over the particle filter that is integrated in the PINE sampling line by the manufacturer, while cycles of flush – expansion – refill are conducted. The measurement temperature should reflect the typical conditions at which PINE is operated. After about one hour, no aerosol particles, cloud droplets, or ice crystals should be detected anymore by the OPC. If the background does test is not successful additional defrosting is needed (see 2.1.8). We recommend to perform the background check directly after the daily fixed temperature run.

PINE does not require a correction for larger aerosol particles to be misclassified as ice particles (see Möhler et al. (2021) for a detailed discussion). At the same time, a potential aerosol background number concentration is recorded automatically in the analysis software, calculating the number of aerosol particles in the flush mode which are larger than the ice threshold determined for the respective cloud formation experiment (*INP\_cn\_flush*).

### 2.1.8 Defrosting

In order to avoid the formation of an ice layer internally on the chamber walls, PINE should be defrosted frequently. The frequency thereby relates to the difference between the measurement temperature and the dew point temperature. E.g., at a  $T_{min}$  of -25 °C and a dew point temperature of -15 °C, a defrosting operation should be conducted once a week. For this, the wall temperature of PINE is set to a value higher than the dew point temperature, but still below 0°C to avoid melting of the ice. This avoids flooding the OPC with water from melting ice from the walls. Under these conditions, the sampled air is ice-subsaturated, which leads to the sublimation of the ice from the walls. During those experiments, fixed temperature runs should be conducted. Once the chamber is ice-free, no liquid cloud droplets should be visible anymore during the expansion. The duration of such a defrosting procedure can last multiple hours, but depending on the thickness of the ice layer.

### 2.1.9 Chamber leak test

Leak tests are done to verify that no substantial amount of surrounding air and thus aerosol particles and humidity enter the chamber. For this, the inlet valve is closed and the chamber is evacuated until the pressure in PINE is reduced by 300 mbar as compared to the ambient pressure. Then the flow is set to 0 LPM and all valves are closed. Thereafter, the pressure is

monitored for 30 minutes. Please note that within the first 5 minutes, a pressure increase of a few mbars will be observed as the chamber will equilibrate its temperature after the pressure reduction. These first five minutes should not be considered for the pressure leak test. If the pressure increase is less than 20 mbar per hour, the chamber is considered to be leak-tight. If the pressure increase is larger, the source of leakage has to be identified and rectified. Such tests have to be repeated once a month.

#### **2.1.10 Inlet and sample line leak test**

In order to verify that the aerosol inlet, the dryers, and the tubes upstream of PINE are clean and leak-tight, they need to be tested when setting up PINE. For this, an aerosol filter is installed upstream of the sampling line and fixed temperature runs (see Section 2.1.3) should be conducted, and should be noted as a background operation in the logbook. The aerosol concentration in the flush mode, as well as the cloud droplet and ice crystal concentration in the expansion mode should be zero after approximately ten cycles. If the concentrations are non-zero after approximately ten cycles, the inlet tubes should be cleaned and searched for potential leaks, as they allow aerosol particles that are not sampled via the aerosol inlet to enter PINE. After cleaning and fixing the leak, the inlet and sample line background test needs to be repeated until it is successful. Such a test has to be performed when setting up PINE, and thereafter once per month.

#### **2.1.11 Limit of detection**

INPs are a small subset of the ambient aerosol population and their ambient concentration can be very low, which often challenges measurement techniques. Moreover, their ambient concentration is typically a strong function of temperature. During one experiment with PINE, an air volume of typically 2 litres is analyzed. This relates to a limit of detection (LOD) of 0.5 INP per litre.

#### **2.1.12 Data quality control and upload**

The NF has to provide the so-called Level 0 data on an hourly basis (near-real time). Level 0 data is the instruments three-second-binned raw data formatted in the EBAS NASA-Ames format and includes well-defined station, instrument, and experiment metadata.

At the ACTRIS in-situ Data Centre (DC), the submitted data is then further processed to Level 1 and Level 2 data undergoing an automated quality control (QC). The different data levels are defined in Figure 3.

At least once a year, the Level 0 data has to be fully quality controlled, e.g. by manually checking for outliers, spikes, or instrument malfunctions and re-uploaded. From this, Level 1 (three-second-binned INP concentration) and Level 2 data (run-wise for INP number concentration and T-scan-wise for INP temperature spectrum) are produced again at the DC. This will be done by the NFs and checked by CCIce with the measuring background information saved by the NF (e.g. in the form of an electronic lab book or another documentation system). For the PINE instrument, CCIce will provide a software for the near-real time data formatting and data submission to the DC (Büttner et al., 2025).

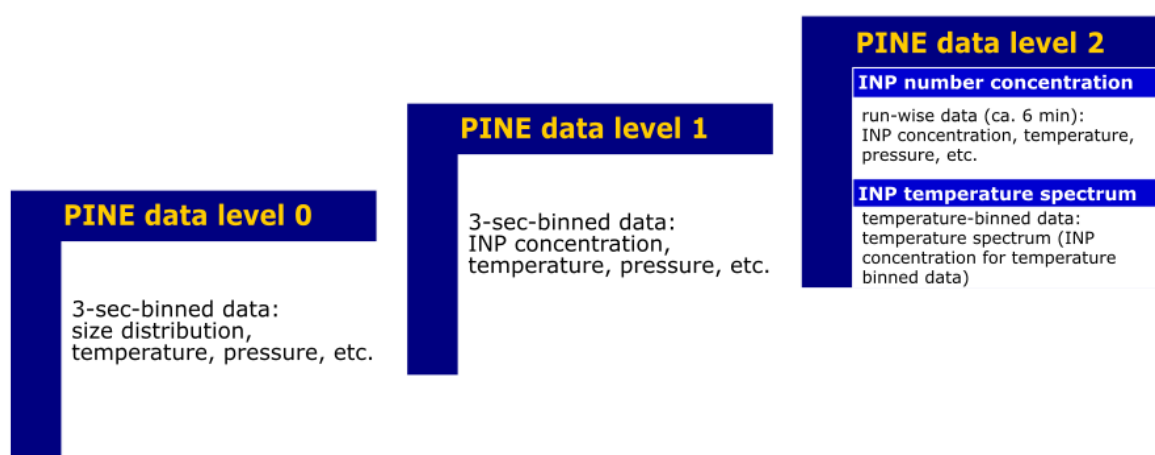


Figure 3: ACTRIS data levels (ACTRIS)

### 2.1.13 Calibration, validation, and reference experiment

CCIce will organize regular calibration, validation, and intercomparison experiments at the AIDA facility, as soon as the new calibration facility is in place. The focus of the calibration experiments will be the PINE temperature sensors and the system to apply the flows. Please note that PINE temperature sensors are calibrated at the manufacturer (Bilfinger SE) before delivery. Validation experiments for the ice nucleation efficiency with a reference INP sample will be conducted under well-controlled conditions. Alternatively, validation of the instruments will be done by intercomparison measurements to other INP methods, if this is feasible. Every instrument needs to be validated in this way every 3 years.

In addition, CCIce will provide material and descriptions for performing reference experiments, which should be performed with PINE at the NFs directly, at least on a yearly basis.

## 2.2. Measurement guideline for the HINC-Auto instrument

There are several parameters that users can set in the python guided user interface (GUI, Figure 4) to control HINC-Auto:

- Operating mode, including Measure-Background (M-B) cycle at constant lamina temperature  $T_{\text{lam}}$  and relative humidity ( $RH$ ),  $RH$  scan at a constant  $T_{\text{lam}}$ , and  $T_{\text{lam}}$  scan at a constant  $RH$ ;
- Chamber thermodynamic condition, including  $T_{\text{lam}}$ ,  $RH$ ,  $\Delta T_{\text{lam}}$ , and  $\Delta RH$ ;
- Control parameters, including warm wall temperature partial-integral control parameters  $k_p$  and  $k_i$ , warm wall coolant solenoid valve loop time, drainage pump, and sample inlet valve.

For ACTRIS-CIS long-term INP number concentration ( $INP_{cn}$ ) monitoring, M-B cycle is the most frequently used operating mode for HINC-Auto and will be introduced in detail in Section 2.2.9 below.

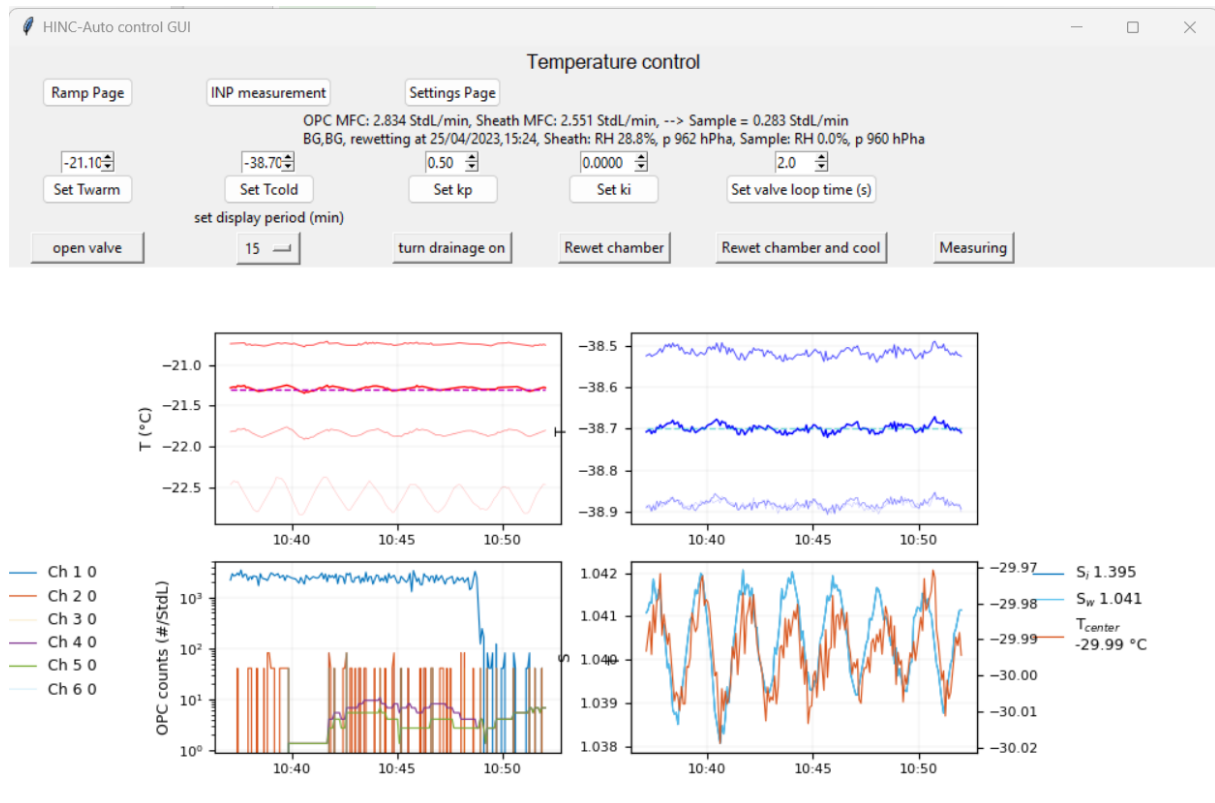


Figure 4: Main window of the guided user interface (GUI) to control HINC-Auto

Top row buttons: *Ramp Page* leads to the window to run *RH* or *T* ramps (see Figure 4), *INP measurement* leads to the window to run M-B cycle INP measurements, and *Settings Page* leads to the window to change additional settings. *OPC MFC* shows the current flow rate reading of the OPC MFC, and *Sheath MFC* analogously shows the flow rate of the sheath flow MFC, and *Sample* reports the difference between both MFCs, which corresponds to the current sample flow rate. *BGRamp* shows the target state of the chamber, in this case “measuring the background after or before a *RH* or *T* ramp”, *BG* shows the current state of the chamber, *rewetting at* indicates the time of the next planned re-wetting procedure (UTC), *Sheath* indicates the *RH* and pressure (*p*) of the sheath air as it enters the chamber (measured at mid-height within the chamber upstream of the mesh and thus at the same temperature as the chamber is set to), and *Sample* indicates the *RH* and *p* of the sample air (just downstream of the sample diffusion dryer).

Center row buttons: *Set Twarm* sets the target temperature of the warm wall, *Set Tcold* sets the target temperature of the cold wall, *Set kp* and *Set ki* set the proportional gain *kp* and integral gain *ki* of the PI controller to control the wall temperatures, and *Set valve loop time (s)* defines the duration of a loop to actuate the warm wall solenoid valve.

Bottom row buttons: *open valve* manually opens and closes the warm wall solenoid valve, *set display period (min)* defines the amount of historic data to be shown in the four graphs below, *turn drainage on* manually actuates the pump to drain the chamber during re-wetting, *Rewet chamber* executes the re-wetting procedure, *Rewet chamber and cool* executes the re-wetting procedure and cools the chamber back down to the set temperature of the chamber, and *Measure* changes the chamber’s state and valves to sampling or background measurement.

The top left graph shows the warm wall temperature (all three thermocouples, the computed mean wall temperature, and the set temperature). The top right graph shows the cold wall temperature (all three thermocouples, the computed mean wall temperature, and the set temperature). The bottom left graph shows the counts reported by the OPC for each of the six size bins. Here, size bin 1 (CH 1) is set to 0.3  $\mu\text{m}$ , CH 2 set to 1  $\mu\text{m}$ , CH 3 set to 3  $\mu\text{m}$ , CH 4 set to 4  $\mu\text{m}$ , CH 5 set to 5  $\mu\text{m}$ , and CH 6 set to 6  $\mu\text{m}$ . The bottom right graph shows  $S_w$  ( $RH_w/100$ ) and  $T_{\text{lam}}$  for the center lamina (calculated).

### 2.2.1 Standard operation: field observation using M-B cycles

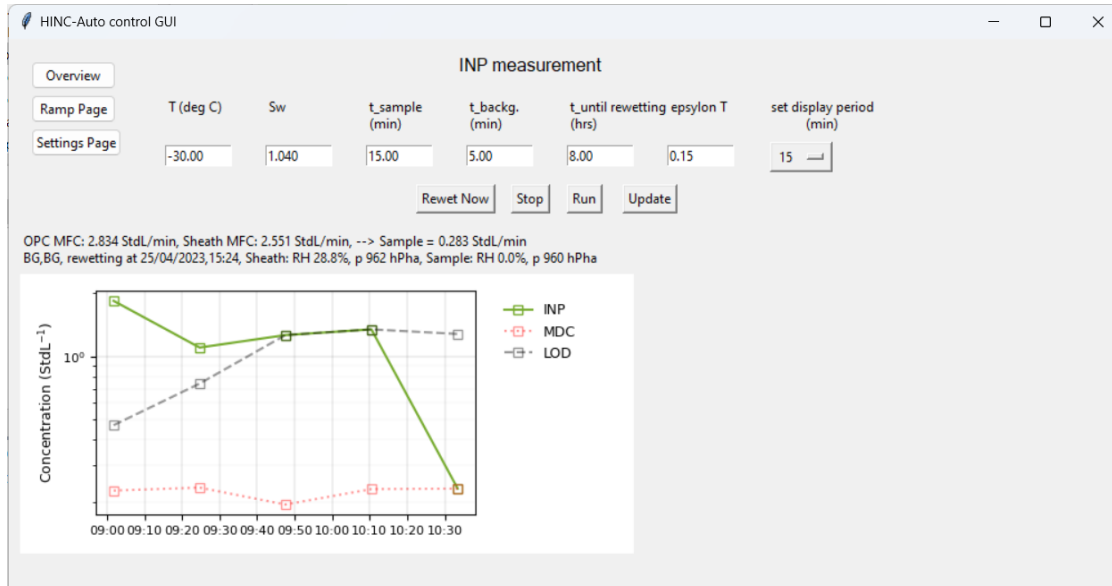


Figure 5: Window of the guided user interface for *INP<sub>cn</sub>* measurements with HINC-Auto.

Since the aerosol population sampled changes temporally during field observations, the standard practice for online field *INP<sub>cn</sub>* measure is to expose ambient aerosols to constant chamber lamina conditions, including constant  $T_{lam}$  and  $RH$ . Constant chamber conditions for field observation can be customized by entering the INP measurement page shown in Figure 5.  $t_{sample}$  and  $t_{backg}$  denote the time periods when the inlet valve is switched to aerosol line (Measure) and through a HEPA (Background), respectively. Such consecutive M-B cycles, as shown in Figure 6, take background INP uncertainty into account and ensures data quality.

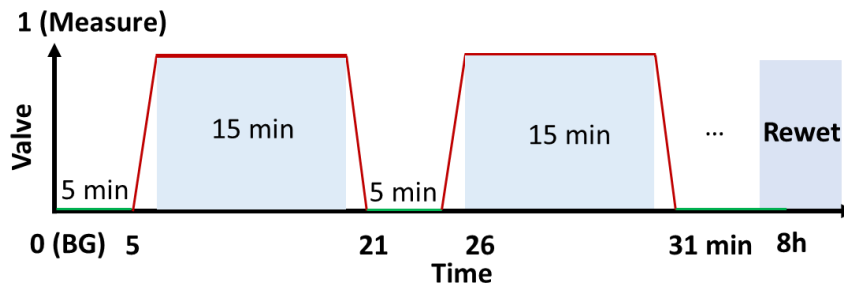


Figure 6: Schematic of HINC-Auto M-B cycles.

### 2.2.2 Data management

Level 0 data refers to the 5-second interval instrument's raw data output from the python program, including the timestamp (Date and Time) in UTC, temperature readings of all six thermocouples for both walls, user-setting chamber conditions, OPC counts for six size bins, instrument operating status,  $RH$ , and  $p$  readings for both sample and sheath gas, as well as OPC and sheath flow rates. Level 0 data is stored locally at the NF.

Level 1 data refers to the 20-min interval  $INP\_cn$  data converted from the OPC counts in a certain size bin (most commonly  $\geq 4 \mu m$ ) with background correction. The derivation of  $INP\_cn$  is introduced in detail below:

False positive counts can arise from large particles other than ice nucleated on an INP. Dominant false positives arise from frost grown on inner chamber surfaces which break off and get carried with the prevailing airflow until they exit the chamber, where they are detected by the OPC. To assess and correct the measurements for these false counts, before and after a measurement period of 15 minutes, a background measurement of 5 minutes is performed. During the background measurement, the sample air is directed through a HEPA filter before being sampled in the chamber. The mean time-normalized background counts before and after each INP measurement in the  $\geq 4 \mu m$  bin are subtracted from the  $\geq 4 \mu m$  OPC counts during the INP measurement. The  $INP\_cn$  is calculated as follows:

$$INP\_cn = \left( \frac{\sum INP \text{ counts}}{\sum N_{INP \text{ samples}}} - \frac{\sum BG \text{ counts}}{\sum N_{BG \text{ samples}}} \right) \times \frac{1}{V t_{OPC}}$$

where:

- $\sum INP \text{ counts}$  is the sum of all counts (particle number) in the  $\geq 4 \mu m$  OPC size bin during the INP measurement,
- $\sum N_{INP \text{ samples}}$  is the total number of OPC intervals during the INP measurement,
- $\sum BG \text{ counts}$  is the sum of the background counts (particle number) in the  $\geq 4 \mu m$  OPC size bin before and after the INP measurement while sampling through a particle filter,
- $\sum N_{BG \text{ samples}}$  is the total number of background OPC intervals before and after the INP measurement,
- $t_{OPC}$  is the duration of each OPC interval in minutes (here 5 s; thus, 0.083 min),
- $V$  is the sample mass flow rate, here = 0.283 LPM

Level 1 data is uploaded in quasi-realtime (about every 20 min) to ETH Polybox and ETH institute server.

Level 2 data refers to the 20-min interval  $INP\_cn$  data after Quality Assurance and Quality Control (QA/QC), which will be introduced in detail in Sect. 2.2.9. Level 2 data is supposed to be uploaded to ACTRIS data centre once per hour.

### 2.2.3 Standard operation: temperature scan

Supersaturation scan (see Figure 7) can determine the ice nucleation onset  $RH$  at different temperatures for different INP species. Below, the test conditions are given for different

apparatus employed, i.e., using one single chiller or two separate chillers to control wall temperatures:

|                | One chiller | Two chillers |
|----------------|-------------|--------------|
| $T_{lam}$ (°C) | -45 to -25  | -55 to -15   |
| $S_w$          | 0.8 to 1.1  | 0.5 to 1.3   |

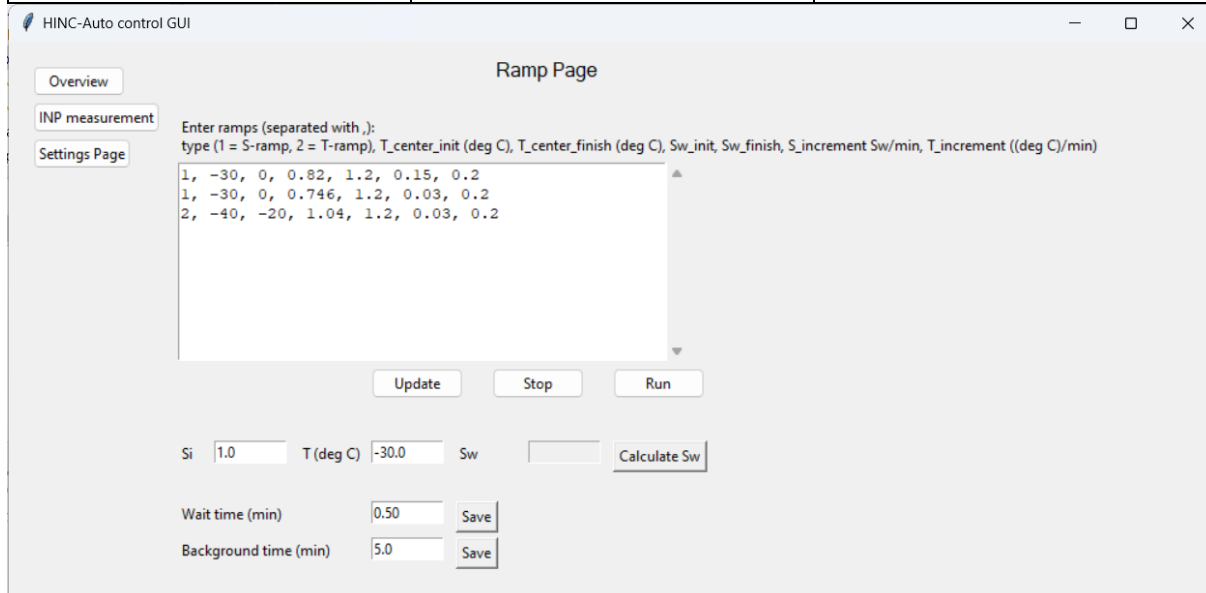


Figure 7: Window of the guided user interface used to control  $RH$  or  $T$  ramps with HINC-Auto.

#### 2.2.4 Thermocouple calibration

There are six thermocouples (Transmetra TEMI313, type K, NiCr-Ni) in total for HINC-Auto. On each wall of HINC-Auto, three thermocouples are distributed evenly to monitor the wall temperature spatial variation.

Thermocouple calibration should be carried out at least once per year following the 3-point calibration method:

The thermocouples should be calibrated by measuring the melting points of  $H_2O$  (0.0 °C) and  $Hg$  (-38.8 °C), as well as the subliming point of  $CO_2$  (-78.5 °C), in close agreement with the ITS-90 (the official protocol of the international temperature scale). An ordinary least square (OLS) linear regression is performed based on these three points to determine the thermocouple coefficients.

#### 2.2.5 Flow rate calibration

The flow rates are controlled by mass flow controllers (MFCs). A MFC (Bronkhorst, F-201EV, full scale range: 3.5 stdLPM) downstream the OPC is set to 2.83 LPM to regulate the total flow

rate going through the chamber. The sheath flow rate is set to 2.547 LPM by a MKS MFC (MKS MF1, full scale range: 5 stdLPM).

The Gilian® Gilibrator® wet bubble calibrator is used as a reference instrument for volumetric flow rate measurement. The flow rate calibration should be carried out every 6-12 months following the procedures below:

- 1) Set the voltages of the MFCs to 0 V (closed), 2.5 V (half range), and 5 V (full range), respectively;
- 2) Measure the corresponding flow rates at least 5 times, take the average for each voltage as the measured flow rate;
- 3) Adjust the MFC full range setting in python control program based on the measured flow rate.

### 2.2.6 Chamber thermodynamic condition characterization and calibration

The chamber thermodynamic condition is characterized by on site measuring the activation of ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) aerosol (see Figure 8) following the steps described below:

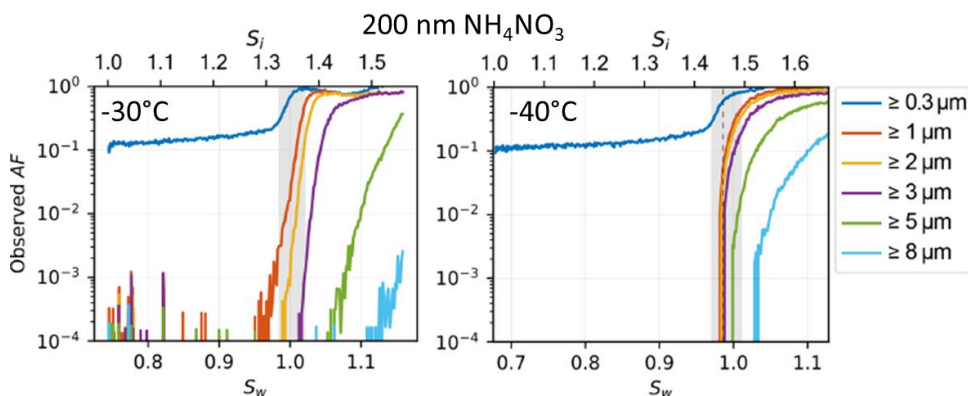


Figure 8: Activation curve for 200 nm  $\text{NH}_4\text{NO}_3$  as a function of saturation  $S_w$  at  $-30^\circ\text{C}$  (left) and  $-40^\circ\text{C}$  (right). Grey shading refers to chamber  $S_w$  uncertainty.

1. Solution preparation: Preparing an  $\text{NH}_4\text{NO}_3$  aqueous solution with a concentration of  $0.1 \text{ mol L}^{-1}$ .
2. Aerosol generation: The  $\text{NH}_4\text{NO}_3$  solution should be atomized and dried using a diffusion dryer to a relative humidity with respect to water ( $RH_w \leq 0.5\%$ ) at  $20^\circ\text{C}$ . The particles should then be size-selected to a mobility diameter ( $d_m$ ) of 200 nm using a differential mobility analyzer (DMA).

3. Activation fraction (AF) determination: A condensation particle counter (CPC) should be connected to measure the particle concentration in parallel to HINC-Auto to obtain the AF. The particle concentration was targeted between 200 and 1000 cm<sup>-3</sup>.
4. Chamber thermodynamic condition characterization: The characterization should be conducted in the *RH* scan mode, with constant lamina temperature, while *RH<sub>w</sub>* increases with  $\Delta RH_w \leq 2\%/min$ .

### 2.2.7 Leakage test

Since HINC-Auto operates at room pressure, the pressure difference within the chamber and ambient is negligible. However, when we open and reassemble the chamber for maintenance, any uneven sealant between walls and spacer or unbalanced stress of screws and bolts could cause leakage in the chamber and affect INP measurement.

To ensure a well-sealed chamber, an annual chamber leakage test should be performed using Ar (99.9999 %). Besides, a chamber leakage test is recommended to be performed every time after the chamber is opened and reassembled.

The leakage test is carried out following the procedures described below:

1. Block the outlet of the chamber;
2. Over-pressurize the chamber with Ar;
3. Test Ar on the six surfaces of the chamber with Ar sensor, especially near the screws and bolts on both walls, and the slits between walls and spacer.

### 2.2.8 LOD determination

The limit of detection (LOD) is calculated as following:

$$LOD = \frac{\sqrt{\sum BG \text{ counts}}}{\sum N_{BG \text{ samples}}} \times \frac{1}{V t_{OPC}}$$

LOD provides a 62.3 % (1 $\sigma$ ) confidence interval.

The minimum detectable concentration (MDC) is one count (particle) in the  $\geq 4 \mu m$  OPC size bin over a 15-min INP measurement with a sample flow rate of 0.283 LPM, which is equal to an MDC of 0.236 L<sup>-1</sup>. The MDC represents the smallest concentration that can be reliably detected under the given sampling time.

### 2.2.9 Data quality assurance and quality control

The instrument control program enables automatic data flag when the instrument operation parameters deviate from the set values. A list of flags is given in Table 6. ACTRIS-compliant *INP\_nc* data flags system will be implemented into the control program once available.

Evaluation of the flag and a potential exclusion of the data need to be done by the NF to obtain Level 2 data.

Table 6: HINC-Auto data flags

| ACTRIS flag | Validity flag | Meaning                                     | Criteria                                                                                                                             |
|-------------|---------------|---------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| 664/677     | 0             | Chamber pressure error                      | Chamber pressure is off by more than 50 hPa from the ambient pressure                                                                |
| 664/677     | 0             | Flow rate error                             | MFC flow rate is off by more than 0.05 LPM                                                                                           |
| 672         | 0             | Wall temperature error                      | One of the wall temperatures is off by more than 0.15 K                                                                              |
| 672         | 0             | Chamber saturation error                    | Chamber lamina $S_w$ is off by more than 0.01                                                                                        |
| 672         | 0             | Chiller error                               | Chiller report an error, e.g. low ethanol level                                                                                      |
| 652         | 1             | Potential construction dust event           | 5 s OPC data has spikes and double-check with CPC data if OPC INP channel $q_{98.5}/q_{10} > 80$ , and $INP_{cn} > 8 \text{ L}^{-1}$ |
| 147/780     | 1             | Negative $INP_{cn}$ , i.e. high BG warning; | MDC is assigned                                                                                                                      |
| 653/654     | 1             | Measurement time warning                    | Measurement duration is longer or shorter than 15 min                                                                                |

|     |   |                               |                                                                                                                |
|-----|---|-------------------------------|----------------------------------------------------------------------------------------------------------------|
| 699 | 1 | Water reservoir level warning | When the water reservoir used to re-wet the chamber walls, is below a defined threshold (approximately 100 mL) |
| 699 | 1 | NBG samples warning           | Total number of background OPC intervals NBG samples does not equal to 60 for one M-B cycle                    |

### 3. Measurement guidelines for offline ice-nucleating particle measurements

INP concentrations can be derived by sampling aerosol particles on filters, which are analyzed offline for their ice nucleation ability by using a droplet freezing assay. With that, the temperature-dependent INP concentration in the temperature range above about -25 °C is derived. At present, ACTRIS suggests to use the INSEKT (Schneider et al., 2021) or any other re-build of the INS (Creamean et al., 2022; Pacific Northwest National Laboratory (PNNL) et al., 2024) for offline INP analysis. Similar droplet freezing assays might be suitable, which has to be approved by CCIce.

Droplet freezing assays investigate ice formation in the immersion freezing mode. For this, the aerosol particles collected on filters are suspended in deionized and particle-free water, aliquoted into small wells (e.g., 50 µL aliquots), and cooled down. Typically, the freezing of the samples in the individual wells is observed with a camera, detecting the brightness change upon phase change of the water.

In the following, the measurement guidelines of INSEKT regarding the preparation of the filters before sampling, the sampling, and the INP analysis are described. Typical tasks for operations and data are given in Table 7 sorted by the execution frequency. Details on the different tasks are given below.

Please note that different protocols for filter preparation, filter handling, and cleaning are allowed if they result in acceptable blank filter INP concentrations. The same goes for using different consumables, e.g. different filter types. The quality of measurements with different protocols or materials has to be demonstrated, e.g. by participation in validation activities. Individual steps in the handling protocol will be noted in the NF specific Standard Operation Procedures.

Table 7: Tasks for INSEKT operations, checks and data

|                         | Operations and checks                      |                                       |                          | Data                                              |                                  |
|-------------------------|--------------------------------------------|---------------------------------------|--------------------------|---------------------------------------------------|----------------------------------|
| Every sampling interval | Filter change and freezing of sample (3.2) | Cleaning of filter equipment (3.2)    | Aerosol collection (3.3) |                                                   | Documentation (3.9)              |
| Every week              | Blank filter (3.4)                         |                                       |                          |                                                   |                                  |
| Every month             | Leak test (3.6)                            | Analysis of filters with INSEKT (3.5) | Filter pre-cleaning (3)  | Raw data upload and Level 1 data processing (3.7) |                                  |
| Every year              | Validation experiments (3.9)               | Temperature calibration (3.8)         |                          | Level 2 manual data validation (3.7)              |                                  |
| Set-up                  | Cleaning of filter equipment (3.2)         | Leak test (3.6)                       |                          |                                                   | Check database information (3.9) |

### 3.1. Filter pre-cleaning

For the analysis with INSEKT, aerosol particles are sampled on Nuclepore filters (0.2 µm pore size). We recommend to pre-clean all filters used, as it reduces INP contamination (Barry et al., 2021). For this, the filters are cleaned with a 10 % H<sub>2</sub>O<sub>2</sub> solution and rinsed with Nanopure that was passed through a 0.1 µm syringe filter (e.g. Whatman®, 6784-2501). Alternatively, the method for sonification in methanol described by Barry et al. (2021) can be followed. Thereafter, the filters need to be dried on fresh aluminum foil, in a laminar flow box to ensure a constant clean and particle free airflow and to avoid contamination. Thereafter, clean filters are packaged inside aluminum foil bags (disinfected by heating to 300 °C for 30 minutes) and stored in clean zip bags. Not more than two filters should be packaged in one aluminum foil.

All equipment that gets in contact with the filters before and after sampling, should be clean and particle-free. In this sense, tweezers and filter holders should be cleaned when the filters are changed. Workbenches and the flow box should be cleaned every day. Personnel handling the filters need to wear particle-free clean gloves and particle free disposable sleeves or lab coats to prevent contamination by particles released from skin or clothes.

### 3.2. Filter changing and storage

When handling filters, the operator needs to wear clean clothes with low particle emission rates, such as gloves, single use plastic sleeves and/or a lab coat (Barry et al., 2021). It is required to clean the gloves between each work step. When handling filters, tweezers (pre-cleaned with H<sub>2</sub>O<sub>2</sub> and dried in flow box) needs to be used rather than touching them directly with gloves. In addition, the filter pre-cleaning preparation procedure and filter changing have to be conducted in a laminar flow box. The equipment itself needs to be cleaned using disinfectant between each filter.

For transport, filter holder ports always need to be closed (e.g., by covering them using fresh aluminum foil) for transporting and the filter holder should be placed in a plastic bag. This avoids contamination by lab air.

Aerosol-loaded filters have to be immediately stored in sterile Petri dishes, which are then wrapped in aluminum foil to prevent any contamination. The foil is then labelled with a unique identifier, such as sample number, site, or campaign, and start date and time of sampling. The filters should be packed in clean zip bags and stored frozen if possible.

The empty filter holder needs to be cleaned and dried. This should be done with laboratory wipes and disinfectant for every filter change and on a monthly basis also with Nanopure water in an ultrasonic bath. The pre-cleaned filter is placed inside a clean and dry filter holder, which is closed thereafter. Please consider that there are two sides of the Nuclepore filter, and the more “shining” one is the one on which the aerosols should be sampled. Thus, this side needs to face the inlet. Again, filter holder ports should be closed for clean transportation from the laminar flow box, where the filter is placed into the filter holder, to the aerosol inlet. The loaded filter holder is then attached to the aerosol inlet before the flow is turned on.

### 3.3. Aerosol collection

To determine the total sampled volume, it is necessary to record the airflow during sampling, ideally throughout the entire sampling period. Typical filter sampling flow rates, collection times, and corresponding LODs are listed in Table 8. For droplet freezing assays the INP concentration ( $INP_{cn}$ ) is calculated as follows

$$INP_{cn} = \frac{\ln(1 - f)}{V_{well}} \cdot \frac{V_{sol}}{V_{air}}$$

With fraction of frozen droplets  $f$ , sampled volume of air at standard conditions  $V_{air}$ , volume of solution  $V_{sol}$ , and volume of the individual wells  $V_{well}$  (Creamean et al., 2022; Vali, 1971). The LOD of the ice nucleating particle number concentration ( $INP_{cn\_LOD}$ ) can be estimated with

$$INP\_cn\_LOD = \frac{1}{V_{air}} \cdot \frac{V_{sol}}{n \cdot V_{well}} = \frac{1}{V_{air}} \cdot \frac{V_{sol}}{V_{ana}}$$

with number of wells filled with the solution  $n$  and volume of analysed solution  $V_{ana} = n \cdot V_{well}$  (Böhmländer et al., 2025).

After aerosol collection, the flow is turned off, and the filter holder is detached from the sampling inlet. The measurement times, flow, filter type, mass flow controller type, and filter name should be noted in a lab book. The use of an electronic lab book is strongly recommended. The filter-changing procedure is described in Section 3.2.

Aerosol collection should be performed at a mass flow rate between 2 and 6 stdLPM (standard liter per minute, a liter at 1013 hPa and 0 °C) depending on the sampling duration (typically between 1 day and 1 week) and the specifications of the filter supplier. It needs to be ensured that the filter is not over-loaded by a too high aerosol concentration within the given sampling time. This is often causing a decrease in the sample flow rate and leads to inefficient sampling.

Table 8: Aerosol collection settings and theoretical  $INP\_cn\_LOD$  for  $\frac{V_{sol}}{V_{ana}} = 1.0$  and  $\frac{V_{sol}}{V_{ana}} = 0.4$

| Sampling mass flow rate (stdLPM) | Sampling duration (days) | $INP\_cn\_LOD$ (L <sup>-1</sup> )<br>( $\frac{V_{sol}}{V_{ana}} = 1.0$ ) | $INP\_cn\_LOD$ (L <sup>-1</sup> )<br>( $\frac{V_{sol}}{V_{ana}} = 0.4$ ) |
|----------------------------------|--------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------|
| 2                                | 2                        | $1.7 \cdot 10^{-4}$                                                      | $4.3 \cdot 10^{-4}$                                                      |
| 2                                | 7                        | $5.0 \cdot 10^{-5}$                                                      | $1.2 \cdot 10^{-4}$                                                      |
| 4                                | 2                        | $8.7 \cdot 10^{-5}$                                                      | $2.2 \cdot 10^{-4}$                                                      |
| 4                                | 7                        | $2.5 \cdot 10^{-5}$                                                      | $6.2 \cdot 10^{-5}$                                                      |
| 6                                | 2                        | $5.8 \cdot 10^{-5}$                                                      | $1.4 \cdot 10^{-4}$                                                      |
| 6                                | 7                        | $1.7 \cdot 10^{-5}$                                                      | $4.1 \cdot 10^{-5}$                                                      |

### 3.4. Blank filter collection

Handling blank filters should be collected every week. For this, a filter is handled the same way as described above, except that no flow is drawn over the filter when attached to the inlet. Handling blank filters should be named in a way that they can be easily identified and the data need to be flagged accordingly. INP contamination from procedural blank measurements are evaluated on a yearly regularly (at least during Level 2 data quality evaluation) and any resulting data correction is to be discussed with CCIce.

### 3.5. Offline INP analysis procedures

Prior to the start of the experiments, the equipment, and the laboratory surfaces need to be cleaned. Also, the preparation area needs to be covered with fresh aluminum foil. See Figure 9 for the different steps of the analysis. For INSEKT experiments, the filter loaded with the aerosol particles is transferred into a centrifuge tube filled with 8 mL of Nanopure water, which was passed through a 0.1  $\mu\text{m}$  syringe filter. The tube containing the aerosol suspension is shaken in a rotator for 20 minutes at 60 rpm to ensure that the particles are released from the filter. Depending on the expected INP concentration, the aerosol suspension can be diluted by 10 and 100, or 15 and 225 -fold volumes of filtered Nanopure water, which enables the investigation of the freezing behaviour of the suspension at lower temperatures. Out of the aerosol suspension, volumes of 50  $\mu\text{L}$  are pipetted into wells of polymerase chain reaction (PCR) plates. In addition to the aerosol suspension, the filtered Nanopure water is also pipetted into some of the wells on the PCR plate to determine the background freezing of water. The PCR plates are then placed into aluminum blocks which are connected to a cryostat. The aluminum block is inside a PVC box which is insulated by Armaflex material. To prevent contamination, the PCR plates are covered with an anti-reflection glass plate, and are flushed with particle-free synthetic air to avoid condensation on the glass. The freezing experiment is started at 0  $^{\circ}\text{C}$ , and the temperature is lowered at a rate of 0.33 K  $\text{min}^{-1}$ . A camera detects the brightness change of the sample upon freezing and determines the temperature dependent frozen fraction of the sample.



Figure 9: Offline analysis procedure with INSEKT; from left to right: The filter is taken out of the filter holder (left), placed in a tube containing Nanopure water and mounted in a rotator (center left), and the resulting suspension is pipetted into wells of a PCR plate (center right), which is then placed into the cooled aluminum box connected to a cryostat (right).

### 3.6. Leak test

Before the start of aerosol sampling, the filter sampling setup (filter holder, pressure sensor, critical orifice, mass flow controller, and pump) has to be tested for leaks. For this, the

pressure in the sampling system is reduced by 300 mbar, all valves with a connection to exterior air are closed, and the vacuum pump is disconnected. The setup is considered to be leak-tight if there is a pressure increase of  $< 0.07$  mbar/min. Such tests have to be repeated every month.

### 3.7. Data quality control and upload

The format and metadata for offline INP data is currently being discussed with the ACTRIS in-situ data centre. We strongly suggest the use of a database for storage of experimental metadata and the detection of freezing events, so that the data files for submission into the ACTRIS database can be easily done as soon as the procedure is verified. Also, the use of an electronic lab book is strongly recommended.

### 3.8. Temperature calibration

All temperature sensors of the droplet freezing assays should be calibrated in the temperature range between  $-40$  °C and  $+5$  °C on a yearly basis. For this, all temperature sensors are dismantled from the instrument and placed in a metal block inside an ethanol bath within a

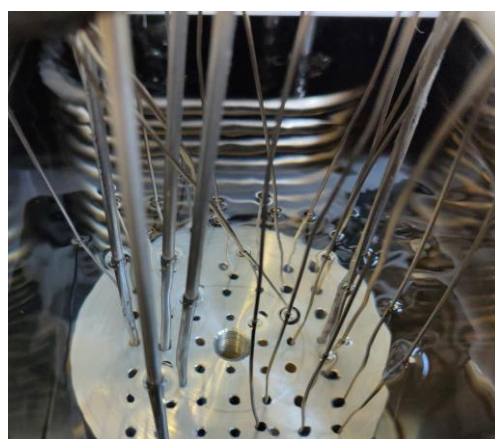


Figure 10: Example setup for calibration of droplet freezing assay temperature sensors (left) with detailed view of metal block with temperature sensors inside an ethanol bath (above).

cryostat bath (see Figure 10: The calibration temperature steps should be at most 5 K and the constant temperature should be kept for at least 20 min. As reference temperature sensor a recently (within one year) certified temperature sensor (e.g. Pt100) should be used.

### 3.9. Data management

The ACTRIS instrument database (DB) is hosted at Sonnblick Observatory but maintained by CIS. Instruments in this database are assigned with a Persistent Identifier (PID), that is used for data reference (metadata). Instruments have to be registered in the DB before ACTRIS data can be uploaded. The database will also be used to note instrument downtimes for calibrations or repairs, so that the annual data coverage can be calculated automatically.

Offline INP instrument implementation into this database is being finalized. NFs will get information how to include their instrumentation as soon as it is available.

Whenever an instrument is re-started after maintenance, repairs, technical adaptations, or calibration, the information in the database has to be checked and updated when required. After major technical revisions, the assignment of a new PID might be necessary. Please contact CCIce if you see the need to update the information in the DB.

#### 3.10. Offline INP instrument validation

CCIce will organize yearly validation experiments for droplet freezing assays. ACTRIS instruments need to successfully participate in two validation experiments within three years. Other droplet volumes, cooling techniques, or detection methods than the ones described above can be used, if their performance has been demonstrated in ACTRIS validation experiments and was verified by CCIce. Individual instrumentation and procedures have to be described by the NFs in the specific Standard Operation Procedures.

## 4. Acknowledgements

Microsoft Copilot was used for stylistic improvements of this manuscript.

## 5. Appendix

### 5.1. Offline INP measurements

Table A1: Overview of materials used for filter sampling and analysis with INSEKT

| Name          | Property                                                                | Function                                                                        |
|---------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Gloves        | powder-free                                                             | used during all steps                                                           |
| Forceps       | polymethylpenten, cleaned with H <sub>2</sub> O <sub>2</sub> before use | used to handle filters                                                          |
| Petri dishes  | sterile                                                                 | storage of filter between sampling and analysis                                 |
| Aluminum foil |                                                                         | provided a clean surface to work on, encapsulates Petri dishes between sampling |

|                         |                             |                                                                                                                  |
|-------------------------|-----------------------------|------------------------------------------------------------------------------------------------------------------|
|                         |                             | and analysis; needs to be baked out at 300 °C for 30 minutes for holding pre-cleaned filters                     |
| Plastic bags            | clean                       | used to store multiple Petri dishes encapsulated by aluminum foil in a fridge                                    |
| Disinfectant            | antibacterial and antiviral | used to clean surfaces, forceps and gloves                                                                       |
| Nanopure water          | 18.2 megaohm ionic purity   | water used for making filter solutions                                                                           |
| Centrifuge tubes        | 50 ml polypropylene tube    | used for filter washing and creatFion of solutions                                                               |
| Pipette tips 0.1-5 ml   | clean/sterile               | used for filling the centrifuge tubes with Nanopure water for filter washing                                     |
| Pipette tips 50-1000 µl | clean/sterile               | used for filling the wells with 50 µl of Nanopure water                                                          |
| Syringe 20 ml           | clean/sterile               | used in conjunction with the 0.1 µm syringe filter for further filtration of Nanopure water                      |
| Syringe 12 ml           | clean/sterile               | used to activate 0.1 µm syringe filters with alcohol before use                                                  |
| Syringe filter 0.1 µm   | clean/sterile               | used to filter Nanopure water further in combination with the 20 ml syringe, used up to 10 times before replaced |
| Laboratory wipes        | clean/sterile               | Used to clean surfaces or filter mount                                                                           |

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