

Topical Centre for Cloud In Situ Measurements (CIS)

Centre for Cloud Ice Nucleation (CCIce)

Technical requirements for ice nucleating particle measurements

Authors: Kristina Höhler, Alexander Böhmmländer, Nicole Büttner, Jie Chen, Romy Fösig, Adrian Hamel, Zamin A. Kanji, Larissa Lacher, Ottmar Möhler and Cuiqi Zhang

Version: 1.0

1. Content

1.	Content.....	1
1.	About this document.....	2
2.	Inlets for online and offline INP measurements	3
3.	Technical requirements for using online INP instruments	4
3.1.	On-site requirements for setting up the PINE instrument.....	5
3.2.	On-site requirement for setting up the HINC-Auto instrument.....	7
4.	Technical requirements for using offline INP instruments	9
4.1.	Aerosol sampling units for offline INP instruments	10
4.2.	Off-site requirements for INP analysis	10
5.	Appendix.....	12
5.1.	Documentation of technical setup	12
5.2.	Consumables for ice spectrometer measurements	14
6.	References.....	15

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 the Central Facility for Cloud In Situ measurements (CIS), the Centre for Cloud Ice Nucleation (CCIce) provides the service for the specializing variables “Ice Nucleating Particle (INP) number concentration” and “Ice Nucleating Particle (INP) temperature spectrum.”

This document describes the technical requirements for ACTRIS observational platforms measuring these two specializing CIS variables. The variables need to be measured on a monitoring basis, requiring automated instruments or regular operator input. One option are so-called online INP instruments located at the NFs themselves, which measure “INP number concentration” in near real-time at a time resolution of minutes. These instruments continuously sample ambient aerosol particles via suitable inlets, expose the samples to cloud-like conditions regarding temperature and humidity, and detect the formed ice particles. Under the assumption that each ice particle has been formed by activation of a single INP, the volume concentration of INPs in the ambient sample can be calculated. Two instruments fulfilling the criteria of precise and continuous near-real time measurements are the online INP instruments PINE (Portable Ice Nucleation Experiment, Möhler et al., 2021) and HINC-Auto (Brunner and Kanji, 2021). These instruments need minimal user input for performing the measurements.

The second option to measure INP variables is the sampling of atmospheric aerosol particles at the station on filters and the post-processing of these in a laboratory, using so-called offline INP instruments. This has the benefit of reduced need for space and energy at the station, which is traded off by an increased human resources requirement for changing the filters and the less autonomous measurements in the laboratory. The time resolution of offline INP measurements is in the range of hours to days, but has the advantage of a larger sample volume, which lowers the limit of detection. A method fulfilling the criteria for offline-INP-instruments is the Ice Nucleation Spectrometer of the Karlsruhe Institute of Technology (INSEKT, Schneider et al., 2021), a rebuilt of the Ice Spectrometer IS (e.g., Hill et al., 2016). Other similar droplet freezing assays might be suitable to determine these CIS variables, which needs to be discussed with CCIce.

Ideally, the CCIce observational platforms also measure atmospheric aerosol number concentration and aerosol size distribution in parallel to the INP measurements, following the specifications given by the ACTRIS Centre for Aerosol In Situ/ European Centre for Aerosol Calibration and Characterization CAIS/ECAC (<https://www.actris-ecac.eu/>).

In the following, the technical requirements for aerosol inlets and for online- and offline INP methods are described separately. This document should be considered together with the measurement guidelines for ice-nucleating particle measurements (Höhler et al., 2026).

2. Inlets for online and offline INP measurements

The described online INP instruments, as well as the aerosol filter collection for offline INP analysis, are operated indoors. Sampling is performed through rooftop inlets and inlet lines configured to minimize particle loss. The inlet design should enable the collection of a representative ambient aerosol particle size distribution, which is crucial for ice nucleation studies. Aerosol particle loss induced by settling or impaction, as well as diffusional losses, have to be minimized. Different INP types and sizes can contribute to the INP population at different temperatures ranging from biological ice nucleating macromolecules in the range of a few nanometers (Pummer et al., 2015) to supermicron dust particles as large as 10 μm (e.g. Hoose and Möhler, 2012).

CIS observational platforms can be within clouds. Thus, measurements should be conducted using a whole air inlet to also sample activated particles (cloud droplets and ice crystals) that can contain INPs. In general, we follow the ACTRIS Centre for Aerosol In Situ (CAIS)/ European Centre for Aerosol Calibration and Characterization (ECAC) recommendation for aerosol inlet and sampling tubes (<https://www.actris-ecac.eu/aerosol-inlets-and-conditioning.html>). It is recommended that the CCIce variables are measured at the ECAC/CAIS whole air inlet, in case the NF is also part of CAIS-ECAC. Otherwise, a similar inlet should be used.

If the observational platforms experience icing conditions, the inlet needs to be heated to avoid clogging by ice. Furthermore, in the heated inlet cloud components evaporate or sublimate, allowing the sampling of inactivated aerosol particles and cloud residuals. The aerosol inlet should be omnidirectional, enabling efficient transmission of aerosol particles regardless of wind direction. Since ambient wind velocity can affect the sampling efficiency of larger particles, the inlet's size-cut must be characterized as a function of wind speed. Additionally, to prevent the intake of precipitation, debris, and insects, the inlet entrance should be equipped with a protective mesh and a cover for snow and rain.

In order to minimize direct impact from the local environment, the inlet stack should be located at a minimum height of 2 m above ground. For sites that are located in an obstructive surrounding (e.g., vegetation, topography, or buildings), higher inlets are recommended.

In case the aerosol sample flow in the inlet is distributed over multiple instruments, it has to be ensured that the flow and thus the aerosol sample under investigation is equally split regarding concentration and size distribution. The use of isokinetic flow splitters is recommended in this case. Moreover, losses due to the exposure of charged particles to an electric field inside the sampling line have to be avoided by choosing electrically conductive and ideally grounded sampling lines. For fixed laboratory installations, it is recommended to

use stainless steel or copper tubing that is electrically grounded. For more mobile applications, suitable conductive flexible tubing may also be used. Ideally, the inlet stack inside the laboratory should be vertically oriented, and the length of the tubing — especially horizontal sampling lines leading to the online INP instruments and the filter sampling setup — should be minimized. Bends and connectors should be kept to a minimum to reduce particle losses. The NF inlet system and the sampling line configuration (including line diameter, length, geometry, and material) must be documented. Furthermore, the entire system should be characterized with respect to sampling losses through theoretical calculations and measurements, as well as cut-off sizes at the respective flow settings (see Appendix Section 5.1).

3. Technical requirements for using online INP instruments

Online INP instruments are placed at the NF and provide near-real-time data of INP concentrations at individual measurement temperatures. In the following, two online instruments that meet the criteria to monitor INP concentrations autonomously and continuously within a relevant temperature range are described: PINE (Möhler et al., 2021) and HINC-Auto (Brunner and Kanji, 2021). In brief, these instruments simulate cloud-like conditions, namely sub-zero temperature and supersaturated humidity conditions. The aerosol population under investigation is exposed to those conditions, and the INPs amongst them can trigger the formation of ice crystals. These ice crystals are then optically detected and quantified relative to the sampled air volume, resulting in a calculated INP concentration. Online methods offer the advantage of near-real-time INP detection and high temporal resolution in the order of minutes. However, their sampled air volume is smaller compared to filter-based offline methods, which increases their detection limit and reduces their sensitivity to very low INP concentrations.

The instrument's transport and installation at the site has to be feasible regarding the instrument dimensions and the weight (see the detailed description of the respective instrument). The setup of the instruments should be in close proximity to the aerosol inlet to avoid sampling losses of particles. Power supply for the instruments has to be provided, as well as stable internet access for remote control and data transfer. It has to be ensured that no loss of collected data occurs, prior to transferring the data to the ACTRIS main server. Thus, a backup energy source for supplying the instrument is required.

The requirements for the inlet and sampling line are independent of the selected online method and are described in Section 2. Below, specific technical requirements for measurements using PINE and HINC-Auto are outlined. Other online instruments capable of providing near-real-time data with high-time resolution and suitable for monitoring INP concentrations may also be used, which is subject to prior approval by CCice.

3.1. On-site requirements for setting up the PINE instrument

PINE (Möhler et al., 2021) is an expansion-type cloud chamber based on the design of the AIDA (Aerosol Interactions and Dynamics in the Atmosphere, e.g., Möhler et al. (2003)). Cloud-like conditions are established by cooling the chamber to subzero temperatures and expanding the air by a rapid pressure reduction. Due to expansion cooling, the air inside the chamber gets supersaturated with respect to ice and water, such that cloud droplets and ice crystals can form on cloud condensation nuclei and INP, respectively. An optical particle counter (OPC) attached downstream of the chamber thereby identifies ice crystals based on their optically larger size compared to the forming liquid cloud droplets. The instrument is operated in a cycled mode (Figure 1, (Brasseur et al., 2022)) of flushing the aerosol under investigation through the chamber (flush mode), expanding the air and forming the cloud (expansion mode), and bringing the chamber pressure back to ambient conditions by refilling it with air (refill mode). PINE is operated without any liquids such as cooling agents. It measures INP concentrations in the immersion freezing mode in the mixed-phase cloud temperature range. It has a temperature uncertainty of ± 1 °C. See Möhler et al. (2021) for more information about

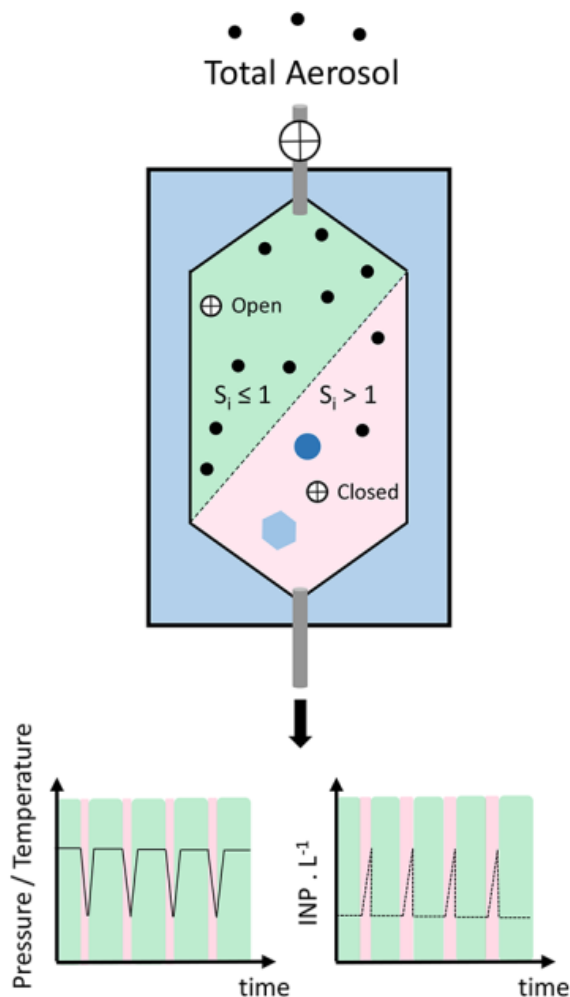


Figure 1: Schematic of the working principle of PINE; during the flush mode (green background) the valve upstream of the chamber inlet is open and the supersaturation with respect to ice (S_i) is below 1, such that only aerosol particles are guided through PINE; during the expansion mode (pink background) the valve is closed and expansion cooling leads to S_i above 1, which leads to ice crystal formation upon INP. Figure taken from Brasseur et al. (2022).

the working principle and validation of PINE, and the measurement guideline document for operation.

The instrument's dimensions are 0.8 x 0.6 x 1.83 m (w x l x h) and it weighs 230 kg. The aerosol inlet of PINE at the chamber entrance has a diameter of 8 mm. PINE's maximum power consumption is 540 W. It can be operated at 110 – 240 VAC. PINE comes with a standard power plug. The operation of the system requires an additional 80 cm space in front of the control panel, and 20 cm on the other three remaining sides (see Figure 2 as an example of the setup in a station).



Figure 2: PINE installed at the Sonnblick Observatory; figure courtesy Pia Bogert.

For setup, the instrument needs to be connected to the station's aerosol inlet (see Section 2), and to an exhaust line. PINE has an included drying system, such that no additional dryers are required. PINE models 3, 4, 5, and 6 require a separate computer, which needs to be connected to the internet and the instrument itself. Higher model numbers have an internal computer, that also needs to be connected to the internet. Then the start-up and measurement procedures are initiated following the manual provided by Bilfinger SE (<https://www.bilfinger.com/de/pine/>).

For a proper operation of PINE, the laboratory should be at stable temperature between 10 °C and 25 °C and a relative humidity with respect to water (RH_w) below 60 %.

3.2. On-site requirement for setting up the HINC-Auto instrument

HINC-Auto (Brunner and Kanji, 2021) (shown in Fig.1) is a fully automated online ice nucleation chamber to measure the number concentration and ice nucleation activity of INPs under mixed-phase- and ice- cloud conditions. HINC-Auto is custom built by ETH Zurich following the working principle of continuous flow diffusion chambers (Al-Naimi and Saunders, 1985; Hussain and Saunders, 1984; Rogers, 1988; Tomlinson and Fukuta, 1985) and is an adaptation of the existing horizontal ice nucleation chamber, HINC (Lacher et al., 2017).

This chamber consists of two horizontally oriented aluminium walls covered by ice (Figure 3a). The temperatures of the two walls are controlled by an external re-circulating ethanol chiller (Figure 3b). The upper wall is held at a warmer temperature than the bottom wall; thereby, heat as well as water vapor are diffused from the warm to the cold wall, establishing linear steady-state temperature and water vapor pressure fields. The thermal gradient across the chamber prevents convection and stabilizes the flow along the chamber. Because the saturation vapor pressure with respect to water and ice are exponential functions of temperature, a supersaturation with respect to ice ($RH_i > 100\%$) is formed between the two walls. Supersaturation with respect to water ($RH_w \geq 100\%$) can be achieved with large enough temperature gradients between the two walls. This design allows HINC-Auto to measure the INPs under a wide range of temperatures and relative humidity conditions ($230\text{ K} < T < 252\text{ K}$, $RH_w < 110\%$).

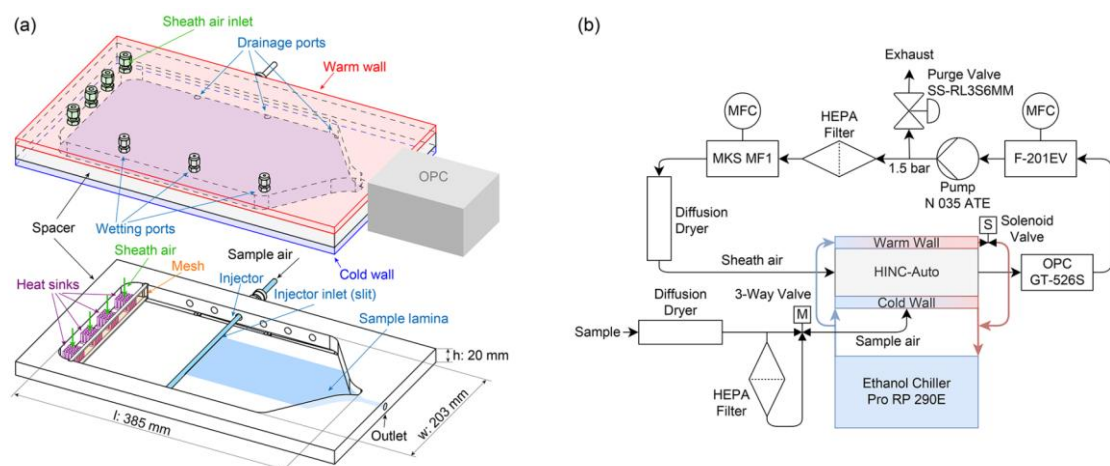


Figure 3: A schematic view of HINC-Auto: (a) the entire chamber and the internal parts (bottom). (b) External components and flow setup. Figure taken from (Brunner and Kanji, 2021).

For measurement, this instrument needs to be connected to an aerosol inlet. Aerosol flow layered in between a particle-free sheath flow is drawn into the chamber and exposed to set T and RH experimental conditions. The sheath air is pre-cooled by the heat-sinks at the chamber sheath gas inlet and its flow uniformised by a mesh to reduce a potential jet effect and the degree of turbulence to maintain a well-developed RH profile within the sampling section. A six-channel OPC is connected downstream of the HINC-Auto to detect the number concentration of the formed ice crystals and thereby the number concentration of INPs. The exhaust air from OPC is filtered with a high-efficiency particulate air (HEPA) filter and recycled back into the chamber as the sheath air. The autonomous measurement, remote control, and

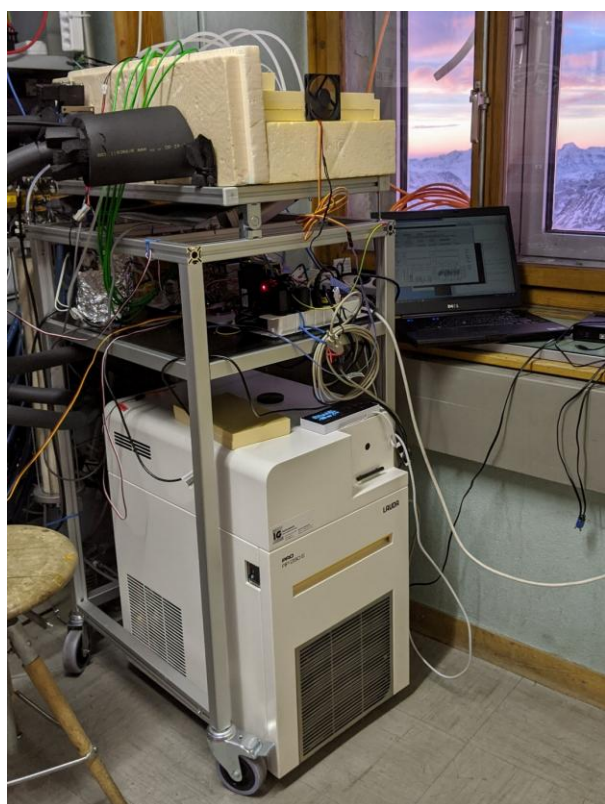


Figure 4: HINC-Auto (in prototype) was deployed for long-term (11 months) continuous INP measurement at the High Altitude Research Station Jungfraujoch JFJ.

the real-time data processing of HINC-Auto are achieved by a custom-developed Python program and GUI. The INP number concentration data collected with a temporal resolution of 20 min and is processed for signal-to-noise ratio and limit of detection and is reported in quasi-real-time (see <https://www.actris.ch/facilities/jungfraujoch/> as an example).

The HINC-Auto has a supersaturation uncertainty of $RH_w = \pm 1.7\%$ and a temperature uncertainty of ± 1.1 K at $T = 243$ K and $RH_w = 104\%$, which is caused by the temperature uncertainty of thermal couples, the temperature variation along and across the walls, together with the displacement of the particles within the center lamina.

The total dimensions of this instrument are 510 x 800 x 1700 mm (W x D x H) including the rack, aerosol dryer, OPC, chiller, etc. (see Figure 4). Operating the instrument requires an additional ca. 300 mm space on the width to accommodate the coolant tubing, and ca. 200 mm on the other three remaining sides to ensure air circulation for the chiller. It weighs approximately 140 kg (50 kg: chamber, accessories including OPC, pump, electronic control board, etc. and 90 kg chiller). The chamber dimension is shown in Figure 3a. The flow setup and other components that are required for a standard measurement are shown in Figure 3b (also see Figure 4 as an example of the setup in the High Altitude Research Station Jungfraujoch, JFJ). HINC-Auto can be operated at 220 V with the 16 A power plug. Its maximum power consumption is 2.8 kW with 2.5 kW for the chiller and the rest for other components (i.e., pump, OPC, electronics, and laptop). The instrument is delivered with a laptop which needs to be connected to the internet for remote control and online display of the INP data. Quasi-realtime data is transferred to remote server via secure shell (SSH) protocol embedded in the python control program. HINC-Auto requires maintenance every 45-60 days depending on the ambient relative humidity, which consists mainly of refilling the deionized water reservoir for rewetting the walls and replacing the molecular sieve dryer material. More details about the startup, calibration, and procedures of HINC-Auto will be presented in the measurement guideline document.

4. Technical requirements for using offline INP instruments

For offline INP measurements, aerosol particles are collected on filters and analysed using droplet freezing assays. In the following, the requirements for INSEKT (Ice Nucleation Spectrometer of the Karlsruhe Institute of Technology; (Schneider et al., 2021), a re-built version of the IS (Ice Spectrometer; Hill et al., 2016) is described. Other than online INP techniques, these methods have a larger sampling volume, which depends on the filter sampling time (typically several days) and the flow applied (typically 5 standard liters per minute, defined at 1013 mbar and 0°C), resulting in a lower limit of detection.

For including other offline techniques than INSEKT or IS or equivalent setups, please contact CCice.

INSEKT investigates the freezing behaviour of aerosol suspensions, mimicking immersion freezing. The measurement temperature is limited to above the freezing of the water that is used to create the suspensions (typically about -25 °C).

4.1. Aerosol sampling units for offline INP instruments

The aerosol sampling units consist of a filter holder, a flow volume control system (preferably using a mass flow controller), and a connection to a pump. As a less preferred alternative to a flow controller, a critical orifice combined with a flowmeter may be used.

Samples must be collected at the whole-air inlet of the observational platform (see Section 2 for a description of the inlet). To minimize losses of larger aerosol particles within the tubing, the filter holder should be installed in close proximity to the inlet.

The aerosol particles are sampled on pre-cleaned filters (e.g. Nuclepore track-etched polycarbonate membrane filters, 0.2 pore size), which are inserted in a filter holder (Figure 5). The filter sampling unit has to be leak-tight, clean, and free of possible contaminants. The filter handling and pre-cleaning procedures require availability to a clean and particle-free workstation, such as a flow box. If the filters are not analysed with INSEKT immediately after the collection of the particles, the filters need to be stored and potentially shipped. Loaded filters need to be handled in a flow box and stored in sterile Petri dishes directly after sampling. The Petri dishes should be wrapped in aluminum foil and stored in a freezer (see also Appendix Section 145.2. for INSEKT consumables).

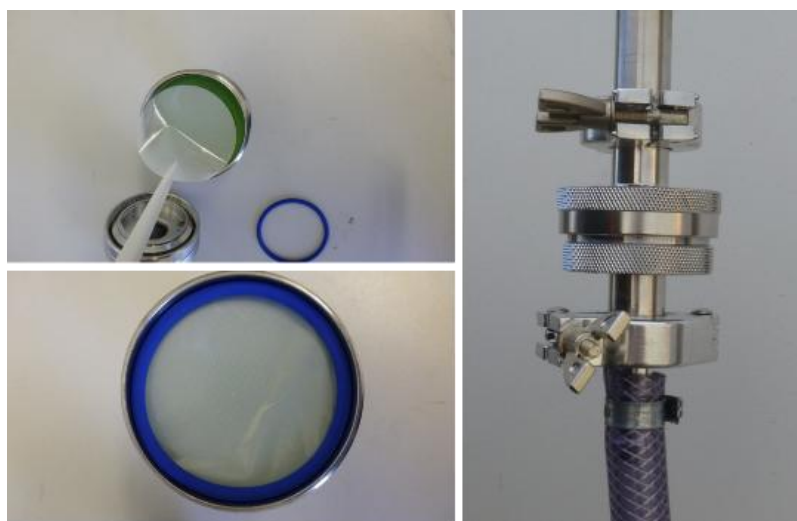


Figure 5: Filter housing with Nuclepore membrane filter

4.2. Off-site requirements for INP analysis

The laboratory analysis of aerosol samples for INP concentrations requires clean working conditions and disciplined and well-trained laboratory personnel (Barry et al., 2021). The laboratory facility used for filter preparation and offline INP analysis must meet high cleanliness standards to prevent contamination. Laboratory personnel must be trained to work in a clean and controlled manner, minimizing the risk of introducing foreign particles (e.g., from skin, clothing, or the work environment).

A clean laboratory space equipped with a flow box for the filter handling is required and particle filters for chemicals and gases needs to be available. Deionized and particle free water, sterile and particle-free consumables, as well as laboratory coats and gloves need to be provided. For INSEKT, Nanopure water is used. The wrong choices of consumables such as particle releasing gloves or test tubes lead to severe contamination of aerosol samples. Thus, all consumables need to be tested for their particle release prior to use, by running blank experiment as described in the measurement guidelines. A list of consumables and instrument description is found in the Appendix Section 5.2.

For the preparation of suspensions, laboratory tubes and a centrifuge or shaking device are required. Ultrasonic devices are not recommended for preparing the aerosol suspensions to reduce the risk of agglomerate-breakup. Usually, the aerosol suspension is stepwise diluted to reach different aerosol concentrations and thus increase the investigated temperature range. Here, sterile, electronic pipettes with low measuring errors should be chosen for adding water to dilute the filter washing water (see description in the measurement guideline document).

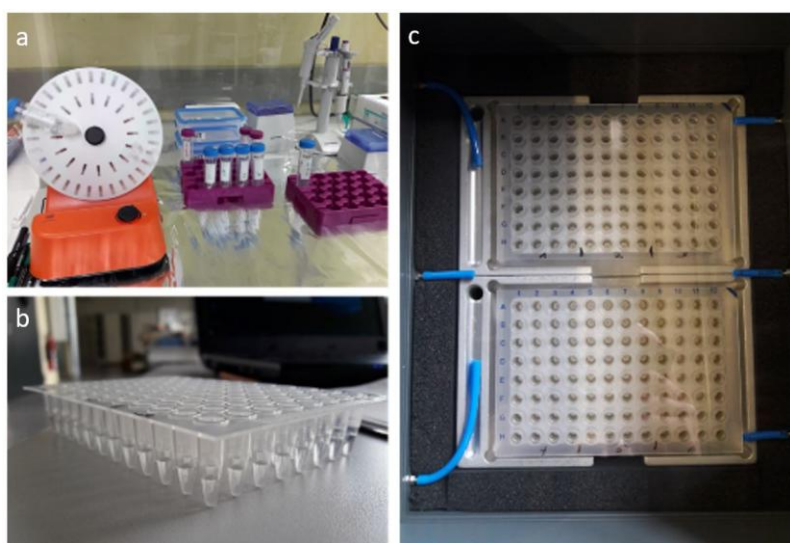


Figure 6: Setup of INSEKT freezing device in the laboratory; centrifuge and tubes (a), PCR plates filled with suspension (b), and in the cooling bath (c).

INSEKT investigates ice formation in the immersion freezing mode. For this, the aerosol particles collected on filters are suspended in Nanopure water by adding the water into a test tube with the filter. Subsequent shaking or the use of a rotator are needed (see e.g. Figure 6a). The aerosol suspension can be further diluted to enlarge the accessible range of freezing temperatures. The aerosol suspension and/or the diluted suspensions are sampled into the wells of the PCR trays, along with a part of the well filled with Nanopure water for determination of the background freezing of the water used for the suspension.

INSEKT consists of two connected 96-well aluminum incubation blocks (see Figure 6b,c). Channels have been drilled in the bottom of the blocks, through which a cooling agent is fed

via an external chiller (e.g. Lauda; Proline RP 890; Lauda Königshofen, Germany). The PCR plates filled with the sample are placed into the respective openings of the incubation blocks. The aluminum blocks are insulated at the bottom and sides and placed in a PVC box with an antireflection coated glass lid. The space between the glass and the PCR plates is flushed with pre-cooled particle-free dry synthetic air to prevent condensation. The temperature of INSEKT is measured at a 2 Hz resolution by eight Pt100 temperature sensors, which are placed inside the aluminum blocks close to the sample location. The freezing of the samples is observed with a camera, detecting the brightness change upon phase change of the water via a polarization filter. Ice spectrometers obtain the temperature-dependent INP concentration in the temperature range above about -25 °C.

A detailed description of the INSEKT can be found in Schneider et al. (2021). The technical setup used at the NFs has to be documented during the ACTRIS labelling process. For custom-built devices that deviate from the INSEKT design, we ask the NF PIs to contact CCIce to discuss the implementation of their instrument.

The measurement guidelines of INSEKT are described in a separate document. These include control of measurement uncertainties due to suspension handling and freezing statistics, calibration of temperature sensors, and data evaluation.

5. Appendix

5.1. Documentation of technical setup

During the planning and set-up of their NF sampling lines and INP instrumentation, NFs are asked to communicate closely with the CCIce unit. CCIce will advise consideration of the individual NF requirements to optimize the INP data quality and to support the labelling process. For granting the ACTRIS label, the NF's specific technical setup has to be documented as an input for the NF instrument database. As the database is still under development, CCIce will provide a template for this documentation, which will include:

Documentation of inlet system:

- Inlet head setup (type, weather protection, prevention of condensation, heating, size range of sampled aerosol, maximum wind speed for proper operation conditions)
- Sampling line setup (line diameter, length, geometry, material, splitters, applied flow)
- Inlet system characterization (sampling losses, cut-off sizes); calculations and measurements
- Changes made to initial setup

Documentation of online INP techniques:

- Instrument (model, serial number)
- OPC (model, serial number)
- Dryers
- Chiller
- Impactors used
- Limit of detection for one experiment
- Operational temperature range
- Changes made to initial instrument setup
- Instrumental uncertainties (temperature measurements; flow uncertainties; INP concentration uncertainties)

Documentation of offline INP techniques - aerosol sampling system and sample storage:

- Filter type
- Filter pore size
- Filter holder
- Flow establishment and control system
- Freezer on-site for filter storage (storage temperature)

Documentation of offline INP techniques - INP measurement system and laboratory equipment:

- Manufacturer and specifications of consumables
- Type of personal protection
- Flow box
- Centrifuge or shaking device
- Manufacturer and purity of chemicals
- Description and specification of INP instrument, including information about
 - Number of wells used
 - Volumes of each droplet in well
 - Chiller model
 - Cooling agent and volume
 - Detection system (e.g., camera model and serial number)

- Instrumental uncertainties (limit of detection; temperature measurements; flow uncertainties)

Available auxiliary measurements:

- Atmospheric pressure
- Ambient temperature
- In- or out-of-cloud conditions
- Wind speed
- Aerosol size distribution
- Aerosol number concentration
- Others: aerosol chemical characterization
- Laboratory temperature

5.2. Consumables for ice spectrometer measurements

This list gives an overview of currently used consumables for INSEKT measurements.

Name	Description	Function
Gloves	disposable latex-free, powder-free	used during all steps
Forceps	polymethylpenten, cleaned with H ₂ O ₂ before use	used to handle filters
Petri dishes	clean/sterile	holds filter between sampling and analysis
Aluminum foil	aluminum foil is baked out before use	provided a clean surface to work on, encapsulates Petri dishes between sampling and analysis
Plastic bags	clean/sterile	used to store multiple Petri dishes encapsulated by aluminum foil in a fridge and to store filter solutions for re-analysis
Disinfectant	bacillocid/virucidal	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 for the different solutions
Pipette tips 0.1-5 ml	0.1-5 ml	used for filling the centrifuge tubes with Nanopure water for filter washing

Pipette tips 50-1000 µl	50-1000 µl	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 15 times before replaced
Laboratory wipes	clean/sterile	used to clean surfaces or filter mount

6. References

- Al-Naimi, R., Saunders, C.P.R., 1985. Measurements of natural deposition and condensation-freezing ice nuclei with a continuous flow chamber. *Atmos. Environ.* 19, 1871–1882. [https://doi.org/10.1016/0004-6981\(85\)90012-5](https://doi.org/10.1016/0004-6981(85)90012-5)
- Barry, K.R., Hill, T.C.J., Jentzsch, C., Moffett, B.F., Stratmann, F., DeMott, P.J., 2021. Pragmatic protocols for working cleanly when measuring ice nucleating particles. *Atmos. Res.* 250, 105419. <https://doi.org/10.1016/j.atmosres.2020.105419>
- Brasseur, Z., Castarède, D., Thomson, E.S., Adams, M.P., Drossaert van Dusseldorp, S., Heikkilä, P., Korhonen, K., Lampilahti, J., Paramonov, M., Schneider, J., Vogel, F., Wu, Y., Abbatt, J.P.D., Atanasova, N.S., Bamford, D.H., Bertozzi, B., Boyer, M., Brus, D., Daily, M.I., Fösig, R., Gute, E., Harrison, A.D., Hietala, P., Höhler, K., Kanji, Z.A., Keskinen, J., Lacher, L., Lampimäki, M., Levula, J., Manninen, A., Nadolny, J., Peltola, M., Porter, G.C.E., Poutanen, P., Proske, U., Schorr, T., Silas Umo, N., Stenszky, J., Virtanen, A., Moiseev, D., Kulmala, M., Murray, B.J., Petäjä, T., Möhler, O., Duplissy, J., 2022. Measurement report: Introduction to the HyICE-2018 campaign for measurements of ice-nucleating particles and instrument inter-comparison in the Hyytiälä boreal forest. *Atmos. Chem. Phys.* 22, 5117–5145. <https://doi.org/10.5194/acp-22-5117-2022>
- Brunner, C., Kanji, Z.A., 2021. Continuous online monitoring of ice-nucleating particles: development of the automated Horizontal Ice Nucleation Chamber (HINC-Auto). *Atmos. Meas. Tech.* 14, 269–293. <https://doi.org/10.5194/amt-14-269-2021>
- Hill, T.C.J., DeMott, P.J., Tobo, Y., Fröhlich-Nowoisky, J., Moffett, B.F., Franc, G.D., Kreidenweis, S.M., 2016. Sources of organic ice nucleating particles in soils. *Atmos. Chem. Phys.* 16, 7195–7211. <https://doi.org/10.5194/acp-16-7195-2016>
- Höhler, K., Lacher, L., Böhmländer, A., Hamel, A., Möhler, O., Zhang, C., Kanji, Z., Büttner, N., Fösig, R., 2026. Measurement guidelines for ice-nucleating particle measurements. <https://doi.org/10.5281/zenodo.22893994>

- Hoose, C., Möhler, O., 2012. Heterogeneous ice nucleation on atmospheric aerosols: a review of results from laboratory experiments. *Atmos. Chem. Phys.* 12, 9817–9854. <https://doi.org/10.5194/acp-12-9817-2012>
- Hussain, K., Saunders, C.P.R., 1984. Ice nucleus measurement with a continuous flow chamber. *Q. J. R. Meteorol. Soc.* 110, 75–84. <https://doi.org/10.1002/qj.49711046307>
- Lacher, L., Lohmann, U., Boose, Y., Zipori, A., Herrmann, E., Bukowiecki, N., Steinbacher, M., Kanji, Z.A., 2017. The Horizontal Ice Nucleation Chamber (HINC): INP measurements at conditions relevant for mixed-phase clouds at the High Altitude Research Station Jungfraujoch. *Atmos. Chem. Phys.* 17, 15199–15224. <https://doi.org/10.5194/acp-17-15199-2017>
- Möhler, O., Adams, M., Lacher, L., Vogel, F., Nadolny, J., Ullrich, R., Boffo, C., Pfeuffer, T., Hobl, A., Weiß, M., Vepuri, H.S.K., Hiranuma, N., Murray, B.J., 2021. The Portable Ice Nucleation Experiment (PINE): a new online instrument for laboratory studies and automated long-term field observations of ice-nucleating particles. *Atmos. Meas. Tech.* 14, 1143–1166. <https://doi.org/10.5194/amt-14-1143-2021>
- Möhler, O., Stetzer, O., Schaefers, S., Linke, C., Schnaiter, M., Tiede, R., Saathoff, H., Krämer, M., Mangold, A., Budz, P., Zink, P., Schreiner, J., Mauersberger, K., Haag, W., Kärcher, B., Schurath, U., 2003. Experimental investigation of homogeneous freezing of sulphuric acid particles in the aerosol chamber AIDA. *Atmos. Chem. Phys.* 3, 211–223. <https://doi.org/10.5194/acp-3-211-2003>
- Pummer, B.G., Budke, C., Augustin-Bauditz, S., Niedermeier, D., Felgitsch, L., Kampf, C.J., Huber, R.G., Liedl, K.R., Loerting, T., Moschen, T., Schauperl, M., Tollinger, M., Morris, C.E., Wex, H., Grothe, H., Pöschl, U., Koop, T., Fröhlich-Nowoisky, J., 2015. Ice nucleation by water-soluble macromolecules. *Atmos. Chem. Phys.* 15, 4077–4091. <https://doi.org/10.5194/acp-15-4077-2015>
- Rogers, D.C., 1988. Development of a continuous flow thermal gradient diffusion chamber for ice nucleation studies. *Atmos. Res.* 22, 149–181. [https://doi.org/10.1016/0169-8095\(88\)90005-1](https://doi.org/10.1016/0169-8095(88)90005-1)
- Schneider, J., Höhler, K., Heikkilä, P., Keskinen, J., Bertozzi, B., Bogert, P., Schorr, T., Umo, N.S., Vogel, F., Brasseur, Z., Wu, Y., Hakala, S., Duplissy, J., Moiseev, D., Kulmala, M., Adams, M.P., Murray, B.J., Korhonen, K., Hao, L., Thomson, E.S., Castarède, D., Leisner, T., Petäjä, T., Möhler, O., 2021. The seasonal cycle of ice-nucleating particles linked to the abundance of biogenic aerosol in boreal forests. *Atmos. Chem. Phys.* 21, 3899–3918. <https://doi.org/10.5194/acp-21-3899-2021>
- Tomlinson, E.M., Fukuta, N., 1985. A New Horizontal Gradient, Continuous Flow, Ice Thermal Diffusion Chamber. *J. Atmos. Ocean. Technol.* 2, 448–467. [https://doi.org/10.1175/1520-0426\(1985\)002%3C0448:ANHGCF%3E2.0.CO;2](https://doi.org/10.1175/1520-0426(1985)002%3C0448:ANHGCF%3E2.0.CO;2)

