BAMS Meeting Summary

Furthering Understanding of Aerosol–Cloud–Precipitation Interactions in the Arctic

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Second QuIESCENT (Quantifying the Indirect Effect: From Sources to Climate Effects of Natural and Transported Aerosol in the Arctic) Workshop

***What*:** Atmospheric scientists shared and discussed recent work to understand the complex interactions between aerosols, clouds, precipitation, radiation, and dynamics at northern high latitudes, as well as recent and upcoming field campaigns to improve that understanding.

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***Where*:** Tromsø, Norway

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The Arctic has been shown to be particularly sensitive to human-induced climatic change. With observed temperatures having warmed by several degrees over the last decades, surface properties are rapidly evolving, with changes in snow and ice cover and vegetation documented at a variety of Arctic locations (e.g., Moon et al. 2021). These changes to the Arctic surface have supported the ice–albedo feedback, in which a darkening of the Arctic surface facilitates further warming, resulting in a positive feedback loop and accelerating Arctic warming (e.g., Curry et al. 1995). Also thought to be of importance is the lapse-rate feedback (Pithan and Mauritsen 2014) in which the vertical structure of temperature and its changes due to forced warming influence surface and top-of-atmosphere longwave radiation. Clouds (see Fig. 1) play a central and critical role in these feedbacks, driving the surface and top-of-atmosphere energy budgets at high latitudes. Changes to cloud cover influence both shortwave radiation in summer months and surface and longwave radiation throughout the annual cycle. As a result of their importance, Arctic clouds have been the focus of a wide variety of studies working to understand the macrophysical and microphysical drivers of cloud lifetime across a variety of Arctic regimes (e.g., Morrison et al. 2012).

As with other clouds, Arctic clouds are dependent upon the presence of small particles to support formation of cloud droplets and ice crystals. These particles can result from local emissions, advection from lower latitudes, or local particle formation. Modeling studies have demonstrated strong dependence of cloud properties on the number of atmospheric particles, with particular sensitivity to the balance between particles forming ice crystals, also known as ice-nucleating particles (INPs), and liquid-forming particles, also known as cloud

Fig. 1. Radiatively important stratiform mixed-phase clouds observed over observing facilities on the NorthSlope of Alaska, where aerosol influence can be significant (photo: G. de Boer).

condensation nuclei (CCN). Numerical studies have demonstrated that the balance of INPs to CCN can significantly influence cloud microphysical properties and cloud radiative impacts (e.g., Klein et al. 2009). Previous studies on such sensitivities have demonstrated potential for increased aerosol number concentrations to reduce frozen precipitation in low-level mixed-phase environments (Norgren et al. 2018). In particular, the relatively low aerosol number concentrations that can be found seasonally in Arctic environments can hinder cloud formation and elevate the importance of transport of particles into regions featuring favorable humidity and dynamical regimes (e.g., Mauritsen et al. 2011). As a result of these sensitivities, detailed understanding of the types of particles making their way into Arctic clouds has been the focus of several recent field campaigns.

In recognition of the importance of Arctic clouds and their interactions with atmospheric particles, the QuIESCENT (Quantifying the Indirect Effect: From Sources to Climate Effects of Natural and Transported Aerosol in the Arctic) community was born. Through scientific collaborations with a variety of international organizations and efforts, including the Cryosphere and Atmospheric Chemistry (CATCH), Air Pollution in the Arctic: Climate Environment and Societies (PACES), and the International Arctic Science Committee (IASC), the QuIESCENT group held their first workshop in Cambridge, United Kingdom, in 2019. This workshop provided a platform to bring together communities focused on Arctic climate, clouds, aerosols, and precipitation processes to discuss the most critical gaps in our current understanding of Arctic cloud properties and life cycle. With an emphasis on integrating early career scientists, the inaugural workshop provided a platform for the integration of a new generation of scientists focused on this important set of topics. Through continued engagement and expansion of the QuIESCENT community, a second workshop was envisioned to reconnect and support the entertainment of additional community members. With financial support from IASC, the second QuIESCENT workshop was organized to coincide with the 2022 Arctic Science Summit Week (ASSW) in Tromsø, Norway. The current meeting summary provides an overview of the second QuIESCENT workshop and the discussions that occurred over the course of this meeting.

Overview of conference

In total, 84 registered participants took part in the second QuIESCENT workshop, which was offered in a hybrid format allowing for both in-person (30 participants) and remote (54 participants) attendance. Of these participants, 17 were from North America (20%), 61 were from Europe (73%), and 6 were from other geographic regions (7%). Thanks to support from IASC, 8 early career scientists were provided with some level of financial support to help offset meeting and travel costs. The meeting participants included 57% early career researchers (<5 years post PhD). The meeting strived to achieve a high level of gender equity for the different presentation types, scheduling a 55/45 (female/male) split for oral presentations and a 47/53 split for poster presentations.

Over the 2.5-day workshop, six oral sessions and one poster session were held, in addition to an early career networking session where principal investigators of recent and ongoing Arctic field campaigns were able to provide overviews of their projects. The first oral session included introductory material for the conference as well as a keynote presentation providing an overview of aerosol and trace gas measurements collected during the recent MOSAiC (Multidisciplinary Drifting Observatory for the Study of Arctic Climate) field campaign. This presentation offered a unique perspective on a full annual cycle of aerosol properties and processes over the central Arctic Ocean. The other five oral sessions were roughly organized by topical areas to allow presenters to summarize ongoing work related to

- aerosol formation and processing supporting aerosol–cloud interactions,
- the origins of Arctic ice nucleating particles,

- ice production and microphysics in Arctic clouds,
- interactions between Arctic clouds and their environment, and
- novel approaches to advance understanding on Arctic aerosol–cloud interactions.

In this section, we provide a brief overview of presentations given in these sessions.

In the area of aerosol particle formation and processing, there were five separate presentations that collectively provided perspectives on the types and number of aerosol particles present in the Arctic. This included work on understanding the prevalence of bioaerosols, thought to be a significant contributor to cloud-producing particle concentrations during summer months when there is a significant amount of open ocean present, and access to the land surface in terrestrial environments. Additional presentations offered perspectives on particle size distribution, including focused presentations on both ends of that distribution with overviews of new particle formation, and of CCN distributions. The latter overview included measurements from a tethered-balloon system, offering insight into the vertical structure of CCN in the Arctic. Finally, there was a presentation on attempts to use models to assess aerosol-deficient regimes and the response of clouds to such events.

The session on the origins of ice nucleating particles featured four presentations offering various perspectives on how the particles supporting ice generation make their way to the Arctic. This included a second keynote presentation focused on unraveling the similarities and differences between marine- and terrestrially generated particles and their relative contributions to ice formation. Additionally, overviews offered perspectives on predicting the background concentration of INPs in the Arctic environment, including the development of an empirical primary ice parameterization based on pan-Arctic observations, and considering the presence and prevalence of bioaerosol particles and the ability of those particles to form cloud ice and snow.

The next session focused on the production of ice in Arctic mixed-phase cloud regimes, including several presentations on how to best simulate ice generation in these complicated cloud structures. This session included several presentations, including one focused on observations and two focused on numerical simulations, that attempted to improve understanding of the role of secondary ice production in the generation of ice particles in mixed-phase cloud environments. This particular topic is one that carried over very directly from the first QuIESCENT workshop, where many participants considered understanding of secondary production of ice to be a very relevant poorly understood topic of interest. In addition, there was a presentation focused on the generation of ice through immersion freezing—another topic that has been discussed for several years. This presentation provided insight into how immersion freezing is handled in particle-based microphysical models, and how that handling supports the simulation of mixed-phase cloud processes.

The fourth session of the meeting focused on the interactions between clouds and their environment. In general, it was agreed that the atmospheric dynamics supporting cloud development and life cycle were underrepresented at this conference, though it was a topic that came up during this session. Presentations covered a variety of environmental topics, including interactions between sea ice concentration and cloud life cycle in the context of the seasonal cycle and the influence of external forcers such as volcanic eruptions on cloud lifetime and radiative response. Additionally, there was a presentation discussing numerical simulations to evaluate air mass transformations during the advection of air from lower latitudes into the Arctic and the impact of such transformations on the availability of CCN and moisture for cloud development. Finally, there was a presentation connecting environmental regimes and cloud properties in cold air outbreak situations in connection with a recently completed field campaign focused on such events.

Finally, the fifth oral presentation session featured presentations covering "gap" topics not included in the rest of the sessions. One such gap was the influence of elevated black carbon events on clouds and precipitation in high latitudes. In addition, there was a presentation that focused on cirrus clouds. With much of the meeting dedicated to low-level and mixed-phase clouds, this presentation offered a welcomed reminder that higher level ice clouds can also have significant influence on the surface energy budget and that, at the temperatures experienced by these clouds, the aerosol processes might be less critical because of the occurrence of homogeneous nucleation. Other presentations in this session provided overviews of work to improve forecasts of clouds and precipitation in the Arctic through the inclusion of aerosol properties in the forecast model and the evaluation of Arctic aerosol and reanalysis products using airborne and spaceborne sensing systems.

In addition to these five oral presentation sessions, there was also a lively poster session, including both in-person and online presentations. These poster presentations additionally touched upon all the topics mentioned above. The posters covered a wide range of different research pathways, including regional and pan-Arctic evaluations, observational and modeling studies, and a balanced distribution of presentations touching upon cloud and aerosol processes.

Each individual science session included dedicated time for discussion on the topics presented, and there were daily wrap-up sessions to further facilitate interactions between meeting participants. These sessions resulted in lively and sometimes controversial discussions about research priorities and levels of understanding on specific topics.

Topics of discussion

In addition to the different scientific sessions, the conference supported open discussion on relevant topics through a variety of means. This included a dedicated 2-h "world café" discussion period that focused groups to openly consider a variety of topics, including

- research priorities for understanding Arctic cloud processes,
- research priorities for understanding Arctic aerosol sources and processes,
- key observational developments for testing in models/missing model knowledge, and
- methods to improve the knowledge pipeline from observations through to global models.

As might be expected, the group identified many research priorities. Specific themes that stood out for clouds included phase transition in mixed-phase clouds, the role of dynamics, advancing cloud observational techniques particularly with respect to improving information on cloud microphysical quantities, revisiting the total water budget of these clouds, vertical velocity within Arctic clouds, and transfer of knowledge from observations to modeling tools across a variety of spatial and temporal resolutions. In terms of themes related to aerosol sources and processes, there was focused discussion on better understanding aerosol sources including emphasis on understanding long-range transport of particles, defining the relative importance of INP versus CCN-relative processes and parameterizations in modeling tools across spatial and temporal scales, new particle formation and the relative importance of the vertical location of new particle formation, and the natural baseline of aerosol particles in the Arctic. With respect to observational advancements, there was a defined need to capture more information on the ice particles in Arctic clouds, including the need for detailed information on ice hydrometeor habit. Additionally, there was interest in attempting to observe local and large-scale dynamical processes and their impact on local supersaturation and entrainment, and processes happening above the cloud top and at cloud base. There was expressed concern for the challenges faced by satellite-based sensor systems due to the unique radiative regime faced over the Arctic, and there was significant discussion and excitement about the potential for uncrewed aircraft systems (UAS) to contribute new perspectives, though it was recognized that we are still quite far from having "regular" UAS observations due to the infrastructure that would need to be in place for such activities. Finally, in terms of advancing the knowledge pipeline between observations and global simulations, several points were raised. One theme that arose included the need to better understand and represent the dynamics supporting cloud lifetime, and it was noted that there was very limited discussion on boundary layer and synoptic dynamics at this workshop. Additionally, there was broad agreement that the field could benefit from enhanced integration of the modeling community in the development and design of field campaigns at a very early stage of the planning. Out of this statement came the idea that we could potentially hold future workshops at an observational site and potentially convene a mini field campaign along with the workshop to facilitate broader interactions between the observational and modeling communities.

Looking ahead: Keeping the discussion going

In addition to the discussion periods discussed in the previous paragraph, the meeting offered numerous opportunities for informal discussions between meeting participants. The level of enthusiasm for the science presented and high level of engagement with the various discussion opportunities speaks loudly to the level of importance that meeting participants assign to understanding these aerosol–cloud–precipitation processes and interactions in the Arctic. Specific areas that were identified as key items for QuIESCENT to focus on and advance included the following:

- Enhancing observations of the vertical structure of key parameters. Despite new observing tools, in particular spaceborne active remote sensing observations, we continue to struggle to obtain enough samples to really understand the vertical distribution of cloud and aerosol properties over Arctic regions.
- Supporting enhanced communication between teams collecting and analyzing observational datasets and those evaluating and advancing our predictive tools. Not only should such enhancement accelerate the pace of progress in accurately representing key processes in models, but it could also allow for more efficient use of numerical simulations for defining key questions and designing field campaigns.
- Fostering discussions with scientists studying midlatitude aerosol processes and the global transport of particles and water vapor to better understand transfer of key quantities from lower latitudes.
- Continued advancement of our understanding and parameterization of INPs in the Arctic. Recent work has pointed toward potential marine and terrestrial sources of INPs that may nucleate at significantly warmer temperatures, thereby helping to explain the generation of cloud ice in environments that have traditionally been considered to be ineffective for ice formation.
- Continued support of the involvement of early career and minority (including female) participants in studying these important processes, and expanding participation by scientists from currently underrepresented regions, including Asia and Southern Hemispheric countries. Perhaps this could be achieved by extending the reach of QuIESCENT to also account for aerosol–cloud–precipitation interactions in the Southern Hemisphere.
- Supporting the development of review papers on key topics related to aerosol–cloud–precipitation–radiation interactions in the Arctic.

In addition, there was some discussion on the best management and governance structure for QuIESCENT moving forward. While the steering committee responsible for the organization of the last two workshops continues to be enthusiastic about continued work to support and advance collaboration in these research areas, there was some recognition of needing to perhaps formalize the oversight to ensure long-term continuity. As a result, there will likely be some turnover in the organizing team, both to entrain fresh energy and new ideas and to extend opportunities for other early career participants to take on some leadership roles. Work to support these exchanges and identify new organizers is currently ongoing.

The conference additionally included several discussions on opportunities for the development of new measurement campaigns. Several presentations highlighted new observing capabilities related to tethered balloon systems, drones, and other autonomous systems, and there was broad excitement about shaping new deployments that included these technologies. There was additional recognition that early career researchers, particularly those leveraging numerical tools for their work, can significantly benefit from field experiences where they get firsthand perspectives on the phenomena that they are studying. While the pathways for developing and advancing QuIESCENT-connected campaigns was not formalized, many ideas were discussed, including connecting an observational effort to the next QuIESCENT workshop and leveraging long-term existing measurement campaigns and seeking support for "add on" efforts to bring some of the new technologies to the field.

In the coming years, the QuIESCENT community plans to continue to expand in number and connect with a variety of groups with similar interests. This includes the development of focused sessions on Arctic cloud and aerosol processes and the connections between them at other community events such as the American Meteorology Society and European Meteorological Society annual meetings and the American Geophysical Union and European Geosciences Union meetings. Additionally, this includes a concerted attempt to expand to other geographic regions where scientists are focused on the Arctic, including Asia. Given the current pace of change in high-latitude weather and climate, it is very important to provide ample opportunities to discuss advancement in understanding of critical drivers like this. In that light, planning is already underway for a third QuIESCENT workshop, with a target meeting date in 2024. Readers are encouraged to sign up for the QuIESCENT mailing list and keep up with group activities through the website at https://sites.google.com/view/quiescent-arctic/home?authuser=0. This website also has additional information on the most recent workshop and will be used for the planning of future workshops.

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