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Atmospheric System Research Workshop Report

New Directions in Atmospheric Ice Processes Research

U.S. DEPARTMENT *of* ENERGY

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Biological and Environmental Research Program

Atmospheric System Research (ASR) Workshop on New Directions in Atmospheric Ice Processes Research

HELD OCTOBER 25–27, 2023

Convened by
U.S. Department of Energy
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ORGANIZING COMMITTEE:

Daniel A. Knopf, Stony Brook University

Susannah Burrows, Pacific Northwest National Laboratory

Jessie Creamean, Colorado State University

REPORT AUTHORS:

Donifan Barahona, NASA - Goddard Space Flight Center

Allan Bertram, University of British Columbia

Sisi Chen, NSF National Center for Atmospheric Research

Minghui Diao, San Jose State University

Jiwen Fan, Argonne National Laboratory

Laura Fierce, Pacific Northwest National Laboratory

Jeff French, University of Wyoming

Ann Fridlind, NASA - Goddard Institute for Space Studies

Zamin Kanji, ETH Zurich

Pavlos Kollias, Stony Brook University

Alexei Korolev, Environment Canada

Alex Laskin, Purdue University

Xiaohong Liu, Texas A&M University

Christina McCluskey, NSF National Center for Atmospheric Research

Ottmar Möhler, Karlsruhe Institute of Technology

Mikhail Ovchinnikov, Pacific Northwest National Laboratory

Vaughan Phillips, Lund University

Raymond Shaw, Michigan Technological University

Matthew Shupe, University of Colorado and National Oceanic and Atmospheric Administration

Israel Silber, Pacific Northwest National Laboratory

Frank Stratmann, Leibniz Institute for Tropospheric Research

Ivy Tan, McGill University

Fan Yang, Brookhaven National Laboratory

Kai Zhang, Pacific Northwest National Laboratory

Xue Zheng, Lawrence Livermore National Laboratory

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Cover Image: The physics of cloud ice is complex, beautiful, and plays an important role in the development and evolution of clouds and precipitation. This image shows a view of a stratocumulus cloud deck, with superimposed images of ice crystals highlighting their intricate and varied geometric structures, or "habits."
Composite Image by Stephanie King | Pacific Northwest National Laboratory

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EXECUTIVE SUMMARY

Atmospheric ice processes are critical for precipitation production, cloud dynamics, and radiative properties and contribute to uncertainties in Earth's energy budget and hydrological cycle, yet they remain poorly understood. To address this, ASR convened a 2.5-day workshop with 28 experts in laboratory measurements, field observations, and cloud modeling. The primary goal was to identify key knowledge gaps and prioritize future directions in atmospheric ice processes research. The outcomes of this workshop are expected to inform ASR and prompt improvements in cloud and Earth system models (ESMs) by advancing the fundamental understanding of ice processes.

Key Knowledge Gaps in Ice Processes

1. **Ice crystal production and growth:** Primary ice production (PIP) and secondary ice production (SIP) are the fundamental drivers of ice formation in clouds, shaping the number and mass of ice crystals.

- Even with recent reinvigoration in understanding PIP, a unified theory for ice nucleating particles (INPs) with comprehensive experimental validation is still deficient. Models still struggle to accurately represent PIP and its impact on cloud microphysics.
- While eight SIP mechanisms have been identified, their relative importance and rates under various atmospheric conditions remain poorly quantified. Many cloud-scale, regional, and Earth system models do not yet include SIP parameterizations.
- The processes governing ice crystal growth, evolution, and interaction with the supercooled liquid phase also require further study.

2. **Cloud-scale processes:**

- Reliable measurements of the ice phase are lacking, particularly for small ice crystals (<100 μm) which are critical for validating PIP and SIP in models.
- It remains unclear how ice processes scale up to influence cloud systems, particularly in the presence of small-scale variations in cloud properties and vertical motions that are not resolved in ESMs.
- Water vapor supersaturation—an essential controlling parameter for both PIP and SIP—is difficult to measure accurately and the small-scale vertical motions driving supersaturation are poorly characterized.

Proposed Solutions

Workshop participants discussed a range of solutions with varying degrees of complexity. The participants categorized the proposed solutions into three groups: (1) immediate solutions achievable with current capabilities with moderate investment; (2) intermediate solutions requiring some capability development or adaptation of existing tools to address new challenges; and (3) long-term solutions necessitating substantial development of new methods or capabilities and infrastructure.

- **Immediate solutions:**
  - Perform targeted experiments and closure studies to intercompare and validate INP parameterizations.
  - Conduct a hypothesis-driven analysis of existing remote sensing data to better understand cloud ice formation across different regimes.

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- **Intermediate solutions:**
  - Source attribution studies for biological INPs to identify the environmental factors driving their emissions.
  - Conduct laboratory, field, and modeling studies to explore how atmospheric transport alters INP concentrations and efficacy.
  - Assess the robustness of current ice formation pathways through multi-model sensitivity studies.
  - Use benchtop and vertical wind tunnel experiments to study high-priority SIP processes, like freezing-induced shattering, ice-ice collisions, and rime-splintering.
  - Perform Lagrangian observational studies to track cloud processes over time to obtain dynamic insights that are difficult to capture with current methods.
- **Long-Term Solutions:**
  - Develop new and improved instrumentation to measure concentrations, composition, sources, and variability of INPs—especially for size-resolved INPs, supermicron INPs, and the biological and organic particles that nucleate ice at warmer temperatures. Co-location with comprehensive physico-chemical measurements of aerosols and cloud ice residuals would be ideal.
  - Develop new instrumentation to measure supersaturation, vertical motions, and small ice crystals, emphasizing rapid deployment in the field to accelerate scientific progress.
  - Enhance integration of observational data into models through stronger interdisciplinary collaboration between experimentalists, theorists, modelers, and instrument developers.
  - Develop novel methods, including methods leveraging machine learning, to bridge the gap between microscale processes and ESMs.
  - Innovate the design of field campaigns by using models to more rigorously inform measurement priorities.
  - Longer-term monitoring of both INPs and aerosols at high-time resolution for comparison with models that enable detailed correlation analysis between temperature-dependent INP variability and related driving parameters, like aerosols, air mass origin, or meteorological conditions.
  - Design and build advanced new cloud chamber capabilities to simulate SIP processes under realistic, turbulent cloud conditions.
  - Develop and refine parameterizations of ice microphysics for use in ESMs that are grounded in an improved understanding from field, laboratory, and high-resolution modeling studies.

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1. INTRODUCTION AND MOTIVATION

Achieving a process-level and predictive understanding of the atmospheric ice phase is one of the grand challenges in the atmospheric sciences. Gaps in current understanding of primary and secondary cloud ice formation processes, and their impacts on cloud evolution, significantly limit the ability of Earth system models (ESMs) to predict future changes in Earth's radiative balance and hydrological cycle. In October 2023, an international workshop was convened in Richland, Washington, USA, to pinpoint critical knowledge gaps related to atmospheric ice processes and outline the necessary research to bridge those gaps. Addressing these challenges is essential for improving the fundamental understanding and predictability of the Earth system.

Ice formation and growth processes impact the atmosphere via multiple pathways. It not only determines the lifecycle of synoptic *in situ* cirrus, but also strongly impacts precipitation of the ice phase in stratiform, orographic, and convective clouds at mid-latitudes and higher, as well as detrainment from widespread deep convection throughout the tropics and mid-latitudes. Figure 1 provides a schematic overview of these processes.

The fundamental gaps in both understanding of ice processes and representation of their emergent effects in large-scale models are a long-standing scientific challenge (2003 National Academies Report: "Critical Issues in Weather Modification Research") that significantly contribute to uncertainties in atmospheric models across scales, including regional and global storm-resolving models (Fan et al., 2017a, b; Sullivan and Voigt, 2021) as well as conventional coarse-resolution global models. Additionally, atmospheric ice processes are a major source of uncertainty in operational weather forecasting; this is especially relevant to civil and military applications that are sensitive to high loading of small ice crystals, icing by supercooled drops, or visibility.

During the past several decades, the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility, Atmospheric System Research (ASR) program, and predecessor programs have contributed to significant progress in understanding atmospheric ice processes, including:

(1) conducting field campaigns (e.g., Indirect and Semi-Direct Aerosol Campaign [McFarquhar et al., 2011], Mixed-Phase Arctic Cloud Experiment [Verlinde et al., 2007], Surface Heat Budget of the Arctic program [SHEBA; Uttal et al., 2002], Multidisciplinary drifting Observatory for the Study of Arctic Climate [MOSAiC; Shupe et al., 2022], ARM Cloud Aerosol Precipitation Experiment [ACAPEX; Leung, 2016], Tropical Warm Pool – International Cloud Experiment [Fridlind et al., 2012a], Storm Peak Validation Experiment [STORMVEX; Cziczo, 2016], Aerosol-Ice Formation Closure Pilot Study [AEROICESTUDY; Knopf et al. 2021] and many others;

(2) developing novel ground-based remote sensing and retrieval products (e.g., ARSCL (Active Remote Sensing of Clouds), MIXCRA (the MIXed-phase Cloud property Retrieval Algorithm), and the ShupeTurner product); and

(3) leading and contributing to model intercomparison studies (e.g., ARM summer 1997 Single-Column-Model Intensive Observational Period) of a continental deep convection case; ARM March 2000 cloud intensive observational period on midlatitude cirrus clouds, Idealized Cirrus Model Comparison Project and Cirrus Parcel Model Comparison Project; Working Group 1 ARM, continental shallow convection case; TWP-ICE; Mid-latitude Continental Convective Clouds Experiment;

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Squall Line Cloud-Resolving Model Intercomparison [Fan et al., 2017a; Han et al., 2019]; M-PACE, SHEBA, and Indirect and Semi-Direct Aerosol Campaign Arctic mixed-phase clouds [Klein et al., 2009; Morrison et al., 2011; Ovchinnikov et al., 2014]; and ongoing activities, such as Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE)-Model Intercomparison Project).

Together, these efforts have substantially contributed to scientists' current understanding of cloud ice formation and growth processes at different latitudinal regions. However, as described in this document, critical knowledge gaps remain in the fundamental understanding of these processes.

The purpose of this workshop report is to inform the ASR program about the most important current scientific gaps and priorities in atmospheric ice processes research. The report particularly highlights opportunities to leverage existing and new capabilities and datasets from the ARM research facility to address these knowledge gaps, including using long-term datasets from ground-based remote sensing, careful design of field experiments, and improved integration of measurements and models.

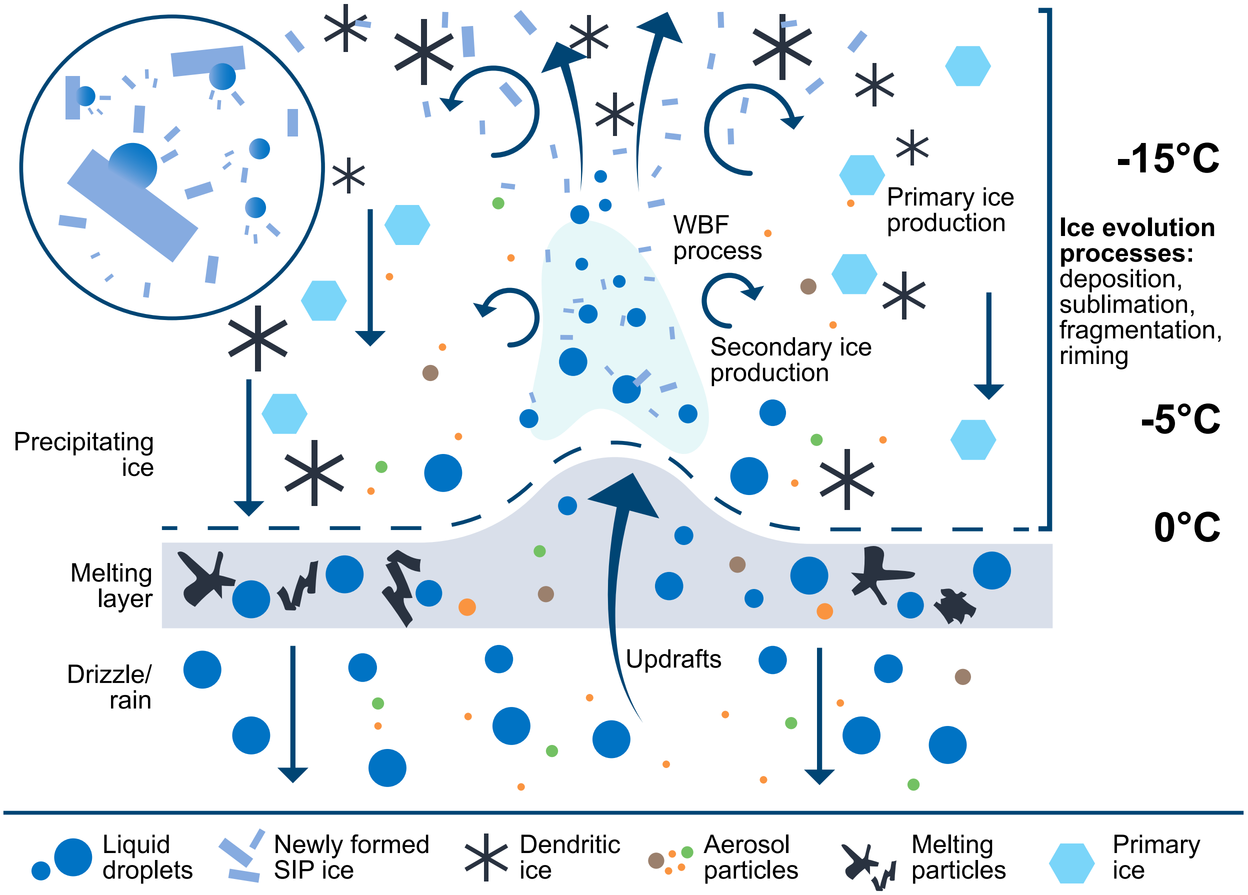

Figure 1. Overview of ice processes in clouds, adapted from Korolev et al. (2020). Cloud ice is formed through both primary and secondary ice production and evolves through multiple processes that modify ice crystal size and morphology.

2. PERSPECTIVES FROM DOE ASR

The **goal of ASR** *"is to improve understanding of the key cloud, aerosol, precipitation, and radiation processes that affect the Earth's radiative balance and hydrological cycle, especially processes that limit the predictive ability of regional and global models."* Atmospheric ice processes directly impact both radiation and precipitation budgets. However, scientists' incomplete fundamental understanding of these processes and the challenges of accurately representing their impacts on clouds limit the predictive capabilities of ESMs to inform questions involving the energy sector.

The **ARM research facility** provides strategically located *in situ* and remote-sensing observatories designed to improve the understanding and model representation of clouds, aerosols, and their interactions, as well as their coupling with the Earth's surface.

Due to the close relationship between ASR and ARM, this report emphasizes opportunities to leverage existing and new ARM capabilities and datasets to advance the understanding of atmospheric ice processes. These opportunities include analysis of long-term datasets from ground-based remote sensing, Lagrangian field experiments utilizing ARM atmospheric measurement facilities and aerial capabilities, and multi-model intercomparison studies using cases from past or future ARM field experiments.

3. WORKSHOP FORMAT

This workshop was initiated by ASR program managers and the workshop cochairs during the October 2022 Joint ARM User Facility and ASR Principal Investigator Meeting. In spring 2023, DOE funding was acquired to include international and non-ASR-supported experts. In May 2023, potential participants were invited to apply to the workshop and respond via a survey, which identified opportunities, knowledge gaps, and technology barriers in atmospheric ice processes research. In August 2023, potential attendees were informed and requested to register for this workshop. Almost all invitees responded affirmatively. The agenda was sent to all attendees two weeks before the workshop.

The workshop mornings focused on brief overview presentations in laboratory and field observations and modeling, outlining the status quo and knowledge gaps and then followed with a discussion. Afterwards, attendees divided into breakout sessions, which focused on laboratory measurements, field observations, or modeling. Each attendee participated in one focus group. Rapporteurs for each focus group then prepared summary slides which were discussed with all workshop participants at the end of the day. All notes and documents were shared among all attendees throughout and after the workshop. Details of the workshop agenda and participants are given in the Appendix.

SPONSOR: Department of Energy, Office of Science, Biological and Environmental Research, Atmospheric System Research.

WHEN: October 25–27, 2023; 9:00 am to 5:30 pm; 8:30 am to 5:00 pm; 8:30 am to noon, Pacific Daylight Time.

WHERE: Pacific Northwest National Laboratory, Richland, WA.

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INVITEES: Approximately 28 scientific experts covering primary and secondary ice processes in laboratory measurements, field observations, and cloud-resolving and Earth system modeling; ASR program managers joined virtually.

DESIRED OUTCOME: A workshop report and a possible peer-reviewed perspective document assessing current knowledge gaps and providing suggestions for research opportunities that focus on the physical mechanisms of ice production and evolution processes in laboratory, field, and model settings.

TOPIC AREAS: Primary ice nucleation, secondary ice production processes, aerosol, mixed-phase and cirrus clouds, laboratory and field measurements, and modeling studies.

SKILL SETS OF ATTENDEES: Laboratory measurements of primary and secondary ice processes; field observations (ground-based and airborne); remote sensing and modeling at a range of scales, including large-eddy simulations (LES), regional, and global models.

FORMAT: The workshop took place over 2.5 days; the first two days consisted of about three hours per day of short presentations that were immediately followed by extended discussions. This was followed by two daily breakout sessions with three groups reflecting on laboratory, field, and modeling areas guided by identified knowledge gaps. Day three consisted of a general discussion with all attendees to integrate, synthesize, and summarize the findings from the previous two days of discussions.

OTHER: By invitation and in-person only; no recordings. Invitees committed to engage in the entire meeting and contribute to writing this report.

4. KEY SCIENCE QUESTIONS AND KNOWLEDGE GAPS

Over the past two decades, scientists' understanding of atmospheric ice nucleation, also called primary ice production (PIP), has undergone remarkable advancement. In addition to improving the understanding of homogeneous freezing of aerosol solutions at highly supercooled temperatures, the scientific community has meticulously characterized numerous varieties of ice INPs that promote freezing at higher temperatures and lower relative humidities, including mineral dust, sea spray, and select proteins and organics (Burrows et al., 2022; Kanji et al., 2017; Knopf et al., 2018; Lukas et al., 2022; Murray and Liu, 2022). Furthermore, notable progress has been made in identifying a diverse array of biological ice nucleating particles (bio-INPs), such as primary biological aerosol particles and other macromolecules (e.g., Augustin et al., 2013; Després et al., 2012). PIP parameterizations have been formulated to leverage field and laboratory data, taking into account aerosol properties as well as thermodynamic and dynamic conditions (DeMott et al., 2010; Jakobsson et al., 2022; Knopf and Alpert, 2013; Li et al., 2022; McCluskey et al., 2018; Niemand et al., 2012; Schneider et al., 2021; Wieder et al., 2022). INP-aerosol closure studies using ground-based and remote sensing observations have begun to investigate whether parameterizations can use observed aerosol characteristics to predict INP concentrations observed in the ambient atmosphere (Ansmann et al., 2019; Knopf et al., 2021; Mamouri et al., 2023; McCluskey et al., 2023).

However, under certain conditions with significant variability in particle size or composition, different methods of measuring INPs can yield results that vary by an order of magnitude (Alpert and Knopf, 2016; Cabriolu and Li, 2015; Cornwell et al., 2023; Knopf and Alpert, 2023). Limitations remain in

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measuring and characterizing the full aerosol size distribution to the largest sizes, which complicates observational INP closure studies. Furthermore, there is ongoing debate regarding the most appropriate theoretical methods for simulating ice nucleation in various applications. These discrepancies contribute to uncertainties in interpreting and applying observations from various instruments to improve atmospheric models (Raman et al., 2023).

Secondary ice production (SIP) remains a critical and persistent challenge in cloud microphysics (Field et al., 2017; Korolev et al., 2020; Phillips et al., 2018; Sullivan and Voigt, 2021). A lack of measurement capabilities and laboratory constraints of SIP poses a massive barrier in experts' understanding and limits numerical representations of mixed-phase clouds that impact estimates of cloud feedback. In contrast to PIP, where an INP leads to an ice crystal, SIP involves the formation of single or multiple new ice particles from pre-existing ones, with the potential for exponentially increasing production of many ice particles through a process often referred to as ice multiplication. At least eight physical mechanisms for SIP have been proposed, as outlined in Table 1 (James et al., 2021; Knight, 2012; Korolev and Leisner, 2020).

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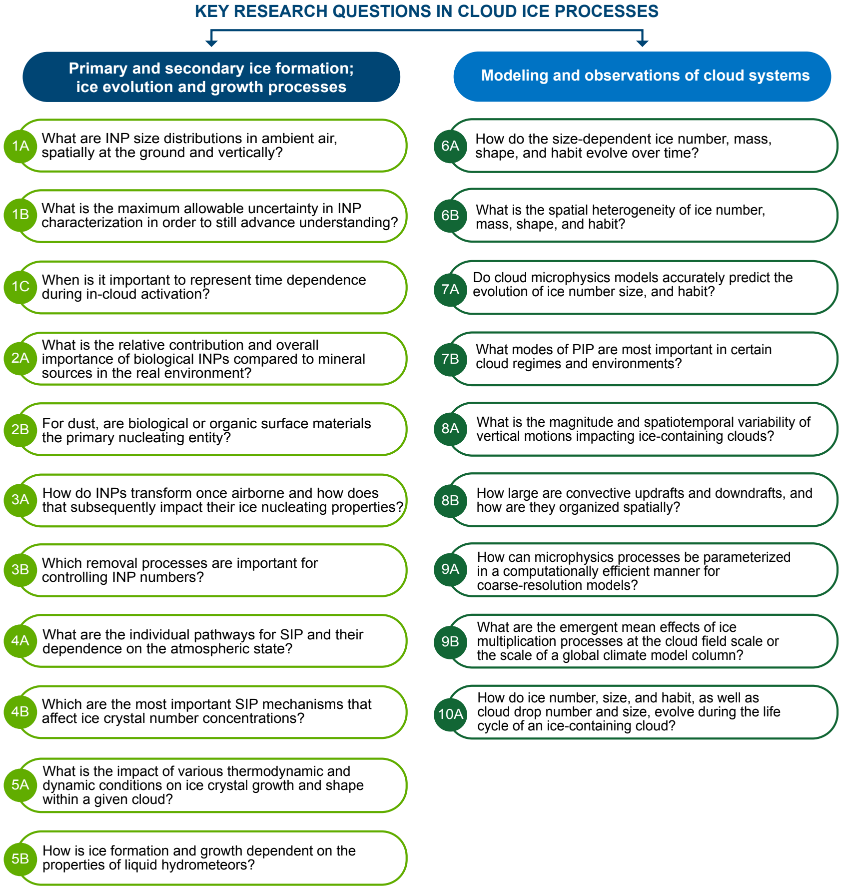
Table 1. Current proposed SIP pathways, including the experiment type needed to test these pathways, research priority rating, and anticipated level of difficulty of quantifying each process as a function of atmospheric state of each pathway.

SIP pathway	Experiment type	Priority based on expert judgment of atmospheric importance	Level of difficulty (Low / Moderate / High)
Single-hydrometeor SIP processes			
Shattering during freezing	Benchtop	High	Moderate
Ice particle fragmentation due to thermal shock	Benchtop	Moderate	Moderate
Fragmentation during ice growth	Benchtop	Moderate	Low
Fragmentation of sublimating ice	Benchtop	Low	Moderate
Two-hydrometeor SIP processes			
Fragmentation due to ice-ice collision	Benchtop and vertical wind tunnel	High	Moderate
Rime-splintering (H-M)	Benchtop and vertical wind tunnel	High	Moderate
Fragmentation of supercooled water via impact with large ice	Vertical wind tunnel	Moderate	High
Activation of INPs in transient supersaturation around freezing drops	Vertical wind tunnel Cloud chamber	Low	High
SIP with ensembles of hydrometeors			
Ice multiplication due to multi-hydrometeor SIP processes under realistic turbulent cloud conditions	Cloud chamber	High	High
	Remote Sensing	High	Moderate

In total, there are at least eleven documented mechanisms through which ice can form in the atmosphere, including at least three by PIP and at least the proposed eight by SIP. Despite recent advances in instrumentation technologies (e.g., Seidel et al., 2024), significant technical hurdles persist in accurately quantifying key variables, such as the number concentration of INPs, rates of cloud ice crystal production, ice crystal number and mass concentrations, and supersaturation. Moreover, in numerous cloud regimes, pinpointing the specific processes predominantly responsible for ice formation and growth poses a formidable challenge. Consequently, the development of improved predictive capabilities for atmospheric ice formation and evolution, as well as the emergent large-scale impacts of ice processes on clouds, the energy budget, and the hydrological cycle, has remained a central focus of research endeavors for decades.

What is limiting progress? The workshop participants identified three critical limitations that constrain the field: (i) shortfalls of current *in situ* ice observation technologies, (ii) insufficient laboratory constraints on key processes, and (iii) the need to strengthen model-data integration by both leveraging proven strategies and developing new methods to more effectively use process-level observations for model assessment and development.



KEY RESEARCH QUESTIONS IN CLOUD ICE PROCESSES

Primary and secondary ice formation; ice evolution and growth processes

1A What are INP size distributions in ambient air, spatially at the ground and vertically?

1B What is the maximum allowable uncertainty in INP characterization in order to still advance understanding?

1C When is it important to represent time dependence during in-cloud activation?

2A What is the relative contribution and overall importance of biological INPs compared to mineral sources in the real environment?

2B For dust, are biological or organic surface materials the primary nucleating entity?

3A How do INPs transform once airborne and how does that subsequently impact their ice nucleating properties?

3B Which removal processes are important for controlling INP numbers?

4A What are the individual pathways for SIP and their dependence on the atmospheric state?

4B Which are the most important SIP mechanisms that affect ice crystal number concentrations?

5A What is the impact of various thermodynamic and dynamic conditions on ice crystal growth and shape within a given cloud?

5B How is ice formation and growth dependent on the properties of liquid hydrometeors?

Modeling and observations of cloud systems

6A How do the size-dependent ice number, mass, shape, and habit evolve over time?

6B What is the spatial heterogeneity of ice number, mass, shape, and habit?

7A Do cloud microphysics models accurately predict the evolution of ice number size, and habit?

7B What modes of PIP are most important in certain cloud regimes and environments?

8A What is the magnitude and spatiotemporal variability of vertical motions impacting ice-containing clouds?

8B How large are convective updrafts and downdrafts, and how are they organized spatially?

9A How can microphysics processes be parameterized in a computationally efficient manner for coarse-resolution models?

9B What are the emergent mean effects of ice multiplication processes at the cloud field scale or the scale of a global climate model column?

10A How do ice number, size, and habit, as well as cloud drop number and size, evolve during the life cycle of an ice-containing cloud?

Figure 2. The main topical areas for cloud ice process research discussed at the workshop and key research questions associated with each. Details are provided in Table 2.

What are the key research questions used to address to advance progress? Figure 2 summarizes the key research questions that fall under each research gap described in Table 2. Key gaps and research questions are broken down into two main categories: (1) PIP and SIP; ice evolution and growth processes; and (2) modeling and observations of cloud systems. Table 2 summarizes the solutions and approaches needed to address the questions, along with their deliverables and expected difficulty levels, which are discussed in detail in Sections 5 and 6. An overall workshop summary is provided in Section 7.

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Table 2: Overview of key science knowledge gaps, their solutions and technical approaches, and level of difficulty for addressing key research questions discussed in this workshop report. Difficulty is rated as 'low' when research questions can be addressed with current technology. 'Moderate' indicates that while required methods are not widely available or have important limitations, some community experience is available to achieve expected results. 'High' denotes that the necessary laboratory, modeling, or field instrumentation capabilities are not yet available to address the science question, and field campaigns or modeling studies have not yet been conducted in the required way to respond to the research questions.

Key science gap & associated research questions	Solution(s)	Approach(es)	Deliverable(s)	Level of difficulty (Low/Moderate/High)
Primary and secondary ice formation; ice evolution and growth processes				
1. INP physicochemical properties and how those translate to parameterizations of primary freezing. **1a)** What are INP size distributions in ambient air, spatially at the ground and vertically? **1b)** What is the maximum allowable uncertainty in INP characterization in order to still advance understanding? **1c)** When is it important to represent time dependence during in-cloud activation?	Additional field studies on ambient INP populations, emphasizing: **(1)** INP closure studies, and **(2)** exploratory studies targeting a range of specific and diverse INP populations.	Field measurements of aerosol and INPs including size-resolved composition and full size distribution, especially in the supermicron range.	Improved understanding of the full range of INP sizes (especially in the supermicron regime), and tests of INP parameterizations (INP closure) under ambient field conditions.	**High**
	Laboratory experiments designed to test theory, especially on mixed-source INP populations.	Intercomparison of theoretical approaches using benchtop experiments with multiple instruments. Aim for a unifying theory that accurately predicts ice nucleation across time scales.	Improved understanding of and confidence in theoretical approaches to modeling primary ice formation under a wide range of realistic environmental conditions.	**Low**
	Experiments to understand primary freezing kinetics in the presence of diverse aerosol populations.	Cloud chamber experiments with externally- and internally-mixed aerosol populations, paired with associated process modeling.	Validation of microphysical process understanding of primary ice formation kinetics.	**High**
	Instrument development.	Development of new capabilities to measure supermicron INP abundance and composition.	Improved understanding of a potentially significant portion of the INP population that is typically unobserved.	**Moderate to High**
		Modification and improvement of existing INP measurement techniques, including instrument intercomparisons.	Reduce measurement uncertainty to obtain accurate INP numbers and increase sampling efficiencies for higher time resolution data across the temperature spectrum.	**High**

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Key science gap & associated research questions	Solution(s)	Approach(es)	Deliverable(s)	Level of difficulty (Low/Moderate/High)
2. Biological (bio-)INP sources and atmospheric relevance. **2a)** What is the relative contribution and overall importance of biological INPs compared to mineral sources in the real environment? **2b)** For dust, are biological or organic surface materials the primary nucleating entity?	Instrument development to enable more accurate quantification of ambient INPs at temperatures from -2 to -15°C.	Development of novel measurement techniques that can probe warmer freezing temperatures with high throughput down to a single-particle level.	More specific characterization of bio-INPs, and of primary freezing in the warm-temperature regime.	**High**
	Source attribution studies for biological INPs.	Field measurements of bioaerosols and INPs, accompanied by source-receptor modeling in a wide range of ecosystems.	Determine biological INP sources and quantities, and the controlling land surface properties and meteorological conditions.	**Moderate**
3. The life cycle of INPs. **3a)** How do INPs transform once airborne and how does that subsequently impact their ice nucleating properties? **3b)** Which removal processes are important for controlling INP numbers?	Laboratory studies of physical and chemical aging processes representative of long-range transport and cloud processes, and their effects on INP propensities and INP closure studies.	Benchtop studies exposing laboratory-generated INPs to a range of physical and chemical aging effects.	In-situ molecular and single-particle characterization of the impacts of physical (e.g., coagulation, condensation, fragmentation) and chemical transformation (e.g., multiphase chemical processes, cloud aqueous chemistry) on typical INP types under both simpler controlled conditions and more complex, realistic ambient conditions.	**High**
		Smog chamber studies characterizing physicochemical aging processes of INPs.		**High**
		Cloud chamber studies characterizing INPs from diverse aerosol populations that have undergone physicochemical aging processes representative of long-range transport.	Determine conditions of ice formation as a function of physicochemical aging processes under a range of aerosol populations.	**High**
	Field measurements of aging and transformation effects on INPs.	Lagrangian field measurements that characterize the physicochemical properties of INPs during transport.	Determine the change in INP propensities during atmospheric transport as a result of photochemical and physical transformation processes.	**High**
	Process modeling accounting for sources, sinks, and transformation of INPs.	Detailed cloud-resolving models at high spatial and temporal resolution with prognostic INPs.	Understand the impacts of various source, sink, and transformation processes on the availability of INPs to clouds.	**Moderate to High**

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Key science gap & associated research questions	Solution(s)	Approach(es)	Deliverable(s)	Level of difficulty (Low/Moderate/High)
4. A fundamental understanding of secondary ice production (SIP) processes. **4a)** What are the individual pathways for SIP and their dependence on the atmospheric state? **4b)** Which are the most important SIP mechanisms that affect ice crystal number concentrations?	Novel laboratory experiments to isolate and quantify SIP processes under a range of atmospheric conditions. Some experiments will require new laboratory capabilities. Field measurements targeting SIP in clouds via remote sensing.	Benchtop cloud chambers that study SIP involving 1-2 hydrometeors to improve physical and quantitative understanding of ice production from individual SIP mechanisms as a function of atmospheric state.	Single-hydrometeor SIP under accurate control of major environmental parameters. Validation of existing SIP parameterizations and development of new parameterizations of SIP processes.	**Moderate**
		Vertical wind tunnel experiments employing hydrometeors to realistically simulate droplet-ice and ice-ice collisions.		**High**
		Cloud chamber experiments to validate predictive understanding in realistic cloud environments. Study SIP under realistic turbulent cloud conditions in a highly instrumented cloud chamber, paired with high-fidelity simulations of the chamber.	Validation of process models for ice multiplication under realistic but controlled conditions; development of parameterizations suitable for cloud-resolving models.	**High**
		Employ high-resolution radar and lidar instrumentation to resolve in-cloud hydrometeor distribution.	Detection of frequency and location of SIP and associated conditions of atmospheric state and droplet-ice crystal relationship.	**Moderate**

Key science gap & associated research questions	Solution(s)	Approach(es)	Deliverable(s)	Level of difficulty (Low/Moderate/High)
5. Ice crystal growth and evolution of ice properties. **5a)** What is the impact of various thermodynamic and dynamic conditions on ice crystal growth and shape within a given cloud? **5b)** How is ice formation and growth dependent on the properties of liquid hydrometeors?	Laboratory experiments studying ice growth under controlled conditions.	Benchtop microscopy experiments to examine ice growth and shape.	Derive ice growth rates and shapes under accurate control of major environmental parameters and INP types.	**Moderate**
		Cloud chamber experiments to examine ice crystal growth and evolution among other ice crystals with limited water vapor.	Ice growth rates and shapes for ensembles of INPs under consideration of limited water vapor. Assess the magnitude of the Bergereon-Wegener-Findeisen process under typical mixed-phase cloud conditions.	**Moderate**
	Field measurements targeting hydrometeor size distributions in a Lagrangian manner. Ambient ice crystal collection allows for offline ice crystal shape determination for various cloud conditions.	Employ high-resolution radar and lidar instrumentation to resolve in-cloud hydrometeor distribution. Employ cloud probes and particle imaging instrumentation to sample in-cloud. Collected *in situ* ice crystals for offline microscopic shape analyses.	Assess the evolution of the size and shape of ice crystals. Observation of ice crystal growth, sublimation, and shape allows for evaluation of laboratory measurements and development of parameterizations.	**Moderate**

Key science gap & associated research questions	Solution(s)	Approach(es)	Deliverable(s)	Level of difficulty (Low/Moderate/High)
Modeling and observations of cloud systems				
6. Accurate measurement of the ice phase. **6a)** How do the size-dependent ice number, mass, shape, and habit evolve over time? **6b)** What is the spatial heterogeneity of ice number, mass, shape, and habit?	Deployment and evaluation of existing, recently-developed ice phase measurement instrumentation.	Evaluation of recently developed technologies (e.g., holographic methods) in the field (aerial platforms) and laboratory (cloud chambers), and fostering more skills with use of these techniques within the community. A central facility responsible for the standardization, evaluation, and calibration of instrumentation for measurement of aerosol and cloud particles.	Evaluation of measurement accuracy for key metrics, especially the number of small ice crystals (< 100 μm) in clouds; also ice crystal number, mass, shape, habit, and orientation; liquid drop size distributions. Monitoring the evolution of the ice crystal budget including size, mass and habit. Significantly improved observational basis for evaluating simulations of newly formed cloud ice, and the evolution of cloud ice properties by various microphysical processes. Improved capabilities for airborne measurement of supermicron aerosol and liquid drop PSDs to the largest sizes under ambient conditions.	**Moderate to High**
	Development of new instrumentation for both ice crystals and liquid cloud drops in ambient clouds.	Further instrument development, if current technologies prove insufficient.		**High**

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Key science gap & associated research questions	Solution(s)	Approach(es)	Deliverable(s)	Level of difficulty (Low/Moderate/High)
7. Predictive understanding of ice production under a range of natural cloud conditions. **7a)** Do cloud microphysics models accurately predict the evolution of ice number size, and habit? **7b)** What modes of PIP are most important in certain cloud regimes and environments?	Multi-model sensitivity studies to gain improved insight into the relative importance of ice formation pathways, and the robustness of key findings across models.	Capability development & simulations in LES and cloud-resolving models. Updated treatments of ice formation and evolution processes in models, incorporating recent advances in fundamental understanding.	Improved understanding of the collective effect of various ice formation & evolution processes, and their relative impacts on ice crystal numbers in different cloud regimes. Evaluate INP vs. ice crystal number concentrations.	**Low to Moderate**
	Carefully designed field experiments and observing networks more closely coordinated with modeling objectives. Validation of simulated ice formation against observations of naturally occurring clouds under field conditions for various cloud regimes (e.g., tropical deep convective clouds, mid-latitude stratiform clouds, orographic clouds, Arctic mixed-phase clouds).	Determine the technical and engineering requirements to achieve specific scientific goals in advance, through field campaign design exercises and the use of modeling studies to support campaign planning. Improve the mapping of observations to science goals using tools such as a science traceability matrix or a stage-gate innovation process to ensure that design requirements are met before proceeding to execution.	Clear identification of which ice processes are most critical to represent in GCMs; a path towards improved GCM parameterizations of cloud ice processes.	**Moderate to High**
8. Insufficient measurements of heterogeneity at small scales 8a) What is the magnitude and spatiotemporal variability of vertical motions impacting ice-containing clouds? 8b) How large are convective updrafts and downdrafts, and how are they organized spatially?	Improved quantification of small-scale heterogeneity in atmospheric thermodynamic properties (e.g., supersaturation), and vertical motions impacting ice-containing cloud formation and evolution (e.g., gravity waves impacting cirrus, convective updrafts/downdrafts).	Development and deployment of new instrument capabilities, observing platforms, or retrieval methods.	Quantification of vertical profiles of vertical wind velocities, with high time resolution. Quantification of key thermodynamic properties (e.g., supersaturation) and their spatial heterogeneity within clouds.	**High**

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Key science gap & associated research questions	Solution(s)	Approach(es)	Deliverable(s)	Level of difficulty (Low/Moderate/High)
9. Parameterization of the impacts of sub-grid processes for coarse-resolution models **9a)** How can microphysics processes be parameterized in a computationally efficient manner for coarse-resolution models? **9b)** What are the emergent mean effects of ice multiplication processes at the cloud field scale or the scale of a GCM column?	Cloud microphysics model development in coarse-resolution models, subsequent to improvements in fundamental process understanding.	Adaptation of new and improved microphysical process parameterizations for use in existing bulk microphysics parameterizations in GCMs.	Reduced uncertainty and improved confidence in global simulations of cloud phase and climate sensitivity.	**Moderate to High**
	Development and application of novel methods for bridging gaps from the cloud microphysics scale to the global scale.	Thoughtful and well-designed applications of ML/AI methods, emerging capabilities such as global 3 km-resolution models, or other methods, to bridge the gap in scales.		**Moderate to High**
	Analysis of satellite- and ground-based remote sensing to infer and constrain the emergent mean effects of ice processes at scales relevant to both cloud and climate models.	Hypothesis-driven analysis of long-term observations from satellite- and ground-based remote sensing.		**Low to moderate**
10. Understanding cloud ice processes in a Lagrangian framework. **10a)** How do ice number, size, and habit, as well as cloud drop number and size, evolve during the life cycle of an ice-containing cloud?	Lagrangian analysis of existing observations.	Extend current approaches used for Lagrangian analysis of satellite observations to observations of ice-containing clouds.	Preliminary understanding of the life cycle of ice-containing clouds, as a function of their initial state.	**Moderate**
	New Lagrangian observations that track the evolution of cloud properties as clouds move with the synoptic-scale mean flow.	Development and application of emerging observation platforms, such as balloons, airships, and uncrewed aerial vehicles; and novel applications of established capabilities, such as radar and piloted aircraft.	Datasets that provide unique constraints on the time evolution of INPs and cloud microphysical variables.	**Moderate**
	Lagrangian modeling, coordinated with field experiments.	LES simulations of case studies from Lagrangian observations, in addition to; model evaluation.	Evaluation of current and updated predictive understanding of the evolution of ice-containing clouds and cloud systems over time.	**High**

5. PRIMARY AND SECONDARY ICE PRODUCTION AND SUBSEQUENT ICE EVOLUTION AND GROWTH PROCESSES

Workshop discussions highlighted that progress in understanding ice processes is fundamentally constrained by the limitations of current laboratory and field observations and their connection to models. Although modern cloud-resolving models (CRMs) can accurately simulate warm clouds in many scenarios, the gaps in the scientific community's understanding of ice processes are so significant that scientists cannot confidently identify which specific processes drive ice crystal formation under many common atmospheric conditions. Therefore, the primary focus will be on the fundamental, process-level understanding of ice production and evolution mechanisms. This section outlines potential solutions, methods, and deliverables in response to identified key research questions following Table 2.

5.1 INP chemical and physical properties and parameterizations of primary ice production

Despite significant advancements in understanding of INPs, important questions remain, such as: What are the sources of INP and respective source strength and fluxes of INPs? What are the INP size distributions in ambient air, and how do they vary spatially? How can uncertainties in INP measurements be reduced? Under which atmospheric conditions is it appropriate to consider time-independence or -dependence of the ice formation process?

These questions can be addressed by targeted laboratory and field studies, newly designed instrumentation, and a combination thereof. Process-oriented field studies with clear hypotheses are vital to enhance understanding of basic ice processes. Furthermore, observations should provide useful data for model assessments. In the field, aerosol-INP closure studies enable validation of INP parameterizations accounting for different INP types and sizes (Ansmann et al., 2019; Burrows et al., 2022; Knopf et al., 2021).

Aerosol-INP-ice closure studies focus on cases where SIP is not significant, given the complexity of ice microphysical processes. In an ideal world, field campaigns focusing on ice processes would include: i) measurements of the aerosol particle size distribution covering the size range from the Aitken to the coarse mode; ii) simultaneous determination of size-resolved aerosol particle composition (including refractory and biological components) and their cloud condensation nuclei activation potential; iii) assessment of INP types and number concentrations; iv) observations of the liquid droplet and ice crystal size distributions; and v) a suite of observations characterizing the cloud thermodynamics and dynamics, as well as ambient conditions.

Characterization of sampling line and instrument inlet transmission efficiencies is important. Vertical sampling stacks, such as the new system recently installed at the ARM Southern Great Plains site, can alleviate some of the challenges associated with inlet losses. New instrument development that allows measurement of the supermicrometer-sized INP abundance and composition and ice crystal residuals (Cziczo et al., 2017; DeMott et al., 2010; Knopf et al., 2021) should accompany these research activities. These activities can yield improved understanding of the full range of INPs, aerosols, droplets, and ice particles allowing for development and evaluation of PIP parameterizations.

Platforms like tethered balloon systems (TBSs) and research aircraft, such as the upcoming ARM Bombardier aircraft and uncrewed aerial systems

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(UASs), can be used to observe the vertical distribution of aerosol size distributions and INPs—crucial information for model simulations and predictions. Combining *in situ* measurements with multi-wavelength high spectral resolution lidar observations can leverage remote sensing to better understand the spatial distribution and temporal evolution of INPs.

Exploratory aerosol and INP measurements close to potential INP sources allow identification, characterization, and discovery of previously unknown or understudied INP types, as well as source strength. Determination of INP fluxes would be an ideal outcome of such activities.

Bench-top ice formation experiments analyzing the behavior of individual particles can provide evidence to support and quantify, or perhaps falsify, a proposed physical mechanism (Kanji et al., 2017; Knopf et al., 2018; Murray et al., 2012). Through repetition of such experiments, process rates can be obtained for the studied set of conditions. These experiments have been and continue to be essential for understanding the dependence of ice nucleation on factors, including INP properties, temperature, water vapor, time, and droplet concentration and size (Alpert and Knopf, 2016; Herbert et al., 2014; Knopf et al., 2020; Lüönd et al., 2010; Steinke and Burrows, 2022). Most experiments focus on a single component particle system with variations of INP size and number, but relatively uniform particle composition. Extending these types of experiments to mixtures of different INP types, hence more closely emulating ambient conditions, would enable a meaningful intercomparison of different PIP parameterizations acting simultaneously on a realistic but well-constrained aerosol population under a range of atmospheric conditions. In general, the highly constrained experimental conditions that ensure the accuracy of such measurements, however, also often restrict the applicability of results to the much broader range of conditions found in natural clouds.

Cloud chamber experiments (Alpert et al., 2023; Stratmann et al., 2008) can yield a bottom-up understanding of ice formation by prescribing a diverse aerosol population—including externally and internally mixed particle populations—and monitoring the resulting ice crystal number concentrations. These exercises yield a microphysical process understanding of primary ice formation kinetics under typical in-cloud constraints, such as competition among INPs for activation and development of supersaturation.

Optimization of INP measurements results in greater accuracy, which is much needed. This requires continuous modification and improvement of techniques (Cziczo et al., 2017). Necessary technical improvements include better temporal, size and range, compositional, morphological, temperature, and humidity resolution while increasing sampled particle numbers (Alpert and Knopf, 2016; Burrows et al., 2022). Techniques that allow a high-throughput of aerosol particles at the single-particle level which covers a wide range of tropospheric conditions are desirable.

5.2 Biological (bio-)INP sources and atmospheric relevance

It is well-documented from laboratory studies and field observations that bio-INPs offer high efficiency ice nucleation sites, often dominating immersion-mode INPs at temperatures between -2 and -15 °C. However, models do not account for these potentially important bio-INPs due to outstanding important questions that remain: What is the relative contribution and overall importance of biological INPs compared to mineral sources in the atmosphere? In soil dusts, are biological or organic surface materials the primary nucleating entity?

Bio-INPs freeze at relatively high temperatures in the immersion mode (Hill et al., 2016), while their role in serving as deposition INPs is less understood (Knopf et al., 2018). Increased concentrations of bio-INPs have been observed in association with windblown soil dust (Hill et al., 2016; Suski et al., 2018) and following precipitation events (Huffman et al., 2013; Joung et al., 2017).

However, a clear understanding of the global importance of bio-INPs is limited by gaps in knowledge about their atmospheric sources and source strength, as well as the lack of reliable parameterizations for their emissions and freezing efficacies (Cornwell et al., 2023). Limitations of current instrument technologies and extremely diverse and often sporadic distribution of the bio-INP population both contribute to this research gap. Primary biological aerosol particles are present in low number concentrations in the atmosphere (Després et al., 2012; Fröhlich-Nowoisky et al., 2016; Steiner, 2020), so collecting statistically significant samples of bio-INPs in the ambient atmosphere is technically challenging. Novel high-throughput instrumentation that can probe these high freezing temperatures at greater INP number concentrations, and that physicochemically identifies the INP would enable improved characterization of primary bio-INPs and may lead to improvements in bio-INP freezing parameterizations (Huffman et al., 2020; Santl-Temkiv et al., 2020).

The source strengths of bio-INPs, which are necessary for models to simulate bio-INP concentrations, are not well constrained (Burrows et al., 2009; Després et al., 2012; Fröhlich-Nowoisky et al., 2016; Steiner, 2020). Field measurements can be combined with well-designed source-receptor modeling to improve predictive understanding of the types and quantities of bio-INPs and their relationship to the terrestrial biosphere (e.g., soil moisture, land cover, biogeochemistry) and meteorological conditions (e.g., surface wind speed, relative humidity, precipitation).

5.3 Life cycle of INPs

In addition to emissions of INPs, there is a need for an improved understanding of the processing of INPs in the atmosphere. During atmospheric transport, aerosol particles and INPs physically and chemically transform (Kanji et al., 2017; Knopf et al., 2018). How these processes impact the ability of INPs to induce ice nucleation is not well understood. Furthermore, quantification of the dominant INP sinks and removal processes, both outside and within clouds, needs to be achieved. Processes such as "pre-activation" (Knopf and Koop, 2006; Mahrt et al., 2020; Wagner et al., 2014), coating by condensed gas species (e.g., Augustin-Bauditz et al., 2014; Kulkarni et al., 2014; Maclean et al., 2021), and transitions to "glassy" phase states (Knopf et al., 2018; Shiraiwa et al., 2017) can significantly alter the ice nucleation efficiency of INPs. These effects are typically not accounted for in models, therefore their large-scale impacts on INP abundance in the atmosphere and on cloud freezing are not well-understood.

Atmospheric transport, removal, and recycling processes are critical to the INP lifecycle (Fan et al., 2009; Solomon et al., 2015). Large-scale atmospheric models with prognostic aerosol (e.g., regional and global atmospheric chemistry models typically rely on the sub-grid convection and boundary-layer turbulence parameterizations to compute the transport of particles by unresolved vertical motions. Wet and dry deposition processes are also treated by separate parameterizations. However, these models typically do not differentiate how INPs are affected by each process. Studies have shown that the transport of INPs to high latitudes (Haga et al., 2013) and their impact on high-latitude clouds (Knopf et al., 2023; Savre and Ekman, 2015) are extremely sensitive to assumptions regarding INP depletion in mixed-phase clouds, pointing to the importance of improved understanding of this process.

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The potential for INP concentrations to evolve in ways that are not directly tied to the aerosol mass, number, hygroscopicity, or optical properties raises the question of whether models should include additional aerosol or INP tracers to enable simulation of INP depletion. CRMs at a high resolution with a prognostic treatment of INPs (i.e., accounting for sources, sinks, and physicochemical transformations of INPs) can answer this question by providing process-level understanding of how the lifecycle of INPs ultimately impacts the reservoir INP available for primary ice formation in clouds (Fridlind et al., 2012b; Knopf et al., 2023; Solomon et al., 2018).

Observed vertical profiles of INPs are heavily influenced by transport and removal processes, making them a critical observational constraint for modeling these processes. Existing research aircraft as well as the recent emergence of observing platforms, such as TBS and UAS, may provide pathways to fill these gaps (de Boer et al., 2018; Cheng et al., 2022; Creamean et al., 2018; Vandergrift et al., 2022).

Laboratory experiments conducted in aerosol, smog, and cloud chambers, as well as combinations thereof, can be employed to study the impacts of various types of chemical and physical aging during long-range particle transport. Studies exposing well-controlled aerosol and INP populations to multiphase chemical processes (Knopf et al., 2024), such as oxidative aging (Kanji et al., 2013), condensation of inorganic (Friedman et al., 2011; Gao and Kanji, 2022; Sullivan et al., 2010) and organic vapors (Kanji et al., 2019), and physical transformation—including coagulation, water uptake (Gao and Kanji, 2022), and fragmentation of particles—improve scientists' understanding of how such processes change the INP population. While benchtop experiments can be used to evaluate the role of particle transformation on specific INP types and sizes applying an aerosol or particles-on-substrate approach (Brooks et al., 2014; Cziczo et al., 2009; Eastwood et al., 2009; Kanji et al., 2008; Kulkarni et al., 2014, 2016; Wang and Knopf, 2011), smog chambers can simulate photochemical particle aging under realistic conditions (Chou et al., 2013; Isaacman-VanWertz et al., 2018; Kim et al., 2024, 2023). Thus, smog chambers can be employed to target transformation of various INP populations. Combined benchtop experiments and smog chamber studies could enable a detailed understanding of the role of physicochemical transformation of selected INP types and their ice formation propensity. In addition, cloud chamber studies enable the scientific community to determine the impact of physical and chemical aging on INPs stemming from a diverse aerosol population while also considering ice cloud processing (Kanji et al., 2019; Möhler et al., 2008; Wagner et al., 2017).

Field measurements can yield a Lagrangian perspective on particle aging processes, which has proven to be a fruitful approach in studies of aerosol chemistry (e.g., Zaveri et al., 2012). Similar field campaigns can be designed to monitor the physicochemical change in INPs by characterizing INP properties close to the source of emission (e.g., forest fire, wave breaking, wind-blown dust) and downwind at a distance that enables the observation of physical and chemical (multiphase) processes.

5.4 A fundamental understanding of secondary ice production processes

Cloud observations indicate that the ice crystal number concentrations often exceed the numbers of INPs present (Field et al., 2017); this is specifically the case for mixed-phase clouds. Predicting the correct ice crystal number concentration is crucial since it impacts other cloud parameters, such as the liquid and ice water content. Subsequently to PIP, SIP can yield amplification of ice crystal number concentrations. SIP is less studied than PIP, and how the individual pathways are influenced by meteorological conditions is not well understood. Additionally, it remains to be seen which are the most important SIP mechanisms that affect ice crystal number concentrations and cloud evolution for a given cloud regime.

Despite the established importance of SIP, many cloud and ESMs still do not include parameterizations of SIP primarily due to a lack of observational constraints. Of the eight known SIP mechanisms, the “Hallet-Mossop” rime-splintering process is the most frequently represented by models based on laboratory results from Hallet and Mossop (1974) and Mossop and Hallett (1974). Yet, recent field observations and modeling studies suggest that other SIP mechanisms, such as fragmentation during droplet freezing and breakup during ice-ice collisions, may be the dominant SIP mechanisms in many clouds, challenging previous assumptions regarding the dominance of the Hallet-Mossop process (Huang et al., 2021; Yano and Phillips, 2011). Furthermore, recent laboratory studies of rime splintering have failed to reproduce the results of the original study by Hallet and Mossop (Seidel et al., 2024), calling into question the validity of the widely used Cotton et al. (1982) parameterization. One goal of the SIP laboratory studies is to obtain a function describing the process rate for each SIP mechanism for a well-defined set of meteorological conditions.

Advancing understanding of SIP can be viewed as a two-step process: (i) identify the functional dependencies and relevant coefficients for each SIP process (e.g., determine the parameters influencing a specific SIP mechanism and how the SIP rate varies with these parameters), and (ii) reproduce realistic in-cloud microphysics and dynamics with the necessary and sufficient conditions for SIP initiation (e.g., conditions near the melting level in a deep convective cloud where falling drops, ice crystals, and updraft conditions coexist). Step (i) can be achieved via benchtop experiments, while step (ii) requires experiments in a large multiphase laboratory facility, such as a tall cloud chamber or a large wind tunnel.

Benchtop and vertical wind tunnel experiments offer a practical means to quantify and advance the physical understanding of SIP involving 1-2 hydrometeors as a function of atmospheric state (Korolev and Leisner, 2020). This is a necessary step in producing SIP rate equations and reproducibility for secondary ice formation, which can be implemented in models.

Recent laboratory studies of ice crystal fall speed (Weitzel et al., 2020), fragmentation of freezing droplets (Keinert et al., 2020; Kleinheins et al., 2021; Lauber et al., 2018), droplet-ice (James et al., 2021) and ice-ice collisional breakup (Grzegorczyk et al., 2023), and rime-splintering (Seidel et al., 2024) mechanisms employed benchtop-size laboratory setups. These are relatively small cloud chambers with volumes varying from a few cubic centimeters to a few liters. Such experiments can make use of naturally falling ice crystals and snowflakes to study SIP (Vardiman, 1978).

Wind tunnels can resolve SIP under realistic droplet-ice and ice-ice collision energies (Grzegorczyk et al., 2023; Seidel et al., 2024). To study SIP processes involving colliding hydrometeors, a facility enclosure would need to be tall enough to allow for the sufficient occurrence of steady-state mixed-phase or ice collision and breakup conditions, where the height ensures that hydrometeor residence times are at least of the same order of magnitude as the mean collision time (e.g., Connolly et al., 2012; Thomas et al., 2023; Wang et al., 2024). Vertical wind tunnels overcome the height limitation by providing a stream of air that can support rapidly sedimenting particles but have the limitation that only one particle size can be suspended for extended periods.

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A unique advantage of cloud chambers is that they enable investigators to study the evolution of a large population of hydrometeors, which enables the second step in establishing the realistic evolution of SIP processes. A recent workshop on cloud chamber facility concepts concluded that a sufficiently tall convection cloud chamber would be suitable for studies of SIP (Shaw et al., 2020). Cloud chambers can also be used to investigate non-collisional interactions of and competition between supercooled droplets and ice particles in turbulent conditions relevant to various types of mixed-phase and ice clouds; these types of experiments may have less stringent chamber height requirements (e.g., Desai et al., 2019; Simpson et al., 2018). It is expected that the diversity of SIP processes that need to be studied in progressive steps will be highly challenging and require multiple approaches; enabling these within a unified facility could achieve economies of scale that do not currently exist elsewhere in the world for the study of SIP.

Laboratory experiments can yield greater improvements in understanding if they are closely coordinated with modeling activities. Benchtop cloud chamber studies can be coordinated with the development of, and simulations by, ultrafine resolution models of the same scales, such as phase-field modeling (e.g., Staroselsky et al., 2021), or direct numerical simulations, (DNS) or Lagrangian-particle cloud models (e.g., Chen et al., 2023; Shima et al., 2020), to directly simulate the SIP mechanisms. Closely linking cloud chamber and wind tunnel experiments with model simulations would enable the direct validation of process-model SIP parameterizations and development of new SIP parameterizations suitable for implementation in cloud-resolving and other high-resolution or large-scale models. In this way, a hierarchy of models can be matched to a hierarchy of experiments to help better understand the physics of SIP processes and bridge the gap between chamber scales and cloud scales.

5.5 Ice crystal growth and evolution of ice properties

Workshop participants emphasized the importance of first focusing on clarifying PIP and SIP processes, as these control the formation of ice in clouds. However, ice crystal growth is another fundamental process in cloud systems which influence cloud radiative properties, precipitation, and dynamics. Growth occurs through several pathways: deposition of water vapor onto ice crystals (which depletes atmospheric vapor), collision and aggregation of ice crystals (which alters the ice crystal size distribution), and riming where supercooled water droplets freeze onto existing ice and reduce the droplet number concentration. These processes influence both the size and shape (habit) of ice crystals, which in turn affect the radiative properties, fallout, and growth rates of hydrometeors (Harrington et al., 2021; Hartmann, 2016; Jensen et al., 2009; Lawson et al., 2019; Lohmann and Roeckner, 1995; McFarquhar et al., 2002). Understanding how specific in-cloud conditions impact these growth pathways is essential for accurately modeling cloud processes and predicting cloud behavior.

Predicting the growth and shape of ice crystals remains challenging due to significant uncertainties in fundamental ice physics. Key areas of uncertainty include:

(1) **Accommodation coefficient:** The accommodation coefficient, which represents the probability of water molecules adhering to ice surfaces during vapor deposition, is a critical factor in determining the growth rate of ice crystals and is poorly quantified (Harrington et al., 2021; Lamb et al., 2023).

(2) **Metamorphosis of ice shapes:** This is how ice crystals change shape in response to varying atmospheric conditions (Bailey and Hallett, 2009).

(3) **Depositional growth rates:** This is how growth rates for ice particles vary with their shape and are influenced by meteorological conditions, such as temperature and supersaturation (Libbrecht, 2003; Pokrifka et al., 2023).

(4) **Aggregation:** The aggregation (sticking) coefficient quantifies the probability of aggregation during collisions of multiple ice crystals as a function of ice crystal shape and size (Connolly et al., 2012; Karrer et al., 2020).

(5) **Riming:** Riming occurs when supercooled droplets freeze onto the surface ice crystals (Avila et al., 2009; Jensen and Harrington, 2015).

(6) **Wegener-Bergeron-Findeisen (WBF) process:** The interaction of ice crystals and liquid droplets through the water vapor phase impacts the rate of ice crystal growth and water droplet evaporation (Khain et al., 2022; Omanovic et al., 2024).

Fundamental uncertainties around these fundamental ice physics processes across a range of cloud conditions lead to discrepancies in model predictions of cloud radiative properties, which are critical tools used to model the Earth's energy budget.

Due in part to the uncertainties surrounding these processes, most current CRMs treat ice particles simplistically and often represent them as spheres. New laboratory studies and models have begun to consider more realistic ice shapes, which better capture the complexity of ice growth under varying meteorological conditions (Harrington et al., 2013). Such advances are critical for improving the representation of ice in numerical simulations. Quantitative analysis of ice crystal evolution under varying atmospheric conditions remains limited. While laboratory experiments and field measurements have offered valuable insights into how temperature and humidity affect ice crystal shapes (Pokrifka et al., 2024; Bacon and Swanson, 2000; Bailey and Hallett, 2009; Baumgardner et al., 2017; Field et al., 2017; Fugal and Shaw, 2009; Henneberger et al., 2023; Kobayashi, 1961; Korolev et al., 2000; Magono and Lee, 1966; Rottner and Vali, 1974), most studies focus on macroscopic classifications, such as distinguishing between columnar and plate-like forms. Recent electron microscopy studies, however, have revealed intricate surface features on ice crystals that challenge traditional models of ice shape and optical properties (Magee et al., 2014, 2021). These unprecedented microscale observations provide new insights that have the potential to significantly improve model parameterizations of ice habit evolution and its effects on cloud radiative properties.

Currently, cloud chambers are underutilized for studying ice crystal habit growth and sublimation. Equipped with the latest hydrometeor imaging technologies (Baumgardner et al., 2017; McFarquhar et al., 2017), cloud chambers could provide valuable insights into the growth rates and shapes of ice crystals formed using different mixtures of aerosols and INPs, thereby accounting for different sinks of water vapor. These controlled environments would also be ideal for studying the WBF process, which plays a key role in mixed-phase clouds (Desai et al., 2019; Wang et al., 2024).

6. MODELING AND OBSERVATIONS OF CLOUD SYSTEMS

CRMs suggest that the partitioning of liquid and ice within mixed-phase clouds is very sensitive to the specific pathways of ice formation and growth (e.g., primary ice formation, riming, and depositional growth) (Fan et al., 2017b). Both phase partitioning and ice crystal properties, including size and orientation, influence cloud optical thickness (Stillwell et al., 2019) and contribute to the cloud-phase feedback in ESMs (Korolev and Milbrandt, 2022; McCoy et al., 2022; Tan et al., 2016). Consequently, poorly understood processes that control cloud-phase partitioning challenge high-resolution models, such as CRMs and convection-permitting models, in accurately predicting cloud radiative properties and precipitation. They also limit the ability of regional and global models to confidently simulate the impacts of future and past changes in aerosol emissions that drive PIP and cloud droplet activation.

The estimated magnitudes of the cloud-phase feedback and related cloud optical thickness feedback vary widely among ESMs (Rasch and Carslaw, 2022; Terai et al., 2016; Zelinka et al., 2020), and model errors in the simulation of cloud-phase partitioning have been identified as a potentially important contributor to these inter-model differences (Tan et al., 2016; Tan and Storelvmo, 2016). Narrowing these uncertainties will require fundamental advances in the understanding of cloud-ice processes, improved approaches that represent their large-scale effects in models, and improved observational constraints on the interactions between cloud-ice processes and meteorological conditions. The major science questions and knowledge gaps pertaining to both the modeling and observation of ice processes and their impacts in cloud systems are summarized in this section.

6.1 Accurate measurement of the ice phase

Accurate measurement of cloud-phase, ice crystal number concentration, and ice crystal habit is essential for understanding cloud microphysical and optical properties (e.g., Järvinen et al., 2018). These properties, including ice crystal number, mass, and shape, evolve over time and influence cloud radiative behavior and precipitation processes. Reliable observation of these variables is critical for both validating models and advancing scientists' knowledge of mixed-phase cloud microphysics.

Accurate measurement of small ice crystals (<100 μm in diameter) in field campaigns is one of the most persistent challenges in cloud and precipitation research. Early *in situ* measurements had significant errors due to the shattering of ice crystals upon impact with instrument surfaces; this led to overestimates in ice number concentrations by orders of magnitude (Korolev et al., 2013). Advances in instrument housing and analysis techniques have mitigated the shattering issue (Jackson et al., 2014; McFarquhar et al., 2017), but accurate and well-characterized measurements of small ice crystals in field campaigns remain elusive. Additionally, no current instruments can fully distinguish between ice water content and liquid water content (LWC). Traditional optical methods, which rely on the shape of hydrometeors to differentiate liquid from ice, face significant limitations when applied to small ice crystals. These methods are further hampered by the uncertainties inherent in two-dimensional projections, complicating mass and number quantifications (Baumgardner et al., 2017).

In situ observations, while critical, are limited to finite flight tracks or specific profiles, while remote sensing is more limited in its availability (e.g., Kalesse et al., 2016; Matrosov et al., 2017; Oue et al., 2021) and faces its own set of challenges due to uncertainties in ice crystal shape and potential misclassifications (e.g., Zamora et al., 2022).

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Recent decades have seen a sustained effort to develop new technologies for ice cloud measurements, such as digital holographic imaging (Fugal and Shaw, 2009; Henneberger et al., 2013), electron microscopy revealing nanoscale ice particle features (Knopf, 2023; Magee et al., 2014; Wang et al., 2016), and instruments that directly measure light scattering patterns (Abdelmonem et al., 2011; Ulanowski et al., 2006). However, these technologies are rarely incorporated into field campaigns; when they are, the uncertainties in key observations, such as size-resolved ice crystal number concentration, are often not reported. This lack of uncertainty reporting limits the usefulness of these measurements for modelers and other data users.

Well-characterized remote sensing instrumentation could be deployed in combination with emerging technologies to improve ice cloud measurements. Higher-frequency radars, such as G-band and THz, offer the potential to provide better insights into population-wide ice crystal properties—particularly for smaller crystals, though further development is needed (Lamer et al., 2021). Ultra-high-resolution radars, lidar systems, and spectral techniques combined with machine learning (ML) and artificial intelligence can significantly advance the understanding of cloud dynamics and the spatial heterogeneity of ice clouds (Yang et al., 2024; Zhu et al., 2024) (Lamer et al., 2018; Luke et al., 2021; Silber et al., 2022).

Characterizing and deploying recently developed hydrometeor imaging instruments under diverse field and laboratory conditions is essential for understanding their capabilities and limitations. Cloud chamber facilities, such as the German Aerosol Interaction and Dynamics in the Atmosphere chamber, continue to play a critical role in testing and validating these instruments (e.g., Schnaiter et al., 2016). Cloud chambers also can benefit from and contribute to the miniaturization of instrumentation, which is valuable for use on UAS, TBS, and ground- or tower-based platforms that measure ice microphysics.

Despite these technological advances, the rate of technology transfer into comprehensive field experiments with well-characterized instrumentation remains slow. Without faster progress in improving and deploying instrumentation for cloud ice observations, the scientific community's understanding of cloud ice formation and evolution will continue to be hindered by these observational gaps.

6.2 Predictive understanding of ice production under a range of natural cloud conditions

Understanding the dynamics of ice production and evolution across different cloud systems is one of the most significant challenges in atmospheric science. Recent improvements in computational power have enabled cloud and ESMs to include more detailed representations of cloud microphysical processes—particularly for ice formation and growth. However, as Morrison et al. (2020) noted, there is a widening gap between the complexity of these microphysics schemes and the observational data available to constrain and validate them. This raises an important question: Can current cloud microphysics models accurately predict the evolution of ice crystal number, size, and shape under a range of natural cloud conditions?

Recent advances in modeling, particularly the use of Lagrangian-particle-based approaches, have enhanced the ability to simulate the stochastic behavior of cloud hydrometeors. The super-particle method (Shima et al., 2009) in LES and particle-by-particle approaches in DNS (Vaillancourt and Yau 2020) provide more realistic representations of ice particle formation compared to traditional bulk and bin microphysics schemes, which tend to oversimplify cloud dynamics (Morrison et al., 2020; Grabowski et al., 2019).

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Beyond in-cloud processes, the treatment of precipitating ice in models can have profound impacts. For example, in one study, including the radiative effect of snow in an ESM was shown to amplify cloud feedbacks (Cesana et al., 2021). In another study, including the radiative effect of falling ice in a model was shown to lead to faster sea ice retreat (Li et al., 2019). However, many models treat precipitating ice crudely and neglect critical processes, such as the influence of INPs, despite evidence of their importance in temperatures warmer than -20℃ (Bigg, 1953).

High-resolution atmospheric models, including DNS, LES, and CRMs, offer the most accurate simulations of cloud processes. Global kilometer-scale models are emerging as an approach to global simulations that resolve mesoscale cloud processes, potentially reducing the range of sub-grid processes that remain unresolved. As researchers' understanding of ice formation advances, further capability development will be necessary to incorporate these advances into high-resolution models.

Exploratory studies using these models suggest a significant influence of SIP on regional and global cloud ice concentrations (Atlas et al., 2022; Patade et al., 2022), cloud radiative effects (Zhao and Liu, 2021), and cloud dynamics (Qu et al., 2022). Achieving a predictive understanding of SIP is particularly important for explaining the observed efficiency of ice production in weakly supercooled clouds, especially in convective systems (e.g., Ackerman et al., 2015). Further exploration through model sensitivity experiments could help clarify the anticipated relative importance of individual PIP and SIP mechanisms in different cloud regimes (e.g., tropical convection, mid-latitude mesoscale convective systems) and across a range of relevant conditions (e.g., with variations in cloud droplet number concentrations, updraft velocities, and lower tropospheric stability).

Multi-model sensitivity studies can offer valuable insights into the robustness of findings on SIP across different models. Historically, multi-model studies using ARM data have significantly advanced the understanding and representation of key boundary-layer and warm cloud processes (Krueger et al., 2016). Building on this approach, a coordinated community effort could focus on assessing the relative importance and sensitivities of ice formation pathways in multiple LES and CRMs. Such an effort would improve the scientific community's understanding of the relative contributions of different ice formation pathways and also test the robustness of key findings across varying model structures, including differences in ice process parameterizations and the representation of other critical processes like boundary-layer turbulence and warm cloud microphysics.

The two-way integration of modeling and field observations remains a challenge; however, field experiments are critical for validating model simulations of ice formation and cloud ice variations across various cloud regimes and conditions. Better integration of models into field experiment planning and execution (Anon, 2003; Feingold et al., 2022; Pressel et al., 2023), could help ensure observations are suitable and sufficient to meet campaign science goals, and may also lead to more effective observation campaigns and faster data utilization. By engaging modelers early in the process and ensuring close collaboration throughout, the scientific community can better connect observational data with model validation and parameterization development.

Finally, addressing both modeling and observational uncertainties is essential to improving campaign design and model-data fusion. Established methods, such as observing system simulation experiments (Metzger et al., 2021), data assimilation, Bayesian inference, and emerging ML methods, offer opportunities to quantify uncertainties and advance the community's

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understanding of cloud-ice processes. Instrument simulators also play an important role in model-data integration efforts (e.g., Silber et al., 2022), including improving quantification of uncertainties in key observed variables.

6.3 Insufficient measurements of heterogeneity at small scales

Field experiments are indispensable for advancing the scientific community's understanding of ice formation processes in various cloud regimes, including tropical deep convective clouds, mid-latitude stratiform clouds, and Arctic mixed-phase clouds. Yet, interpreting field data is often challenging due to limitations in instrumentation (e.g., Baumgardner et al., 2017) and the dynamic nature of clouds, which vary across a wide range of spatial and temporal scales (from nanometers to kilometers and from milliseconds to hours). This complexity makes it difficult to isolate specific ice production mechanisms, especially in complex natural settings where multiple processes interact simultaneously.

Our understanding of ice processes in clouds is particularly hampered by limitations in observing the small-scale atmospheric conditions that influence ice formation and evolution. Vertical atmospheric motions—such as gravity waves, convective updrafts, and downdrafts—play a critical role in determining the microphysical properties of clouds, yet these motions occur at scales that are unresolved in many ESMs. Small-scale variations in vertical velocity, temperature, supersaturation, and LWC are tightly linked to the processes of ice formation, growth, and sedimentation.

Existing observational techniques, such as *in situ* sampling and ground-based remote sensing using radars and lidars, provide valuable data but lack the resolution needed to capture these fine-scale processes effectively. As a result, key questions about the small-scale heterogeneity in cloud systems remain unanswered. For instance: What is the magnitude and variability of vertical motions and supersaturation in clouds containing ice? How large are convective updrafts and downdrafts, and how are they organized spatially? At what scales does the spatial heterogeneity of ice and liquid water significantly influence cloud evolution?

Efforts to address these gaps have been limited by the constraints of current measurement technologies. New instrument capabilities, observational platforms, and retrieval methods are needed to better characterize (1) the vertical profiles of vertical wind velocities with high-time resolution, and (2) the spatial heterogeneity of key thermodynamic properties (e.g., supersaturation) and hydrometeors within clouds.

Recent technological advancements offer promising solutions for improving the scientific community's understanding of cloud processes and SIP by providing better insight into sub-grid heterogeneity of cloud properties. Field campaigns targeting idealized cloud scenarios to observe SIP can benefit from multi-wavelength radars and lidars with polarimetric and spectral Doppler capabilities. These techniques allow in-cloud detection of the spatial distribution of hydrometeor populations, including the size and shape of contributing ice crystals. This information in turn can enable detection of rapid ice crystal formation indicative of SIP (Billault-Roux et al., 2023; Korolev et al., 2022; Luke et al., 2021; Zhu et al., 2024). Emerging opportunities include improving rapid in-situ sampling, increasing the vertical resolution of ground-based remote sensor observations (Zhu et al., 2024; Yang et al., 2023, 2024), and better quantifying atmospheric moisture content (Roy et al., 2020). Multi-angle snowflake cameras (Helms et al., 2022) and holographic imaging systems can provide detailed observations of ice particles at small scales, offering new insights into ice growth, habit, and sedimentation. Remote sensing can be

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augmented by *in situ* measurements of vertical profiles from UAS and TBS to connect ground-based and cloud-level observations (Henneberger et al., 2023; Marinou et al., 2019; Zinke et al., 2021).

Cirrus clouds present unique observational challenges due to their high altitudes and thin structures. Cirrus research has benefited from aircraft sampling and advanced remote sensing technologies, such as scanning multi-wavelength high spectral resolution lidar observations, which allow for more precise measurements of ice particle properties. Innovative methods, such as the use of cryo-encapsulation balloons, which were demonstrated in the ICE-Ball pilot experiment (Magee et al., 2021), enable the collection of pristine ice crystals to advance understanding of ice crystal growth processes in cirrus clouds. These advancements contribute to a deeper understanding of cirrus cloud microphysics, which is critical to improving cloud, weather, and ESMs.

6.4 Parameterizing sub-grid processes for coarse-resolution models

Sub-grid spatial heterogeneities in cloud hydrometeors and thermodynamic conditions represent a significant source of uncertainty in coarse-resolution model simulations of cloud glaciation and phase partitioning (e.g., Yip et al., 2019, Tan et al., 2016). In large-scale models, such as ESMs, small-scale vertical motions are critical for controlling temperature, supersaturation, and liquid water content. These are not explicitly resolved. Instead, their effects on cloud microphysics must be parameterized or omitted (e.g., Maciel et al., 2023; Patnaude et al., 2024). Key microphysical properties, such as ice supersaturation and cloud-phase partitioning, vary at spatial scales that are much smaller than typical ESM grid boxes (e.g., Coopman and Tan, 2023; Diao et al., 2014, 2017; Korolev and Milbrandt, 2022; Qu et al., 2022; Shupe et al., 2008; Tan et al., 2016). This unresolved variability complicates the simulation of key processes like ice nucleation in cirrus clouds or the WBF process in mixed-phase clouds (Storelvmo et al., 2008; Wang et al., 2014; Zhang et al., 2019). SIP mechanisms are also expected to be sensitive to parameters that vary substantially at sub-grid scales, including hydrometeor quantities and sizes, and thermodynamic conditions.

Addressing these challenges requires improved parameterizations of ice microphysical processes for coarse-resolution models, which can better capture the large-scale effects of unresolved small-scale variability. High-resolution models, such as LES and CRMs, provide valuable testbeds for evaluating and improving these parameterizations. LES simulations, for instance, can be used to assess ESM parameterizations in a single-column model framework or to develop emulators that represent small-scale processes within ESM grid cells or columns.

Recent developments in scale-aware comparison techniques have enabled better integration of high-resolution observational data with coarse-resolution model outputs (e.g., D'Alessandro et al., 2019; Yang et al., 2021; Desai et al., 2023). These techniques allow for more accurate cross-validation of simulated and observed cloud processes, improving the scientific community's understanding of how sub-grid processes manifest at larger scales. Despite this progress, significant challenges persist with global-scale simulations, even at kilometer-scale model resolutions.

Many ESMs include parameterizations of aerosol-cloud interactions (ACIs) as well as PIP, but must significantly simplify the representation of cloud microphysics schemes by representing only certain classes of ice (Milbrandt and Yau, 2005; Morrison et al., 2005) and assuming a fixed shape for the ice crystal size distribution and fixed fall speeds (Pinsky et al., 2018).

Although kilometer-scale global models, such as the DOE's Simple Cloud-Resolving Energy

Exascale Earth System Model Atmosphere Model (SCREAM), offer higher resolution for simulating atmospheric dynamics and cloud processes, they currently exhibit significant biases in simulated cloud properties (Zheng et al., 2024). Furthermore, most do not yet include aerosol-aware parameterizations for cloud droplet and ice formation, limiting their utility for studying ACIs.

These limitations highlight the need for continued development of robust parameterizations of the impacts of cloud microphysics, ACIs, and cloud ice processes for both traditional ESMs and kilometer-scale global models. A variety of approaches that leverage ML methods are being explored by the community; while still in their early stages, these efforts offer a new potential path toward addressing fundamental structural challenges in cloud parameterization.

6.5 Inferring the cloud-scale impacts of ice processes from observations

Observational data plays a critical role in evaluating the accuracy of parameterized processes in models. Building on lessons from research on liquid clouds, where satellite-retrieved aerosol and cloud properties have provided valuable constraints (McCoy et al., 2020), similar approaches are now being applied to ice-containing clouds (e.g., Villanueva et al., 2020). These efforts can improve the scientific community's understanding of mixed-phase clouds' responses to aerosol perturbations and ultimately provide constraints on parameterized processes.

These datasets, which include multi-radar and lidar profiles, are poised to expand with the integration of new aerosol and INP measurements. After controlling for key meteorological drivers, these data will allow scientists to analyze co-variabilities between cloud hydrometeors and thermodynamic conditions, leading to more accurate assessments of sub-grid ice process impacts.

Datasets from long-term observational sites like the DOE ARM sites at the Southern Great Plains and North Slope of Alaska are essential for improving understanding of ACIs (e.g., Mülmenstädt et al., 2012) and developing regional cloud climatologies (e.g., Shupe, 2011). These sites provide extensive datasets, including multi-radar and lidar profiles, which are poised to be expanded with new aerosol and INP measurements in the near future (Creamean et al., 2022, 2024). These data can be leveraged in hypothesis-driven studies to analyze co-variabilities between aerosols, cloud hydrometeors, and thermodynamic conditions, while controlling for key meteorological drivers. This will lead to more accurate assessments of sub-grid ice process impacts at the cloud scale (e.g., Patnaude and Diao, 2020; Maciel et al., 2023; Yang et al., 2021).

Satellite retrievals can be combined with ground-based remote sensing to leverage their complementary strengths. Spaceborne lidar and radar offer a top-down view of cloud properties, which is complemented by the more detailed bottom-up perspective of ground-based observations. Analyses that combine data from multiple remote sensing instruments must confront technical challenges, such as differences in the spatial resolutions of space-based and ground-based instruments. These differences must be accounted for in analyses. Despite these challenges, combined approaches can help mitigate the limitations of each method alone, such as the attenuation of spaceborne lidar in optically thick clouds or ground clutter in spaceborne radar (Blanchard et al., 2014; Liu et al., 2017). Together, satellite and ground-based observations can provide a more comprehensive picture, allowing for better evaluation and constraint of parameterized sub-grid ice processes in coarse-resolution models.

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6.6 Understanding cloud ice processes using observations: Lagrangian frameworks, long-term observations, and perturbation responses

Lagrangian approaches that track the evolution of cloud processes over time have been recognized as a key strategy for improving understanding of ACI (Pinsky et al., 2010; Sullivan et al., 2022). Such an approach allows the examination of how cloud ice crystal number concentration, size, and habit, as well as cloud drop number concentration and size, evolve during the life cycle of an ice-containing cloud, thereby, assessing the ice budget (e.g., Khain et al., 2022).

Multiple strategies exist to observe and understand cloud processes within a Lagrangian framework, including analysis of long-term observations, spatiotemporally aware field experiments, and perturbation experiments. Analysis of existing long-term datasets continues to be a fruitful pathway for research on ACI processes, with Lagrangian methods playing an increasingly important role. Lagrangian tracking of cloud systems within satellite datasets is a promising approach to understand cloud evolution over time (e.g., Christensen et al., 2020). However, satellite-based observations have key limitations. For example, profiling cloud processes at the base and below cloud decks is also important, yet challenging with satellites, especially in high latitudes where ice processes are prevalent and poorly understood. Ground-based observations and field experiments can play a critical role in providing increased insight into these processes, complementing satellite-based approaches. Communications and computational cyberinfrastructure can support the real-time coupling between satellite and ground-based observations and provide enhanced Lagrangian observations (Kollias et al., 2020).

Valuable progress can be made by studying idealized observation scenarios, such as mixed-phase cloud systems in near-steady-state conditions. For example, stratiform mixed-phase clouds such as exist in extended cold-air outbreaks (see COMBLE; Geerts et al., 2022), gravity wave induced cirrus, or lake effect snow systems could serve as locations for aerosol-INP-ice closure experiments. For such studies, it would be valuable to plan coordinated ground based remote sensing and airborne *in situ* sampling efforts at several locations from upwind to downwind (e.g., Kirbus et al., 2024), providing a pseudo-Lagrangian sampling of key observable aerosol and cloud variables.

True Lagrangian observations of ice processes in clouds would provide valuable new insights into the causal relationships between the processes controlling the formation of cloud ice, its evolution, and its removal to precipitation. Emerging aerial platforms show promise to deliver Lagrangian observations of cloud microphysics, including TBS, UAS, airships, and innovative new approaches to piloted aircraft observations (Businger et al., 2006; Lamer et al., 2023; Maury et al., 2022). These platforms offer unique opportunities to follow cloudy air masses from inception to dissipation. By tracking cloud evolution over time, Lagrangian platforms will provide observations of cloud state variables and their budgets (e.g., droplet and ice concentrations, radiative fluxes) that can be more integrated and directly connected to model simulations of process rates. Aerial deployments can be complemented by ground-based field deployments along climatological Lagrangian paths (e.g., Geerts et al., 2022).

Additionally, high-resolution radar and lidar systems capable of generating size and shape closures for in-cloud hydrometeors provide a complementary tool for tracking their evolution (Billault-Roux et al., 2023; Korolev et al., 2022; Luke et al., 2021; Matrosov et al., 2017; Oue et al., 2018; Zhu et al., 2024). These measurements can

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directly inform estimates of the impacts of growth, sedimentation, and sublimation processes on cloud properties, such as phase partitioning (Silber et al., 2021), while also offering a valuable dataset for evaluating the accuracy of hydrometeor evolution in cloud microphysical models. Field observations and remote sensing are particularly important for evaluating model parameterizations that represent the impacts of ice crystal growth and other sub-grid processes on cloud dynamics and radiative transfer.

Beyond purely observational studies, observing and modeling how the atmosphere, clouds, and precipitation respond to perturbations informs investigators about factors influencing and controlling processes in the natural environment. These experiments, including both carefully designed small-scale interventions in the “natural laboratory” (e.g., DeMott, 1988, 1990; French et al., 2018; Henneberger et al., 2023; Rasmussen et al., 2018; Schwarz et al., 2024; Tessendorf et al., 2019) or “opportunistic experiments” leveraging natural perturbations (e.g., wildfire smoke, volcanic injections), or anthropogenic-driven perturbations (e.g., ship tracks, industrial emissions) (Bräuer et al., 2021; Campbell et al., 2012; Zhu et al., 2022) have proven useful in studying ice-containing cloud responses to changes in INP types and concentrations.

Perturbation experiments can also be designed to use a Lagrangian observational approach. An example of an innovative perturbation experiment is the CLOUDLAB project taking place in stratiform mixed-phase clouds forming over the Swiss Plateau (Henneberger et al., 2023; Omanovic et al., 2024). An UAS seeds the cloud upwind and the cloud is sampled by an UAS, TBS, and ground-based remote sensing methods downwind. Such idealized field measurement scenarios are more likely to be amenable to exploration through process-oriented modeling studies and can inspire laboratory experiments, such as aerosol modulation of cloud glaciation in mixed-phase clouds (e.g., Desai et al., 2019).

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7. CLOSING REMARKS

A grand challenge in atmospheric research is the understanding of ice processes within clouds, spanning both primary and secondary ice formation and ice growth and evolution. These processes significantly affect cloud lifetime, radiative properties, and precipitation initiation; however, they are poorly understood.

There are long-standing barriers in ice process research. Workshop attendees focused on a multifaceted approach to precisely quantify process rates and their controlling conditions while validating predictive understanding across scales. This approach involves integrating laboratory experiments, field observations, and modeling, as illustrated conceptually in Figure 3.

Specifically, the study of SIP has been particularly underdeveloped, and workshop participants emphasized the need for new laboratory experiments in this area. While progress can be made with existing capabilities and moderate investments, several critical questions would benefit from the development of more advanced facilities. For both PIP and SIP, a cloud chamber capable of simulating interactions among large populations of hydrometeors will eventually be necessary to validate process models and assess whether they accurately simulate ice formation, growth, evolution, and multiplication rates under

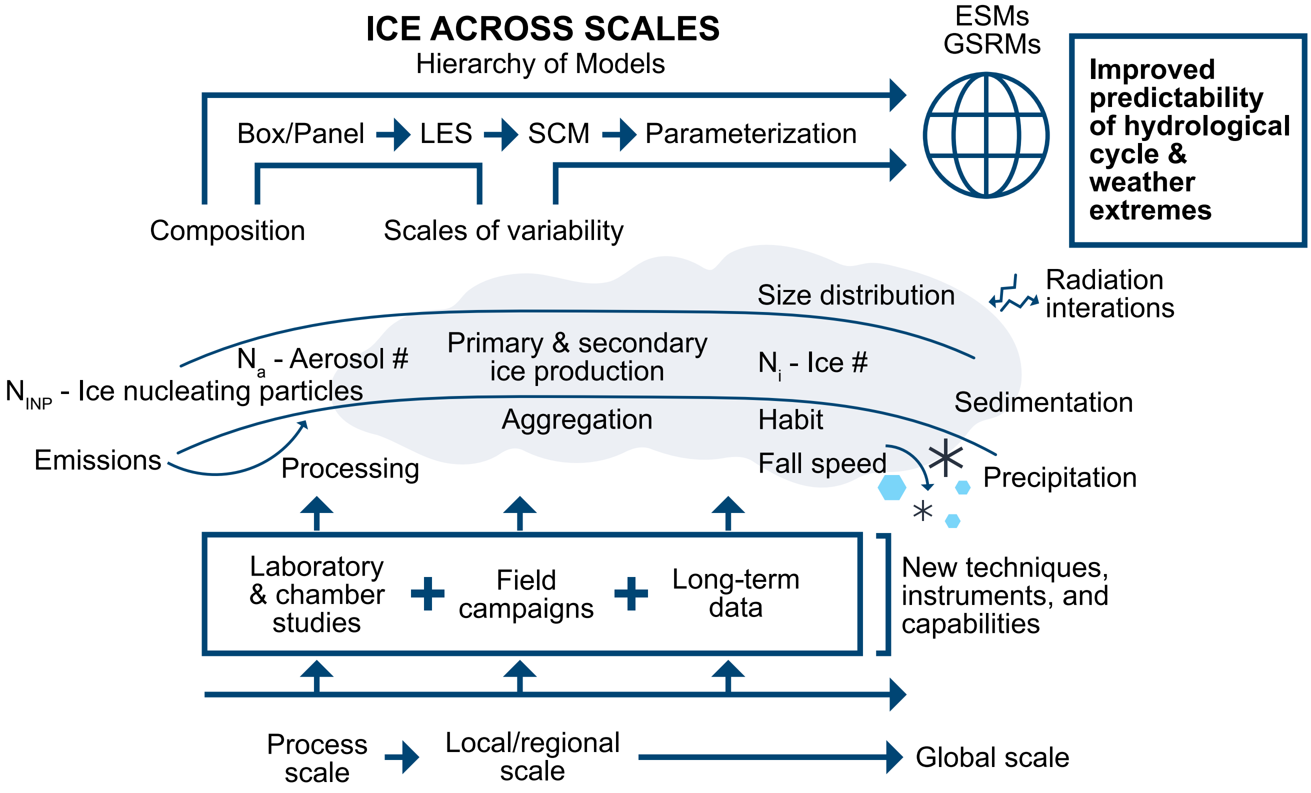

Figure 3. Achieving a comprehensive understanding of ice-relevant processes across the entire continuum necessitates an integrated approach. This involves combining a multi-scaled modeling pipeline, innovative observational facilities, and extensive field measurements. Such integration is essential for enhancing the representation and prediction of cloud ice processes in models.

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realistic conditions. Co-locating such a chamber with other relevant facilities, such as benchtop and wind tunnel setups, could significantly enhance its impact and foster broad collaborations. Additionally, close coordination between laboratory studies and modeling efforts (including chamber simulators) is critical to maximizing the scientific value of such experimental initiatives.

Another particularly critical long-term priority is the development of instruments capable of measuring ice crystals smaller than 100 μm. The absence of such instruments is currently a major limitation in understanding cloud ice processes, especially for field experiments.

Enhancing model-data integration is another key long-term priority that requires stronger interdisciplinary collaboration between experimentalists, theorists, modelers, and instrument developers. Better integration of models into field experiment planning and execution, particularly through systematic approaches like observing system simulation ensembles, could significantly enhance the impact of future experiments and improve the use of observations in model validation and parameterization development.

In the near term, there are significant opportunities to advance research using existing capabilities and datasets. For example, ARM's extensive long-term datasets from ground-based observatories, ARM Mobile Facility (AMF) field deployments, and the ARM Aerial Facility provide valuable resources for evaluating INPs, aerosols, and cloud microphysics. Hypothesis-driven analyses of these ground-based remote sensing datasets and *in situ* measurements can enhance understanding of cloud ice formation across various regimes. Another near-term opportunity is the intercomparison and validation of INP parameterizations. Focused efforts that use existing capabilities, emphasize targeted laboratory experiments and closure studies and could resolve long-standing debates around the interpretation of INP measurements.

In the medium term, solutions can be developed to clarify bio-INP sources and atmospheric transformations. Multi-model sensitivity studies could assess the robustness of findings on ice formation pathways, while Lagrangian field experiments or remote sensing could track cloud processes over time, providing valuable insights into their dynamics.

Opportunities for advancing research objectives also exist through inter-agency and international collaborations. For example, integrating ARM observations with National Aeronautics and Space Administration satellite data can leverage the strengths of both datasets towards improving insight into atmospheric processes. Programs like the EU's Eurochamp "Trans-National Access" provide access to advanced atmospheric simulation chambers and facilitate seamless international collaboration for ASR-funded researchers. ARM's partnership with the European ACTRIS network shows how interagency cooperation can improve understanding of atmospheric dynamics, which could be further strengthened through routine communication, standardized tools, and joint data dissemination. Coordination of ARM/ASR research with international initiatives which organize multi-model intercomparisons, such as the Global Energy and Water Cycle Experiment and AeroCom, can enhance the use of ARM data for modeling studies on cloud processes and ACIs.

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GLOSSARY OF ACRONYMS

ACI	aerosol-cloud interactions
ACTRIS	European Aerosols, Clouds, and Trace gases Research InfraStructure
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
bio-INPs	biological ice nucleating particles
CRM	cloud-resolving model
DOE	Department of Energy
DNS	direct numerical simulation
ESM	Earth system model
INP	ice nucleating particle
LES	large-eddy simulation
LWC	liquid water content
MIP	Model Intercomparison Project
ML	machine learning
PIP	primary ice production
SIP	secondary ice production
TBS	tethered balloon system
UAS	uncrewed aerial system
WBF	Wegener-Bergeron-Findeisen

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APPENDIX I - WORKSHOP AGENDA

Day 1: Wednesday, October 25

Variability in primary and secondary ice formation

9:00–10:30
Welcome and workshop goals/expectations (chairs), attendee introductions (all).

10:30–10:45
Morning Break

10:45–12:15
Overview talks
(geographic, vertical, seasonal, spatial; SIP)

- **Brief overview of DOE ARM measurements and sites:** Daniel Knopf (Stony Brook Univ.) and Jessie Creamean (Colorado State Univ.) (5 min)
- **Lab and field measurements of primary and secondary ice production:** Alexei Korolev (Environ. Clim. Change Canada), Raymond Shaw (Mich. Tech, Univ.), Ottmar Möhler (Karlsruhe Institute Technology) (15 min talk + 30 min discussion)
  - Primary freezing (homogeneous, heterogeneous mechanisms)
  - Secondary ice production pathways
- **Lab and field observations of INPs:** Zamin Kanji (ETHZ), Alex Laskin (Purdue Univ.) (15 min talk + 30 min discussion)
  - Where in the atmosphere, and why do we need measurements of INPs?
  - What needs to be measured and how?

12:15–1:15
Working lunch

1:15–2:00
Overview talks continued
(geographic, vertical, seasonal, spatial; SIP)

- **Brief intro to E3SM's aerosol and ice formation processes:** Kai Zhang (PNNL) and Susannah Burrows (PNNL) (5 min)
- **Modeling of INPs and primary and secondary ice production:** Donifan Barahona (NASA), Christina McCluskey (NSF NCAR), Vaughan Phillips (Univ. Lund) (15 min talk + 25 min discussion)
  - Primary ice formation, secondary ice formation (incl. parameterization approaches and their implications)
  - Spatial/temporal variability of INPs
  - Cloud regimes – which ice formation processes matter in each

2:00–2:15
Afternoon Break

2:15–3:15
Breakout groups session 1

- **Field observations:** Frank Stratmann (TROPOS)
- **Lab measurements:** Allan Bertram (UBC)
- **Modeling:** Ivy Tan (McGill)

3:15–4:15
Breakout groups session 2: Participants rotate to a different group.

- **Field observations:** Frank Stratmann (TROPOS)
- **Lab measurements:** Allan Bertram (UBC)
- **Modeling:** Ivy Tan (McGill Univ.)

4:15–4:45
Break

4:45–5:30
Breakout summary reports (rapporteurs) and concluding remarks for the first day (chairs)

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APPENDIX I - WORKSHOP AGENDA

Day 2: Thursday, October 26

Cloud ice phase and its impacts

8:30–9:30
Chairs: brief summary review of themes from Day 1 discussions; introduce Day 2 topic and remind participants about guidance (goals and scope).

9:30–11:00
Overview talks:

- **Brief introduction to E3SM's P3 microphysics:** Jiwen Fan (ANL) (5 min)
- **Modeling (incl. cloud modeling and Earth system modeling; multiple scales):** Mikhail Ovchinnikov (PNNL), Ann Fridlind (NASA GISS) (15 min talk + 25 min discussion)
- **Brief introduction to ARM radar and lidar measurements:** Pavlos Kollias (BNL/SBU) (5 min)
- **Field observations (incl. remote sensing):** Israel Silber (PNNL), Matthew Shupe (CIRES), Jeff French (U. Wyoming) (15 min talk + 25 min discussion)

11:00–11:15
Morning Break

11:15–12:15
Breakout groups session 1

- **Modeling:** Minghui Diao (San Jose State Univ.)
- **Field observations:** Fan Yang (BNL)

12:15–1:15
Working lunch - Rapporteurs meet with chairs, initial round of feedback and planning

1:15–2:15
Breakout groups session 2: Participants rotate to a different group.

- **Modeling:** Minghui Diao (San Jose State)
- **Field observations:** Fan Yang (BNL)

2:15–2:30
Afternoon Break

2:30–3:15
Breakout summary reports (rapporteurs) and concluding remarks for the second day (chairs)

3:30–5:00
Optional lab tours

Day 3: Friday, October 27

Integration, Synthesis, and Summary

8:30–8:45
Chairs summarize and discuss overarching questions

8:45–11:15
General discussion

11:15–11:45
Post-workshop priority survey.

11:45–12:00
Closing remarks (chairs)

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APPENDIX II - ASR WORKSHOP PARTICIPANTS

Donifan Barahona
donifan.o.barahona@nasa.gov
NASA - Goddard Space Flight Center

Allan Bertram
bertram@chem.ubc.ca
University of British Columbia

Susannah Burrows
susannah.burrows@pnnl.gov
Pacific Northwest National Laboratory

Sisi Chen
sisichen@ucar.edu
NSF National Center for Atmospheric Research

Jessie Creamean
jcream07@colostate.edu
Colorado State University

Minghui Diao
minghui.diao@sjsu.edu
San Jose State University

Jiwen Fan
fanj@anl.gov
Argonne National Laboratory

Laura Fierce
laura.fierce@pnnl.gov
Pacific Northwest National Laboratory

Jeff French
jfrench@uwyo.edu
University of Wyoming

Ann Fridlind
ann.fridlind@nasa.gov
NASA - Goddard Institute for Space Studies

Zamin Kanji
zamin.kanji@env.ethz.ch
ETH Zurich

Daniel Knopf
daniel.knopf@stonybrook.edu
Stony Brook University

Pavlos Kollias
pavlos.kollias@stonybrook.edu
Stony Brook University

Alexei Korolev
alexei.korolev@ec.gc.ca
Environment Canada

Alex Laskin
alaskin@purdue.edu
Purdue University

Xiaohong Liu
xiaohong.liu@tamu.edu
Texas A&M University

Christina McCluskey
cmcclus@ucar.edu
NSF National Center for Atmospheric Research

Ottmar Möhler
ottmar.moehler@kit.edu
Karlsruhe Institute of Technology

Mikhail Ovchinnikov
mikhail@pnnl.gov
Pacific Northwest National Laboratory

Vaughan Phillips
vaughan.phillips@nateko.lu.se
Lund University

Raymond Shaw
rashaw@mtu.edu
Michigan Technological University

Matthew Shupe
matthew.shupe@noaa.gov
University of Colorado and National Oceanic and Atmospheric Administration

Israel Silber
israel.silber@pnnl.gov
Pacific Northwest National Laboratory

Frank Stratmann
frank.stratmann@tropos.de
Leibniz Institute for Tropospheric Research

Ivy Tan
ivy.tan@mcgill.ca
McGill University

Fan Yang
fanyang@bnl.gov
Brookhaven National Laboratory

Kai Zhang
kai.zhang@pnnl.gov
Pacific Northwest National Laboratory

Xue Zheng
zheng7@llnl.gov
Lawrence Livermore National Laboratory