AASCO
Arena for the Gap Analysis of the Arctic Science Co-Operation

The Arena for the Gap Analysis of Existing Arctic Science Co-Operations (AASCO)

White Paper | Summary of the AASCO event on February 4–5, 2025 in Monaco

Helsingin yliopisto / Helsingfors universitet / University of Helsinki
INAR Institute for Atmospheric and Earth System Research
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SAON Sustaining Arctic Observing Networks
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Prince Albert II of Monaco Foundation
Océano Institut Océanographique Monaco

LEAD EDITORS

Hanna K. Lappalainen and Tuukka Petäjä, INAR University of Helsinki

CHAPTER EDITORS

1 Arctic Sea ice and Greenland Ice Sheet

Petteri Uotila, University of Helsinki and Angelika Humbert, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research

2 Short-lived climate forcers (SLCFs)

Heikki Lihavainen, Svalbard Integrated Arctic Earth Observing System (SIOS and Yubao Qiu, International Research Center of Big Data for Sustainable Development Goals

3 Interplay between Arctic processes and the coupled climate system

Timo Vihma Finnish Meteorological Institute and Dorotea Iovino, Foundation Euro-Mediterranean Centre on Climate Change (CMCC)

4 Climate interventions

John Moore, Arctic Centre, University of Lapland and Marc Macias-Fauria, Scott Polar Research Institute

5 Research priorities around Arctic air pollution

Steve Arnold, University of Leeds and Alexander Baklanov University of Copenhagen

6 The role of Co-Production and local communities

Cana Itchuaqiyaq, Virginia Tech and Hanna Snellman, University of Helsinki

7 Pan-Arctic Science Research Collaboration

Jennifer Spence, Harvard Kennedy School and Kamrul Hossain, Northern Institute for Environmental and Minority Law, Arctic Centre

8 Data-sharing and AI

Pier Luigi Buttigieg, Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research and Jørn Kristiansen, Norwegian Meteorological Institute

LIST OF CONTRIBUTORS
(ALPHABETICAL ORDER;
LAST NAME, FIRST NAME, INSTITUTE)

Altenburger, Andreas, Arctic University of Norway, Arnold, Steve, University of Leeds, Arslan, Ali, Nadir, Finnish Meteorological Institute, Avango, Dag, Luleå University of Technology, Badhe, Renuka, organization tbc, Baklanov, Alexander, University of Copenhagen, Berkman, Paul, Arthur Science Diplomacy Center, Borm, Jan, University Paris-Saclay, Burkins, Melody, Dartmouth, Buttigieg, Pier-Luigi, Alfred Wegener Institute, Carlo, Nikoosh, CNC North Consulting, Dethloff, Klaus, Alfred Wegener Institute, Helmholtz Zentrum für Polar- und Meeresforschung, Eckhardt, Sabine, NILU, Frey, Markus, The Alfred Wegener Institute, Fugmann, Gerlis, International Arctic Science Committee, Gardfeldt, Katarina, Swedish Polar Research Secretariat, Gunde, Cimerman, Nina, University Of Ljubljana, Holmén, Kim, Norwegian Polar Institute, Kamrul, Hossain, Arctic Centre – University of Lapland, Hubbard, Alun, University of Oulu, Humbert, Angelika, The Alfred Wegener Institute, Hämeri, Kaarle, University of Helsinki, Ignatiuk, Dariusz, University of Silesia in Katowice, Ikäheimo, Tiina, Arctic University of Norway, Ikävalko, Johanna, Arctic Centre – University of Lapland, Iovino, Dorotea, Foundation Euro-Mediterranean Centre on Climate Change, Itchuaqiyaq, Cana, Virginia Tech, Jackson, Miriam, Institute of Geophysics Polish Academy of Sciences, Jonassen, Marius, University Centre in Svalbard, Kallenborn, Roland, Norwgian University of Life Sciences, Karcher, Michael, the Alfred Wegener Institute for Polar and Marine Research, Krejci, Radovan, Stockholm University, Krieger, Carlo PolarLu, Kristiansen, Jørn, Norwegian Meteorological Insitute, Kuklina, Vera, George Washington University, Kullerud, Lars, University of The Arctic, Kulmala, Markku, INAR University of Helsinki, Lafferty, Anita, University of Alberta, Larose, Catherine, CNRS-University Grenoble Alpes, Leppänen, Leena, University of Lapland, Lihavainen, Heikki, Svalbard Integrated Arctic Earth Observing System, Lindgren, Asa, Swedish Polar Research Secretariat, Luks, Bartłomiej, Norwegian Polar Institute, Lappalainen, Hanna, INAR University of Helsinki, Law Kathy, LATMOS/CNRS, Sorbonne Université, Lund, Marianne, CICERO Center for International Climate Research, Macias-Fauria, Marc, Scott Polar Research Institute, University of Cambridge, Markusson, Eystein, Svalbard Museum, McCarty, Jessica, NASA Ames Research Center, Mooney, Priscilla, NORCE, Bjerknes Centre for Climate Research, Moore, Kent, University of Toronto, Moore, John, University of Lapland, Nickols, Kerry, Ocean Visions, Paulsen, Frederik Dag, the University of the Arctic, Petäjä, Tuukka, INAR University of Helsinki, Pohjola, Veijo, Uppsala University, Qiu, Yubao, International Research Center of Big Data for Sustainable Development Goals, Raymond, Vanessa, Arctic Data Committee, Rudolf, Margaret, University of Alaska Fairbanks, Rødven, Rolf, Arctic Monitoring and Assessment Programme, Scheepstra, Annette, Arctic Centre, University of Groningen Selimovic, Vanessa, University of Michigan, Skov, Henrik, Aarhus University, Snellman, Hanna, University of Helsinki, Snellman, Outi, University of the Arctic, Soderberg, Charotte, Luleå University of Technology, Spence, Jennifer, Belfer Center Arctic Initiative, Harvard Kennedy School, Spolaor, Andrea, Norwegian Water Resources and Energy Directorate, Starkweather, Sandy University of Colorado, Stefansson, Gunnar, University of the Arctic, Stroeve, Julienne, University of Manitoba, Szkarlat, Monika, Maria Curie-Skłodowska University in Lublin, Tjernström, Michael, Swedish Polar Research Secretariat, Turunen, Tuija, University of Lapland, Uotila, Petteri, INAR University of Helsinki, Vihma, Timo, Finnish Meteorological Institute, Vitale, Vito, CNR-Institute of Polar Sciences, Wilson, Simon, Arctic Monitoring and Assessment Programme, Winther, Jan-Gunnar, The Arctic University of Norway, Ypma, Fonger, Arctic Reflections, Ørbæk, Jon Børre, Research Council of Norway

AASCO KEY COLLABORATORS AND PARTNERSHIPS

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Michael Alesi, Palais Princier

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Foreword

The Arctic is at the forefront of climate change, undergoing rapid transformations with significant global consequences. Understanding these changes requires a coordinated, long-term scientific effort that crosses disciplines and national borders. Recognizing this urgency, Arctic experts gathered at the Arena for the Gap Analysis of Existing Arctic Science Co-Operations (AASCO) in Monaco on February 4–5, 2025, at the Oceanographic Museum of Monaco. AASCO 2025 Monaco summit was the 4th event organized as part of the four-year AASCO project (AASCO-I 2020–2022, AASCO-II 2023–2025).

Supported by the Foundation Prince Albert II de Monaco and hosted at the Oceanographic Museum of Monaco, the AASCO meeting brought together researchers from diverse scientific backgrounds, united in their commitment to advancing Arctic science. This White Paper summarizes the key insights and recommendations from AASCO 2025 Monaco summit. The recommendations focus on eight critical topics: Arctic sea ice and Greenland Ice Sheet dynamics, the role of Short-Lived Climate Forcers (SLCFs), the interplay between Arctic processes and the coupled climate system, Arctic climate interventions, Arctic air pollution, the role of co-production and local communities, pan-Arctic collaboration and data-sharing and Artificial Intelligence (AI).

Moving forward, international scientists, policymakers, and stakeholders must work together to close research gaps and support the infrastructure needed for sustained Arctic observation. The findings in this White Paper represent a step toward these goals, ensuring Arctic science continues to inform global climate action.

AASCO 2025 Monaco Organizing Committee

Hanna K. Lappalainen, INAR University of Helsinki (chair), Tuukka Petäjä, INAR University of Helsinki, Outi Snellman, The University of the Arctic, Sandy Starkweather, SAON-ROADS, Heikki Lihavainen, SIOS, Yubao Qiu, CBAS, Paul Berkman, UN-UNITAR, Mike Sparrow, WMO-GAW, Stephen Arnold, PACES, Kathy Law, PACES and Salomé Mormentyn, Prince Albert II of Monaco Foundation

Contents

Introduction

Our existing in-situ observational networks and space-borne instruments, along with strategic research plans (Starkweather et al., 2022), provide a foundation for developing a new Arctic focus.

Referring to previous gap analyses of Arctic research, we can say that observations regarding meteorology and sea-ice physics are relatively well established. This is largely due to investments in operational forecasting services and associated scientific research programs, as well as strong international collaboration. These advancements result from the well-coordinated development of in-situ and satellite observation networks. However, while the global climate modeling community recognizes the Arctic as a key area of interest, it struggles with the complexity and scale of critical processes, their interactions, and their broader impacts. Addressing these scientific challenges, AASCO has identified 13 key topics related to Arctic feedbacks and interactions, calling for a new coordinated framework that incorporates multidisciplinary perspectives (Lappalainen et al., 2024).

The AASCO 2025 Monaco summit is a continuation of the work mentioned above, where we have defined the need for research on feedback processes in the Arctic region mainly from the perspective of the natural sciences. The AASCO 2025 Monaco summit aimed to contribute to key strategic frameworks for Arctic research planning and data needs, including the International Conference on Arctic Research Planning (ICARP) IV, the Sustaining Arctic Observing Networks – Roadmap for Arctic Observing and Data Systems (SAON-ROADS) framework, and preparations for the 5th International Polar Year (IPY) in 2032-33.

The discussions in the AASCO summit were planned beforehand by the coordinating team together with the thematic experts. The discussions in 8 tables were organized around the eight key topics identified during the AASCO process with key scientific and technological questions prepared in advance. The following sections summarize the discussions and provide a short list of key needs and requirements to make advances in the Arctic sciences. Each of the discussed topics is distilled into a single key message at the end of each chapter.

Key topics and key messages

1 Arctic Sea ice and Greenland Ice Sheet

- What are the main research priorities related to Arctic sea ice?
- How could observations and monitoring support these research priorities?
- What would be the next steps in implementing supportive actions
- How to monitor adequately the state of the Greenland ice sheet – from surface processes to sea level rise?
- How to increase knowledge on processes of the ice sheet hydrology?
- How to do we best foster coordinated monitoring programs of Greenland in the International Polar Year 2032/33?

Arctic sea ice is retreating, and we don't know how this will affect biodiversity. It is known that we do not know over 90% of the species in the oceans (Mora et al., 2011). The Arctic benthos is currently characterized as an oligotrophic environment, a situation that is likely to change dramatically with the ongoing retreat of sea ice (Ramirez-Llodra et al., 2024). This transformation is driven by various complex interrelated factors, such as increased light availability, changes in nutrient cycling, and shifts in phytoplankton community structure and primary productivity. The retreat of sea ice creates new open water areas that enhance light penetration, stimulating phytoplankton blooms, which are essential components of marine food webs and biogeochemical cycles (Assmy et al., 2017; Waga et al., 2021). Research is needed to describe both known and unknown biodiversity and to monitor its changes due to the retreating sea ice.

The changing sea acts as a source of particles and aerosols, which impact clouds and the atmosphere (Gong et al., 2023). These particles are released from leads and melt ponds, and radiative transfer in snow is also a key factor. The focus should be on the winter-to-spring transition, especially with the earlier shift in the melt season (Fig.1).

Targeted research campaigns that prioritize aerosols are necessary. Vertical atmospheric profiles are essential for understanding these processes and can be measured using drones, tethered balloons, and satellites. However, there is a need to establish a standardized protocol for these measurements.

It is important to determine whether there are aerosol hotspots, and modelers could help locate them. Additionally, building an expert network that represents various relevant disciplines is crucial. This can be achieved through town hall meetings and workshops to develop a benchmark for future research.

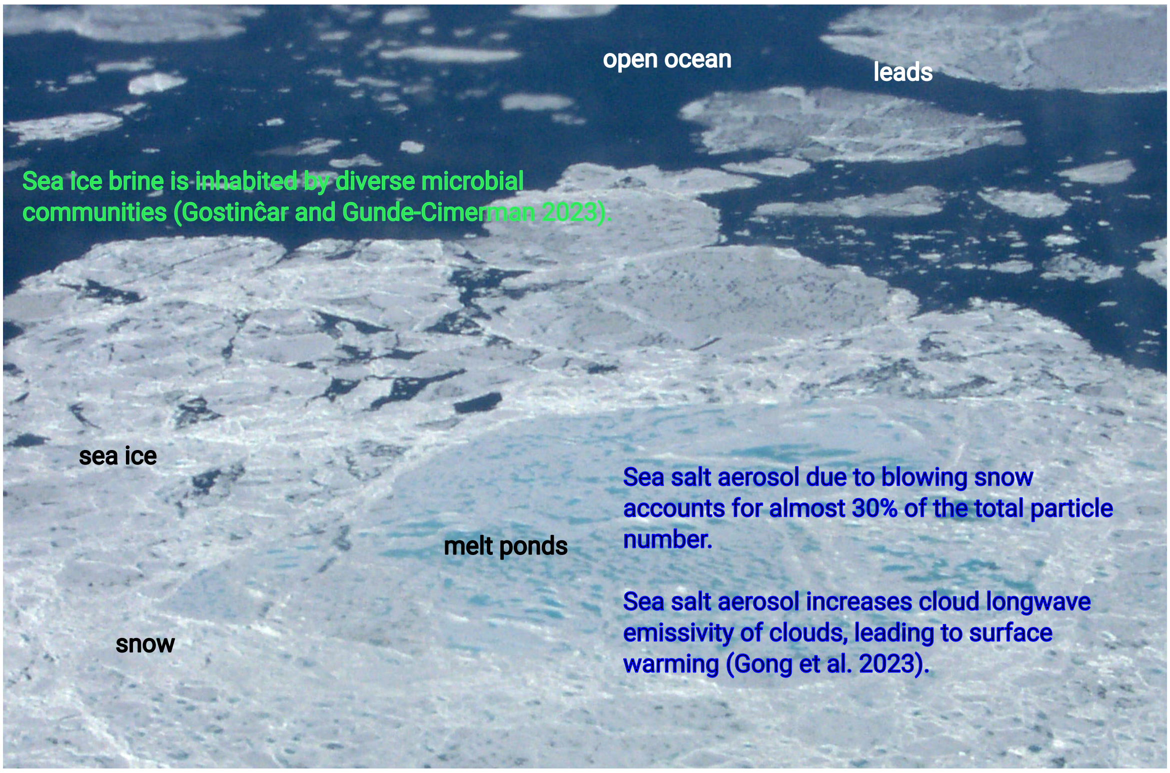

Figure 1: Arctic sea ice provides a heterogenous and dynamic environment for marine ecosystems and is an important regulator of aerosols.

The Greenland Ice Sheet (GIS) has undergone unprecedented mass loss in the observational period. Ice sheet dynamic is gravity-driven lubricated flow, with outlet glaciers of high velocity formed by sliding and topography. About half of the mass loss is due to the acceleration of glaciers, while the other half is driven by surface melting and the change of the surface mass balance. Both are inter-connected, as the surface water reaches the glacier bed through crevasses and drainage of supraglacial lakes, which enhances lubrication and leads to seasonal speed-up. Enhancing the understanding of ice sheet hydrology, from water retention in firn and supraglacial lakes, to englacial pathways and the subglacial system is thus a key topic.

The surface runoff area has increased from 1985–2020 by 29% (Tedstone and Machguth, 2022), the firn meltwater retention capacity is reduced (Vandecrux et al., 2019), partially by ice slab formation, which reduces the permeability of the firn pack across Greenland (Culberg et al., 2021). Surface melt is increased due to the reduced albedo, arising from light-absorbing particles (Cintron-Rodriguez et al., 2022), cryoconite and dust (Ryan et al., 2018) and bare ice exposure (Ryan et al., 2019). Massive amounts of water accumulate in supraglacial lakes, which drain via fracture and moulins over time scales of hours to days (van Das et al., 2008; Chudley et al., 2019), leading to blister formation and acceleration over a few days (Neckel et al., 2020). While the glaciological community has started to explore the hydrological system, many of the mechanisms are not yet well understood, and there is a massive lack of in-situ data. The following key questions should be addressed in future:

Regarding ice sheet hydrology and related feedback, a key question is whether and when (timing) the firn on the Greenland Ice Sheet will lose its water-holding capacity, as well as understanding its current water-holding capacity. Another essential question is *how to model the meltwater retention, refreezing and formation of ice slabs and formation of aquifers, adequately.* Here, the question of *how to bridge the scales from grain size to catchment size is an important topic*. Firn hydrology modeling currently lacks hydraulic parameters. Although some lab experiments have been conducted in Japan, and a few pumping tests have been performed, more research is needed. Bringing together researchers to conduct experiments and measurements is necessary to advance this field.

Basal hydrology needs further exploration literally. Drilling into subglacial channels is important for measuring pressure variations and hydraulic parameters. These campaigns shall be conducted as far upstream of the glacier's terminus as possible. Critical is investigating linkages between supra- and subglacial hydrology, including the mechanisms that facilitate connections between the surface and the ice bed. Additionally, studying the properties of the ice bed and its rheology will help improve our understanding of its impact on ice dynamics.

The International Polar Year (IPY) Greenland is an ideal framework for large coordinated efforts on the above topics. It might also be a good opportunity for using new technologies for in-situ measurements. The Northeast Greenland Ice Stream (NEGIS) could serve as a focal point for a coordinated IPY activity, from its onset down to the outlet glaciers.

Arctic Sea ice and Greenland Ice Sheet – Key Message

The rapid changes in the Arctic demand urgent attention to critical knowledge gaps, particularly regarding sea ice aerosols, biodiversity (Gostinčar and Gunde-Cimerman, 2023), and key processes within the Greenland Ice Sheet. Advancing our understanding requires a close collaboration between observationalists and modelers, establishing and maintaining multidisciplinary research networks, and integrative data analysis of the field observations. Given the significant logistical challenges, coordinated efforts, such as those within the International Polar Year (IPY), provide an ideal framework to facilitate comprehensive and impactful research.

2 Short-lived climate forcers (SLCFs)

- → What would be the main research priorities and knowledge gaps in the context SLCF and Arctic climate?
- → What observations and where are required to fill the knowledge gaps and improve Arctic climate projections?
- → How to avoid biases caused by SLCF data gaps in understanding SLCF emissions and effects now and in climate projections as half of the Arctic is in many ways inaccessible?
- → What would be ambitious enough goals for the 5th IPY in the SLFC context?

What is climate response to changing natural and anthropogenic SLCF emissions? The emissions of natural SLCF in the Arctic are most likely to increase as Arctic is warming, e.g. emissions of biosphere, increased sea salt aerosols due to diminishing sea ice, increased number of forest fires, changing circulation patterns. We can observe clear shift in aerosol properties towards more marine type because changes in circulation and precipitation patterns in Arctic (Heslin-Rees et al., 2020; Pernov et al., 2022). At the same time measures are being taken globally to decrease anthropogenic SLCF emissions to improve air quality and the effects of this trend can be observed also in Arctic (Schmale et al., 2022; Lund et al., 2023), e.g. sulfur dioxide from marine traffic (Ødemark et al., 2012).

The models still represent aerosol SLCF distributions poorly in the Arctic (AMAP 2021), with uncertainties arising from emission inventories/sources, processing along transport pathways and sinks. To improve models' performance, better observations of the vertical structure of SLCFs, Langrangian and process studies, improved emission inventories are needed. Understanding the vertical structure of SLCFs is crucial for assessing their impact on the atmosphere and climate, as it also provides information about transport pathways for aerosols and gases from lower latitude into the Arctic. This can be achieved through observations using advanced remote sensing (e.g.Lidar), balloons, UAVs, and Earth Observation (EO) technologies. Lagrangian studies in particular tracking the air masses and thus the transport and transformation of aerosols and pollutants would also increase the understanding of the processes and thus provide process-based understanding and parametrization to improve the models. Currently our knowledge of SLCF loading and variability above boundary layer is very limited and relies on few airborne campaigns and remote sensing. On a process level these measurements are also critical for proper understanding of atmospheric aerosol distribution and interactions with clouds.

Additionally, utilizing analogies between different regions can provide valuable insights. Comparing environments such as Canada and Russia, the Antarctic and Greenland and Svalbard allows researchers to identify similarities and differences in atmospheric and cryospheric dynamics, ultimately strengthening model development and predictions.

Short-lived climate forcers (SLCFs) – Key Open Questions

SLCF removal process by clouds and precipitation

Clouds also a source of aerosol? – NPF in the vicinity of clouds

The role of high latitude dust

Role of SLCF in climate feedbacks in ice-free Arctic

Magnitude and effects of marine microbiology on atmospheric composition

Is the changing Arctic good place to test dynamics of CLAW hypothesis?

How much SLCF is transported into the Arctic through free troposphere?

Will permafrost be a carbon source or sink in the warming climate

Short-lived climate forcers (SLCFs) – Key Message

SLCFs are expected to continue to play an important role in shaping Arctic climate, and climate-driven feedbacks involving SLCFs have effects well beyond the Arctic domain. Understanding changes is SLCFs properties in Arctic is ultimately important for designing and implementing effective climate mitigation policies as Arctic change is closely integrated with the global climate evolution.

Addressing knowledge gaps in SLCFs transport and effects in the Arctic requires continued efforts, including but not limited to novel strategies/approaches for improving model skill in representing SLCFs distributions, improved model representation of natural aerosol sources, and improving understanding climate driven impacts and feedbacks on SLCF sources, sink, and distributions

Sustained and broad observations and better integration between models and observations is critical, with the establishment of a common language and standardized observation methods to ensure consistency in data collection being one important element.

3 Interplay between Arctic processes and the coupled climate system

- → What are the key knowledge gaps and research priorities regarding local physical processes in the Arctic atmosphere, ocean, and sea ice?
- → How are local processes in the Arctic atmosphere, ocean, and sea ice influenced by heat and moisture transports to the Arctic?
- → How are climate feedback effects expected to evolve during this century and beyond?
- → How do changes in the Arctic system impact weather and climate in mid-latitudes?

A simplified [AC3] schematic of important local and remote processes and feedback mechanisms driving Arctic amplification is presented below. The figure 2. illustrates the initial triggering by global warming (red) and shows examples of process/feedback mechanisms such as the local surface albedo feedback (black), upper ocean effects (brown), local atmospheric processes (green), and remote Arctic – midlatitude linkages (yellow) (Wendisch et al. 2023).

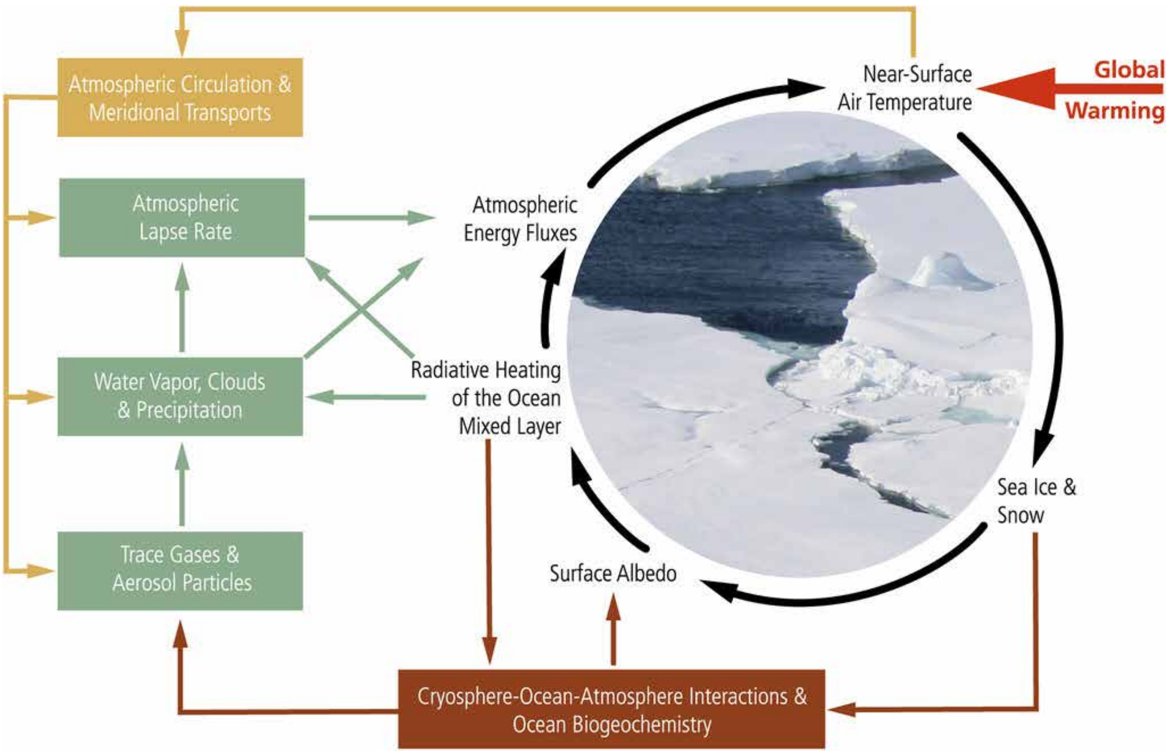

Figure 2. A simplified schematic of important local and remote processes and feedback mechanisms driving Arctic amplification. Reproduced from Wendisch et al. (2023).

The key knowledge gaps and research priorities regarding local physical processes in the Arctic atmosphere, ocean, and sea ice

Energy fluxes through sea ice and snow are determined by the surface energy budget, which is influenced by a variety of factors. These factors include mixed-phase clouds, aerosols, the state of the atmospheric boundary layer, and the thermodynamics of snow and ice. The properties of the sea ice, such as its thickness, the formation of melt ponds, and transformations between snow and ice, play a significant role in these processes. Additionally, the presence of a surface scattering layer, as well as biological components like algae in the snow, affect albedo and extinction.

Air-ice and ice-water momentum fluxes contribute to sea-ice dynamics, including ice drift, deformation, rafting, ridging, fracturing, and the opening and closing of leads. These processes, along with the formation of sastrugi, are linked to feedback mechanisms involving ridges, keels, and sastrugi that influence the momentum flux. The melting and structural weakening of sea ice directly affects its mechanical properties, creating connections between the energy fluxes and ice dynamics.

At the mesoscale and sub-mesoscale, processes in the ocean and atmosphere, such as ocean eddies and Polar lows, further influence the overall system. From a modeling perspective, one of the key research priorities is the development of coupled models that can dynamically integrate atmospheric, oceanic, and sea ice processes across multiple scales, as schematically illustrated below.

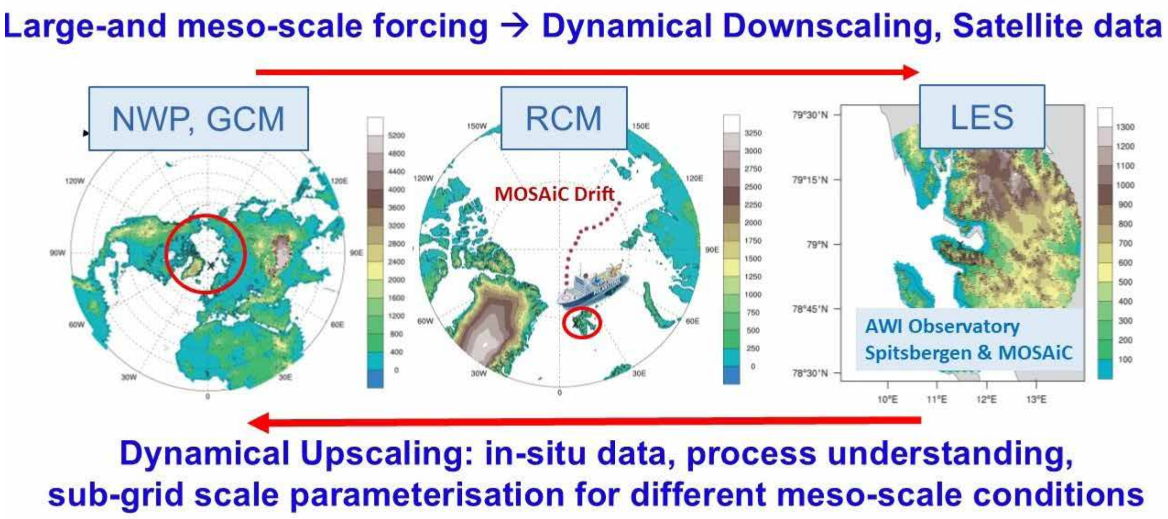

Figure 3. Strategy for development of coupled models integrating processes across multiple scales. Reproduced from Wendisch et al. (2019).

Local processes in the Arctic atmosphere, ocean, and sea ice influenced by heat and moisture transports to the Arctic

Local processes in the Arctic atmosphere, ocean, and sea ice are significantly influenced by the transport of heat and moisture into the region (Serreze and Barry, 2011). Heat and moisture transports into the Arctic are critical drivers that modify the local energy budget. They trigger a cascade of interconnected processes across the atmosphere, ocean, and sea ice, which, in turn, impact the stability and evolution of the Arctic environment (Woods and Caballero, 2016). These transports are central to shaping Arctic conditions and driving many of the observed changes in the region (Doyle et al., 2011).

In the atmosphere, the influx of warm and moist air masses alters the thermal structure, often leading to the formation of temperature and moisture inversions (Pithan and Mauritsen, 2014; Naakka et al. 2018). This influx can also reduce near-surface stratification through wind-driven turbulent mixing. Moisture transport is particularly important for determining the atmospheric moisture content, cloud formation, and precipitation patterns (Nygård et al. 2019). In a warming Arctic, the transport of dry static energy is expected to decrease, while the transport of water vapor will increase, further influencing atmospheric dynamics and the water cycle in the region (Graversen and Langen, 2019).

In the Arctic Ocean, the poleward transport of warm water has a substantial impact on vertical mixing and stratification (Polyakov et al., 2020). This warmer water can contribute to the basal melting of sea ice, which further affects sea ice dynamics and the overall energy balance (Carmack et al., 2016). Additionally, the influx of freshwater into the ocean can create stronger stratification, which inhibits vertical mixing and traps heat in the upper layers (Haine et al. 2015). This process may have significant implications for the dynamics of ocean circulation in the Arctic, potentially altering currents, nutrient transport, and the overall heat distribution within the ocean (Rippeth et al., 2015). How these changes influence ocean circulation is still a key question in Arctic research, with potential consequences for both regional and global climate systems**.**

How are climate feedback effects expected to evolve during this century and beyond?

- Climate feedback effects are expected to generally amplify warming over this century and beyond, although the time-dependent magnitude of these feedbacks remains uncertain due to complex interactions within the system.
- Ice-albedo feedback will finally become weaker when less snow and ice
- Water vapour and cloud feedbacks will become stronger with warming and moistening of the atmosphere, and increasing occurrence of liquid clouds (Ceppi et al., 2017).
- Lapse-rate and Planck feedbacks will become weaker in a warmer atmosphere with less stable stratification (Eiselt and Graversen, 2022)
- Permafrost and carbon cycle feedbacks will become stronger
- Greenland ice sheet and sea ice melt as well as increasing precipitation will result in weakening of AMOC, or possibly even in its collapse (van Westen et al., 2024), which may result in increased poleward transports of heat and moisture in the atmosphere.

How do changes in the Arctic impact weather and climate in mid-latitudes?

- **Direct effect** of Arctic warming: cold-air outbreaks become less cold (Ayarzagüena and Screen, 2016.
- **Indirect effects** are complex. Arctic warming -> weakening of meridional geopotential height gradient -> weaker jet stream in mid- and upper-troposphere -> weaker jet stream more liable to thermal and orographic forcing -> more meandering -> more meridional circulation patterns -> cold extremes in mid-latitudes and warm extremes in the Arctic (Overland et al.,2021).
- Also, meandering jet stream favors the occurrence of high-latitude blockings -> more persistent weather patterns -> potentially increased occurrence of cold winter weather events (e.g, under the influence of Ural blocking) (Overland et al. 2015).
- Changes in temperature gradient and stratification -> changes in baroclinic instability -> effects on cyclogenesis and cyclone tracks (Wickström et al.,2020)
- Further, stratospheric polar vortex is affected. Weakening, disruptions and displacements of the polar vortex affect tropospheric circulation -> may lead to more frequent intrusions of cold Arctic air into the mid-latitudes (Hanna et al.,2024).
- In the ocean, more freshwater from melting sea ice and increased river runoff -> modification of ocean salinity and density -> effects on vertical mixing and stratification, further on heat and carbon exchange between the surface and deeper layers. Stronger stratification -> reduced formation of deep water -> weaker AMOC and also effects on other circulation systems -> further effects on SSTs and weather patterns across mid-latitudes (Liu et al.,2017).

Interplay between Arctic processes and the coupled climate system – Key Messages

To reduce uncertainties related to feedback processes and better identify potential thresholds or tipping points in the Arctic environment, it is essential to refine parameterizations based on detailed observational data and to advance high-resolution modeling techniques.

Moreover, improving data sharing is crucial. This is not only about public access to data but also ensuring that data is more usable for researchers and other stakeholders. This can be achieved by adopting agreed-upon standardized formats and naming conventions to enhance the consistency and usability of shared data. Naturally, this work also necessitates ethical and equitable engagement with Indigenous knowledge bases to ensure that standards, formats, naming conventions align with and reinforce Indigenous inputs into global observing systems.

4 Climate interventions

- What systems in the Arctic are most at risk of collapse, and what, if anything, might delay or avert them?
- What systems might be helped with only local (domestic law) interventions?
- What field tests in the Arctic might be feasible – socially, legally and technically?

Why talk about interventions?

For the last 30 years, the cryospheric research community has repeatedly stated the facts of on-going and accelerating thaw, collapse and retreat across ice sheets, glaciers, sea ice and permafrost. In general, policy makers understand that the situation is bad, and that accelerated warming will make things worse. Furthermore, in recent years the concept of crossing irreversible tipping points has gained traction. While clearly identifying the mechanisms behind the concept may still be needed in many parts of the Earth System, in the case of the phase change from ice to water there is no doubting the physics behind tipping points in the cryosphere. All evidence suggests that we are presently at or past tipping points for the West Antarctic and Greenland ice sheets, Arctic sea ice and permafrost.

There is no prospect of avoiding crossing tipping points within 1.5°C, and it will be extremely unlikely to avoid those triggered at 2°C above pre-industrial temperatures. So, the key question is no longer how to best monitor and observe the collapse of vital components of the cryosphere during the next Polar Year, but rather, what, if anything, might be done to avoid the worst threats?

How might preserving the Arctic cryosphere be paid for?

At this stage, no serious researcher is advocating for any deployment of large scale interventions. But research must be done to resolve if any of the suggested ideas (there are at least 61 proposals identified (climateinterventions.org/) may have benefits that outweigh the very high risks of doing nothing.

Preserving the Arctic cryosphere will require careful consideration of what to protect, how to prioritise efforts, and how to fund these initiatives. One key element to protect is Arctic sea ice, which plays a crucial role in regulating the climate through processes like albedo (reflecting sunlight), influencing the Atlantic Meridional Overturning Circulation (AMOC), cloud formation, and cold air production, all of which impact permafrost in the land regions surrounding the Arctic Ocean. However, global ocean warming is expected to continue to increase heat in the Arctic Ocean, further threatening the sea ice. In addition to sea ice, land use management strategies, such as reindeer herding (or more generally large herbivore management), could be utilized to enhance land albedo, which could also help in cooling the region. When prioritising actions, it is important to focus on local-scale, need-based climate interventions, such as monitoring efforts, which can provide immediate and actionable data. Additionally, prioritising interventions where local and global interests align will ensure broader support and effectiveness. These strategies can form the foundation of a more targeted and feasible approach to preserving the Arctic cryosphere.

How to implement Climate Intervention Research?

Implementing climate intervention research (and potentially its eventual deployment) requires a coordinated, multi-faceted approach. First, it is essential to pursue international agreements for governance to ensure global coordination and shared responsibility in addressing climate change. Governance and ethics should be central research fields in geoengineering, guiding the development of interventions with a strong regulatory and ethical framework. Equally important is the co-design process with Indigenous peoples, incorporating their traditional ecological knowledge (TEK). This knowledge can offer practical, time-tested insights that might inform and enhance the design of climate interventions, ensuring they are culturally appropriate and environmentally sound. Needless to say, and while climate interventions can play a role in navigating the future decades, the primary focus in climate change mitigation should remain on decarbonisation efforts. Climate interventions should thus be viewed as a complementary tool, as decarbonisation is the only realistic and long-term solution to mitigating climate change.

There are huge challenges to climate interventions – as has already been widely noted e.g., in the Antarctic context by Corbett and Parson (2022). But the Antarctic Treaty Secretariat has lived long because it has proven to be adaptable. Furthermore, several influential bodies have released reports on intervention research methods and principles, e.g., the AGU 2024 geoengineering ethics report, and the UNEP report.

The UNEP effort "One Atmosphere Report" (www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment) emphasizes the need to enlist a multidisciplinary expert panel to engage in a comprehensive review of emerging technologies and interventions. As with the AGU report, diversity in governance is identified as key, raising concerns about the dominance of the Global North and the need for equitable access to knowledge and inclusive research. Additionally, the EU Co-Create project, the UArctic (van Wijngaarden, et al., 2024) and the WCRP lighthouse effort are all engaging in the process. Youth and civil society voices e.g., Operaatio Arktis, The Alliance for Just Deliberation on Solar Geoengineering (DSG) are important in addressing the moral hazard of speaking on behalf of others – the Global South and Youth. Indeed, there are clear synergies between the Global South and Indigenous and local long-marginalized Arctic communities.

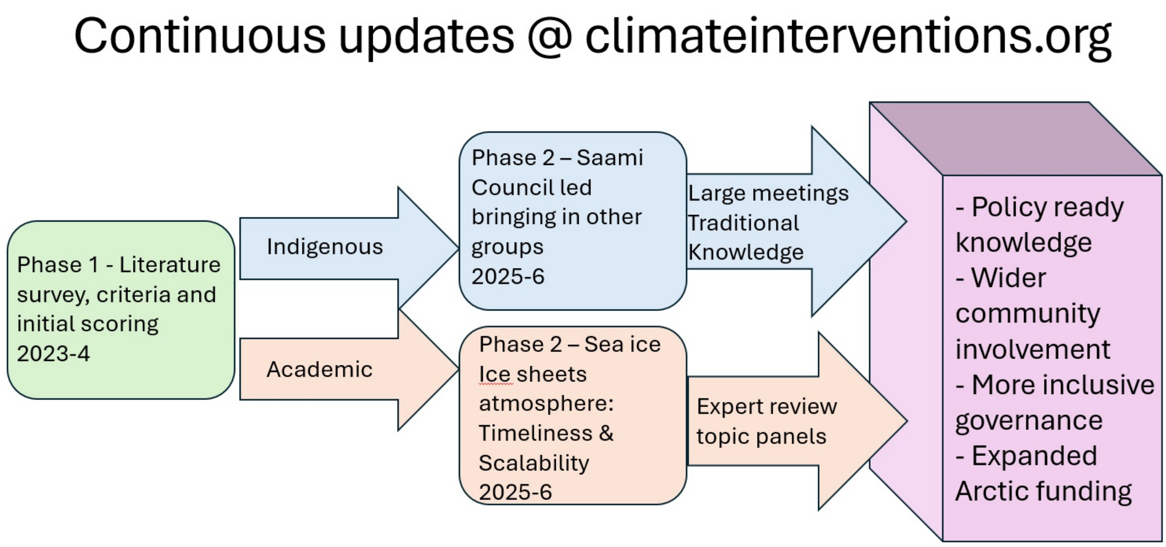

Figure 4. The methodology adopted by University of the Arctic for an evaluation of intervention ideas. The Saami Council are leading the Indigenous knowledge stream but engaging with other Indigenous groups in the Arctic Council. The large meetings include 3 distinct groups: Knowledge Holders that bring in Indigenous Knowledge and the more grounded input to the assessment, Indigenous politicians, and Indigenous experts (the ones that are well-acquainted with the field). The meetings are in a variety of formats, including formalized workshops, "town hall"-meetings, council meetings in addition to awareness raising and general capacity building (climateinterventions.org).

Panel and Round Table View on Climate Interventions

The question of "who pays" for climate interventions involves several important considerations. First, transparency is key – funders should publish both successes and failures, and data should be made available from all types of funding sources. Indeed, many of the research communities working in the Arctic are from institutions which expressly forbid funding from fossil fuel companies: e.g., www.cam.ac.uk/notices/news/the-university-and-funding-from-fossil-fuel-companies; www.uarctic.org/activities/thematic-networks/frozen-arctic-conservation/seabed-curtain-project/principles-guidelines/.

Another consideration is the "polluter pays" principle, where a pollution tax on oil companies could help fund climate interventions, ensuring that those responsible for environmental harm contribute to solutions. Alternatively, some might argue that climate interventions could simply rely on the economic incentive, especially if they are cheaper than other available alternatives, most notably the "do nothing" approach.

Ideally, the panel perceived that government grants should be favoured to enhance public acceptability and ensure that funding is directed toward the most effective interventions. In addition, private investment and philanthropy can play a crucial role in providing bridge funding, helping to fill gaps in financing until more sustainable and large-scale solutions are in place.

Other aspects

There are several additional ideas to consider when thinking about Arctic research and climate interventions. One key point is the need to stay vigilant about security, as climate interventions will likely occur regardless of our preferences. Therefore, it is important to be proactive in shaping these decisions. Another consideration is the issue of data, methods, and technology availability, particularly regarding open-source platforms. The question of who will own these technologies is a critical one that needs to be addressed.

Upscaling capacity is also a significant factor to consider in order to effectively implement solutions. Additionally, the general perception of geoengineering as risky raises concerns about ensuring that interventions do not lead to unforeseen consequences. It's crucial to consider the impact on affected ecosystems and the potential global (non-Arctic) ramifications of such actions. A clear understanding of the Precautionary Approach is needed, as it is often used both to support and to challenge research in this area.

Finally, there is a strong emphasis on the importance of continuing and enhancing Earth observations, which are vital for monitoring and guiding climate interventions effectively.

Climate interventions – Key Message

There is no prospect of avoiding crossing tipping points within 1.5°C, and it is unlikely to avoid those being triggered at 2°C above pre-industrial temperatures. The key question is no longer how to best monitor and observe the collapse of vital components of the cryosphere during the next Polar Year, but rather, what, if anything, might be done to avoid the worst threats?

5 Research priorities around Arctic air pollution

- What are key remaining knowledge gaps in understanding sources and processing of local emitted air pollutants in the Arctic?
- What are the research priorities in better understanding impacts of local Arctic air pollution on health, ecosystems, climate?
- Which science questions could be better addressed by improving frequency and coverage of regular vertical profile sampling of air pollution in the Arctic?

While most Arctic regions are far removed from large industrialized areas, the Arctic atmosphere regularly experiences increases in atmospheric trace pollutants, which can impact the Arctic climate, the health of residents, and sensitive ecosystems (Arnold et al.,2016; Schmale,et al., 2018).

Both local sources and long-range transport of pollutants from middle and low latitudes contribute to Arctic pollution levels and variability (Baklanov et al., 2013; Sharma et al., 2013; Schmale ,et al., 2018). However, significant knowledge gaps remain regarding the origins, relative contributions of different sources, and source apportionment, necessitating further study. In-situ measurements in the Arctic reveal distinct seasonal variations in trace gas and aerosol sources (Moschos et al., 2022). During winter and early spring, pollution transported from lower latitudes dominates up to altitudes of 1–2 km, creating the so-called “Arctic haze”. In contrast, long-range pollution influence is suppressed in summer due to large-scale meteorological patterns and a more dynamic boundary layer, which limit pollutant transport (Klonecki et al., 2003).

Climate change is rapidly altering the natural aerosol baseline in the Arctic (Schmale et al., 2021), leading to shifts in background aerosol levels onto which evolving anthropogenic sources are superimposed (Ren et al., 2020). Understanding these changes, their complex interactions, and their potential impacts – both in the Arctic and beyond – relies on continuous observations, both at the surface and aloft. Additionally, a deeper understanding of physical and biogeochemical processes within the Arctic system and their representation in models is essential. However, capturing the physical and chemical processes that drive pollutant variations in the Arctic remains challenging. A scarcity of observations and the limited accuracy of current models (e.g. Whaley et al., 2022) undermine confidence in predicting how Arctic air pollution and climate will respond to changes in both local and remote pollutant sources.

The rapid pace of Arctic climate change is also driving increased human activity in the region, including urbanization, mining, resource extraction, industry, the expansion of agricultural areas, tourism, and associated transportation and shipping activities (Schmale et al.,2018; Esau et al., 2021; Lappalainen et al., 2016, 2022). These developments are contributing to the further evolution of air pollution sources, with high-latitude dust emerging as a new priority concern (Meinander et al., 2022). The UNCCD and FAO (2024) have highlighted that emerging dust sources in high-latitude regions are linked to Arctic warming, the seasonal or permanent drying of inland waters and river deltas, large-scale deforestation and wildfires, and even the plowing of single fields. Additionally, climate change-driven factors such as snow cover loss, glacier retreat, and increasing drought intensity can create conditions that promote the formation and expansion of dust source areas (Meinander et al., 2025). Vegetation fire regimes at high latitudes are also responding to a warmer climate, with extreme fire seasons increasing in recent years, producing large emissions of black carbon and organic carbon aerosol (McCarty et al., 2021; Silver et al., 2024).

Changes in Arctic atmospheric composition also play a role in high latitude climate feedbacks, contributing to Arctic amplification specifically (Quinn et al., 2014). These feedbacks may include human responses to Arctic change, extending beyond physical and biogeochemical interactions. Understanding these mechanisms requires the further development of seamless, integrated Earth system modeling frameworks tailored to Arctic boundary layer conditions and interactions (Kulmala et al., 2023; Mahura et al., 2024).

Key knowledge gaps regarding sources and processing of locally emitted air pollutants in the Arctic were identified during roundtable discussions and presented below.

Arctic trace gas and aerosol sources, processing – Key knowledge gaps and messages

- Poor characterization of local Arctic pollutant emission sources.
- Potential impacts of local emissions on aerosol-cloud interactions are poorly constrained.
- Interactions between anthropogenic and natural sources, including impacts on new particle formation, in different environments.
- Shifting natural baseline (including dust, fire, marine emissions).
- A need for co-benefit analysis and optimal solutions for muti-sector impacts.
- Need for improved knowledge of both indoor and ambient pollution effects, and how these combine in the specific conditions of the Arctic.
- Modelling challenges: a need for seamless multi-scale integrated new generation Earth System? models
- Better characterize transport and processing of natural sources (local high-latitude and low-latitude dust, fires volcanoes) and local versus remote anthropogenic sources and their impacts on health, ecosystems and climate.
- Geographical gaps. Focus areas for observation campaigns: Iceland, Greenland, Alaska, Canada ?

The key research priorities for improving our understanding of the impacts of local Arctic air pollution on health, ecosystems, and climate are summarized in the following key messages:

Air pollution impacts and strategies for combined CC/ AQ/ health action (win/wins) – Key knowledge gaps and messages

Community Priorities: Local communities may prioritize economic and livelihood impacts over air quality health concerns, highlighting the need for education and awareness.

Community Engagement: More direct engagement is needed to ensure research addresses relevant questions and concerns. Involve local communities in research efforts.

Context-Specific Risks: Health impacts vary due to differences in healthcare infrastructure, baseline health conditions, and pollution types. We need improved understanding of these in Arctic communities.

Exposure Assessment: Better data needed on indoor vs. outdoor pollution under Arctic conditions and how people's activities influence exposure.

Technology Solutions: Could new technologies improve monitoring and understanding of exposure levels?

Mitigation measures: Shift from monitoring to early warning, mitigation and adaptation strategy is needed.

Research programs and initiatives such as PACES, WMO, PEEX, and others (e.g. Arnold et al., 2016; Benedetti et al., 2016; Kulmala et al., 2023) have emphasized the need to improve the frequency and spatial coverage of regular vertical profile sampling of air pollution and its composition in the Arctic. Consequently, PACES roundtable discussions focused on how to enhance vertical sampling and profile measurements of Arctic air pollution, along with addressing related research questions.

A role for improved regular vertical profile sampling in improving understanding of Arctic trace gas and aerosol sources and impacts

- → Which science questions could be better addressed by improving frequency and coverage of regular vertical profile sampling (aerosol, trace gas, temperature, humidity) in the Arctic?
- → What are the potential platforms available to undertake routine vertical profile sampling?
- → Which technological / instrumentation developments can we expect in advance of IPY (2032–33) to help enable routine vertical sampling?

The remaining knowledge gaps and research priorities for understanding vertical distributions and interactions of air pollutants in the Arctic, as identified in the roundtable discussions, are summarized below.

Increased Vertical Sampling – Key research directions to be advanced

- Improved knowledge of aerosol properties: absorbing/reflecting properties of particles – particle composition (e.g. black carbon, dust, sea salt, bioaerosol, pollen).
- Aerosol and trace gas radiative forcing: Better characterization of how aerosols and trace gases (SLCFs) affect Arctic climate.
- Aerosol-Cloud Interactions: Understanding how aerosols impact cloud formation and behavior / sources / processing, and indirect radiative forcing at different altitudes.
- Fire and dust influence: Improved tracking of source origins and long-range transport of dust and fire smoke.
- Arctic profiles near-surface and aloft: In-situ techniques needed to resolve fine-scale vertical structure and atmospheric stability, including near the surface where strong surface-based and elevated inversion layers trap pollution (in winter).
- Meteorological NWP: More vertical observations to improve understanding about Arctic boundary layer processes as well as weather and climate models.

Potential Platforms for Routine Vertical Sampling

- Ground-based remote sensors: LIDAR, FTIR, ceilometers, and other remote sensing tools for pollutants and meteorology.
- Balloon measurements: Cost-effective, in-cloud measurements possible, at fixed location.
- Drones/quadcopters: Low-altitude measurements (spatial and vertical mapping) of air pollutants and meteorological variables.
- Commercial and regional aircraft: Could provide routine data if flights are available.
- High-altitude platforms: NASA's planned 2026 solar-powered launch could support remote sensing.
- Nano-satellites (CubeSats): Need a viable commercial case (e.g., permafrost monitoring, infrastructure stability).
- Community-based monitoring: Engaging Arctic communities for localized observations, including low-cost sensors, associated with monitoring site(s) for Cal/Val.
- Combination, coordination and validation/calibration with in-situ high-quality measurements

Challenges and Future Technological Developments

Satellite limitations, regulatory and geopolitical barriers, emerging technologies, sensor reliability, AI methods for multi-platform data.

The multi-faceted role for Arctic air pollution in Arctic change underscores the urgent need for an improved understanding of Arctic air pollution and its interactions with key components of the rapidly evolving Arctic environmental system. A key recommendation is that rapid changes in both natural and anthropogenic sources must be examined holistically. Such an approach is crucial for developing robust Arctic climate projections, improving regional numerical weather prediction, and assessing risks to the well-being of Arctic residents and ecosystems.

6 The role of Co-Production and local communities

- → How do you ensure that the principle of "nothing about us without us" guides your research, particularly when working with Arctic Indigenous communities?
- → Beyond this principle, what other ethical guidelines do you prioritize to ensure your research aligns with the values and self-determination of Indigenous peoples?
- → What is your process to actively involve local communities as co-creators in shaping, conducting, and disseminating your research to make it meaningful and beneficial to them?
- → How do you approach language justice and meaningful access in your work, such as sharing research findings in Indigenous languages or through culturally appropriate and accessible mediums?

Building relationships can be challenging, as it requires time, effort, and mutual respect. It is important to approach others as genuine human beings, respecting their expertise while also remaining humble and open to learning. Supporting community leadership, especially in Arctic Indigenous communities, involves mentorship, education, and investing in the next generation. It also requires investing in learning about Indigenous community priorities and research protocols (e.g, Heikkilä et al., 2024; Inuit Circumpolar Conference, 2022; Inuit Tapiriit Kanatami, 2018; Kawerak Inc., 2024; ScIQ, 2018). Securing permission and establishing true partnerships from the beginning—rather than treating them as an afterthought—is crucial because "building and attaining equity is foundational to a co-production of knowledge framework" (Ellam et al., 2022). Additionally, sharing the benefits of research, such as funding, employment, and visibility through publications, is key to ensuring ethical and reciprocal collaboration. Creating actionable "next steps" is essential to ensure ongoing progress and long-term impact.

Integrity is fundamental in any collaboration. This means not over-promising results and setting clear, achievable goals. It also requires understanding and respecting constraints and boundaries while following through on commitments made. Effective communication strategies are necessary for successful collaboration, particularly in the Arctic, where linguistic and cultural diversity must be acknowledged. Developing plain language to explain complex ideas takes effort and careful scaffolding, allowing time for ideas to settle and space for feedback and responses.

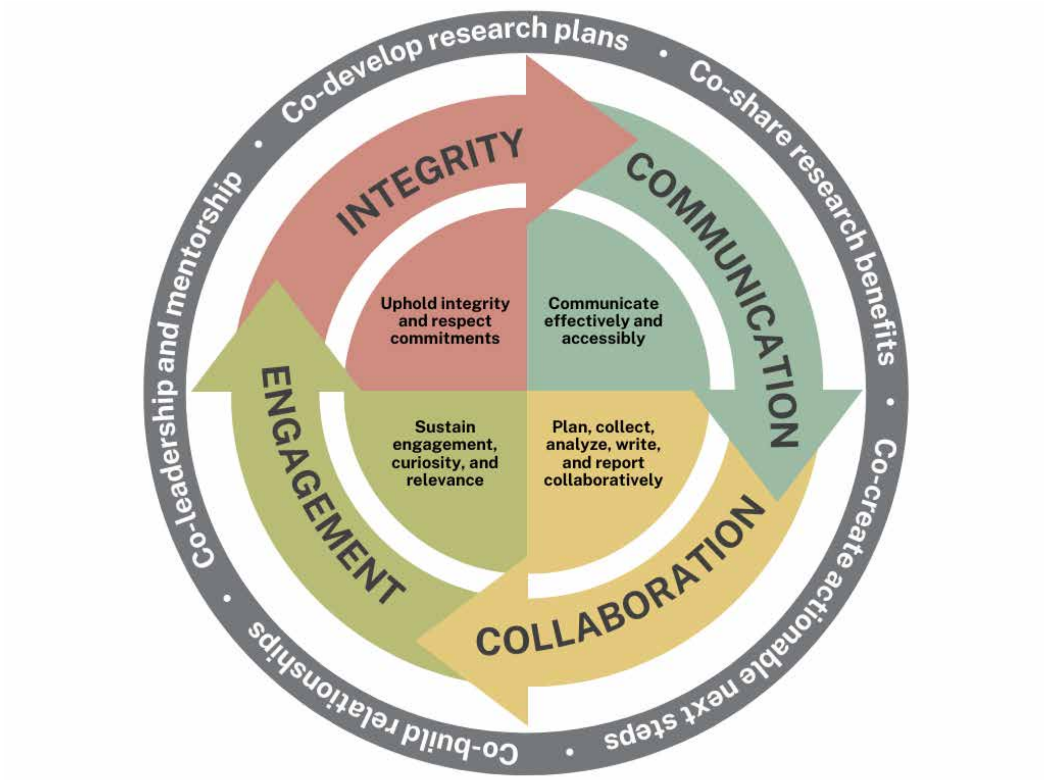

Figure 5. Scheme for Arctic collaboration needs and aspects.

The Role of Co-Production and Local Communities – Key Message

Co-production thrives on relationships built over time through mutual learning, respect, and trust. Investing in Indigenous community capacities and respecting sovereignty—through co-developing research plans, analyzing data, writing together, and reporting back to the community in accessible ways—creates more sustainable and impactful research. Co-production also carries responsibilities: defining roles and goals collaboratively, addressing research fatigue, and ensuring research sparks curiosity.

However, co-production is more than just improving relationships—it is also a strategic investment in the future resilience of Arctic research. Increasing local and Indigenous community participation in on-the-ground research actions—such as data collection, instrument maintenance, and monitoring—enhances efficiency and reduces dependence on expensive and carbon-intensive travel. This localized approach makes Arctic research more environmentally sustainable while ensuring that knowledge production continues even during crises, such as pandemics or funding disruptions. By embedding research capacity within Arctic communities, we future-proof Arctic science, making it more adaptable to economic fluctuations, logistical challenges, and other changes.

Keep the "last mile" in mind: research is relationship. Our work should be structured so that communities can apply, expand, and benefit from the results long into the future, ensuring that research is not only rigorous but also deeply relevant, resilient, and responsive to the needs of Arctic peoples and lands.

7 Pan-Arctic Science Research Collaboration

- → To what extent is Pan-Arctic research collaboration important?
- → What is your vision for Pan-Arctic research collaboration in 2035?
- → What are the challenges for Pan-Arctic research collaboration?
- → What are the tools available and/or do we need to advance Pan-Arctic research collaboration?

Pan-Arctic research cooperation is essential because natural and human systems in the Arctic are diverse yet interconnected, necessitating a collaborative approach. The opportunities and challenges facing the Arctic are complex, and a full understanding can only be achieved through the recognition and inclusion of diverse knowledge systems, disciplines and perspectives. Cooperation is crucial for generating useful knowledge at multiple scales, ranging from local to global, and supporting the entire research-to-action process. For over 30 years, the Arctic region has demonstrated the value of Arctic research cooperation, and dedicated particular attention to prioritizing the needs and voices of the region's Indigenous Peoples. Sustaining these efforts despite growing geopolitical tension in the region is critical for addressing both present and future needs both regionally and globally. Moreover, Arctic research cooperation provides important opportunities to foster mutual understanding and strengthen relationships between rights holders and stakeholders with diverse needs and perspectives. Ultimately, research should inform the development of effective policies and actions, while those policies and actions, in turn, help facilitate the generation of high-quality research.

The vision for Pan-Arctic research collaboration in 2035 is to remain resilient and productive despite geopolitical tensions, focusing on collective action and shared goals for the Arctic. It should be inclusive, incorporating a wide range of knowledges, experts, and perspectives, ensuring that diverse interests are represented and valued and the needs of Arctic communities are prioritized. There should be a significant investment in mechanisms and infrastructure to effectively collect, share, and disseminate data, knowledge, and lessons learned across the global research community. This infrastructure needs to build a sense of common interest and action, leveraging existing tools such as the CAOFA, Arctic Science Cooperation Agreement, Arctic Council, and IASC to coordinate efforts and strengthen collaboration.

By 2035, Arctic research should aim to better integrated, with a more unified approach to addressing challenges and opportunities across disciplines and sectors. The research community can be one that continuously evolves, learning from both its successes and its mistakes to drive better outcomes for the future.

A challenge for Pan-Arctic research collaboration is matching funding to research needs, including issues related to institutional support, startup costs, long-term investments, and operational expenses. Incentivizing collaboration between researchers and other knowledge-holders that there are sufficient motivations and rewards for working together and co-create knowledge across disciplines and borders that are critical for effective collaboration. Finally, decentralized research is an issue, as it is often research fragmented by boundaries and divisions, which can hinder the coordination and integration needed for effective collaboration.

Pan-Arctic Science Research Collaboration – Key message

Pan-Arctic research cooperation is vital due to the interconnected and complex challenges facing the Arctic, which require a collaborative approach that incorporates diverse knowledge systems and perspectives. Emphasizing the needs of Indigenous Peoples and fostering mutual understanding among stakeholders, this cooperation aims to generate valuable insights that support both local and global needs. By 2035, the vision is for productive research communities that prioritizes inclusivity, invests in infrastructure for data sharing, and adapts continuously to improve outcomes. Addressing funding, institutional support, and fragmentation challenges will be crucial for enhancing effective collaboration across disciplines and borders in the Arctic region.

Figure 6. ICARP Research Priority Team 4 "Arctic Research Cooperation and Diplomacy" has identified the four most relevant topics in this context.

8 Data-sharing and AI

- How can data platforms incorporate Indigenous and local knowledge alongside or integrated with scientific data?
- What are the most critical unmet needs of diverse user groups, and how can data-driven services be designed to meet those needs effectively?
- Can interdisciplinary approaches enhance the availability, quality and usability of environmental data?
- How do geopolitical challenges and regulatory frameworks impact polar data sharing and service provision, and what actionable recommendations can address these issues?
- The (artificial) elephant in the room: How do we leverage the AI boom for better data sharing, without it undermining foundational architectures?
- Why can't I find all Arctic data (or even metadata) from trusted sources across all Arctic platforms?
- What is working in delivering scientific data to other societal actors in a way they can react to? Why are most scientific data products still underused or invisible?

  What can we – as an Arctic community – do now to improve the situation?

*) Above are some general questions related to data availability, addressing end-user needs, and the utilization of artificial intelligence. The discussions in Monaco focused on defining an ideal Arctic regional data system.

An ideal Arctic regional data system

An ideal Arctic regional data system should decouple data from specific tools, software, or other hosts and architectures, allowing for more flexibility and accessibility. The system should consist of distributed, independent yet coordinated systems that cross-validate each other's offerings and verify that they align with FAIR (Findable, Accessible, Interoperable, and Reusable) and CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles. User centricity is crucial, especially in a context where there are competing and conflicting user profiles. The data exchanged within the system must support the application-layer operations required by different interest groups, such as providing full spatiotemporal and semantic markup, interoperable licensing, and metadata for usage restrictions. The system should adopt Data as a Service (DaaS) architectures within distributed networks, enabling dynamic sub-setting and abstraction-layer interfaces, eliminating the need to transfer all raw data from its sources. Additionally, the system should have a carefully managed (con) federation of systems, with a strong consensus on collective goals and objectives. Managed redundancy and replication monitoring are essential to ensure digital heritage protection, with agreements on how to handle the deletion of large or low-entropy raw data that is too extensive to store.

An ideal Arctic regional data system should establish baseline common standards as the first-order discovery layer, which would then lead to the creation of context-, region-, domain-, or community-specific "crosswalks" or translation layers to ensure accuracy. Securing funds for developing and maintaining these translation layers is crucial, as they are complex and not easily automated with high accuracy. The system should facilitate inter-system exchanges and orchestration, ensuring seamless communication and integration across different platforms. Additionally, all data should be cross-validated and digitally signed or recognized for authentication and proper crediting. It should also allow for the ability to contest or visibly disagree with digital assets circulating within the system, promoting transparency and accountability. Incorporating AI (Machine Learning + Knowledge Representation) solutions is essential, with transparent training sets or knowledge representations that can be clearly understood and assessed. A consensus on ARCO format specifications will help establish a common "AI-ready" data specification that supports the system's interoperability and integration. The system should also prepare for AI-based consensus assessments, ensuring it can handle emerging technologies and methodologies effectively. Lastly, there will be an even greater need for accurate provenance, licensing, and authorization to ensure that data is used appropriately and ethically across the system.

An ideal Arctic regional data system should establish baseline common standards as the first-order discovery layer, which will then lead to context-, region-, domain-, or community-specific "crosswalks" or translation layers to ensure accuracy. It is essential to secure funding for developing and maintaining these translation layers, as they are complex and not easily automated with high accuracy. The system should facilitate inter-system exchanges and orchestration, ensuring smooth communication and coordination across various platforms. Additionally, data should be cross-validated and digitally signed or recognized to authenticate and credit the contributors properly. The system should allow for the ability to contest or visibly disagree with digital assets circulating within it, promoting transparency and accountability. Incorporating AI (Machine Learning + Knowledge Representation) solutions with transparent training sets or knowledge representations will help improve the system's functionality and fairness. An agreement on ARCO format specifications will help create a consensus on a standardized "AI-ready" data specification, enabling seamless integration and interoperability across systems. The system should also be prepared for AI-based consensus assessments, ensuring it can handle emerging technologies and methodologies. There is an even greater need for accurate provenance, licensing, and authorization to ensure that data is used ethically and appropriately across the system.

Ethical frameworks should be built in from the outset, ensuring that the system is grounded in clear ethical principles. The ethical rationale behind decisions should not only be claimed but also shared in metadata, allowing others to assess and react to it with verified authorship. There must be control over data, supporting the principles of CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics), as well as other specific community requirements. Data should be insulated and localized, with metadata first, negotiated access, digital contracts, and auditing in place to support sovereignty and intellectual property assertions and claims. Contributions to the commons should be deliberate and tightly managed, with protections in place against theft or misuse. A clear legal and regulatory framework should be established, and compliance should be communicated through metadata, such as adherence to GDPR requirements. The system should ensure managed data observability with full provenance tracking, enabling proper auditing of data usage and changes. Additionally, green computing and sustainable data implementations should be prioritized, tracking energy use and carbon equivalent generation within metadata to promote environmental responsibility.

An ideal Arctic regional data system requires human capacity and resourcing to ensure its effective operation. Data isn't magic, and a bright post-doc is not necessarily a data professional. It is essential to have the right mix of professional data staff in each community, including roles such as data curators, engineers, architects, and managers, as each of these positions serves a distinct function. There is a need for re-evaluating community relationships to data, as the current structure can pose challenges. For example, the economy of science often doesn't foster modern data exchanges—papers and many institutional or national archives can easily become data crypts, limiting access and usability. Furthermore, informed consent remains a challenging issue, especially when it comes to data sharing and the ethical implications surrounding it. For the Data sharing, AI table, the key messages include the importance of addressing these challenges and ensuring that the necessary infrastructure and support are in place to facilitate effective, ethical, and collaborative data sharing in the Arctic region.

Proper timing and strategic deployment are essential for the system's success. It is recommended to start with a minimum viable product (MVP) that includes a representative subsample of key stakeholders, such as meteorological offices, Indigenous data hubs, and research infrastructures, before scaling up gradually. It is crucial to have a functional system, at least at the metadata exchange layer, by the International Polar Year (IPY) period, as it will be too late to start the process then.

Data sharing and AI – Key message

Features of an ideal Arctic regional data system-

- Decouple data from tooling/software or other hosts/architectures
- Distributed/independent but coordinated systems – cross-validating each other's offerings, verifying claims of FAIR/CARE alignment
- User centricity in a context with competing and conflicting user profiles
- Data as a Service (DaaS) architectures in distributed networks to allow dynamic sub-setting and abstraction-layer interfaces (no need to move all raw data from sources)
- Inter-system exchanges and orchestration
- AI (ML + KR) solutions with transparent training sets or knowledge representations
- Ethical frameworks
- Human capacity and resourcing
- Re-evaluating community relationships to data
- Timing and deployment

Key takeaways from AASCO 2025 in Monaco

While the global climate modeling community recognizes the Arctic as a key area of interest, it struggles with the complexity and scale of critical processes, their interactions, and their broader impacts. Addressing these scientific challenges, AASCO has identified 13 key topics related to Arctic feedbacks and interactions, calling for a new coordinated framework that incorporates multidisciplinary perspectives (Lappalainen, et al.,2024). The AASCO 2025 Monaco summit continued this analysis and connected the AASCO analysis to the international Arctic Research Planning, the International Conference on Arctic Research Planning (ICARP) process and the Fifth International Polar Year (IPY-5) in 2032–33.

The AASCO 2025 Monaco's key takeaways for research program planners and funders are as follows:

- **There are still critical knowledge gaps in processes and their interactions in the rapidly changing Arctic environment.**

The rapid changes in the Arctic require urgent attention to fill critical knowledge gaps. There remains a long list of processes where improved understanding is still needed, such as sea ice dynamics, aerosol dynamics and aerosol-cloud interactions. The key observational gaps include data regarding absorbing/reflecting properties and composition of atmospheric aerosol particles and biodiversity in the changing Arctic ecosystems.

To better understand vertical profile of the atmosphere in the Arctic both near the surface and aloft, more in-situ measurements are needed to resolve fine-scale vertical structure and atmospheric stability, especially near the surface where strong surface-based and elevated inversion layers trap pollution during the winter months. The vertical observations are necessary to improve our understanding of Arctic boundary layer processes, as well as to enhance the performance of weather and climate models.

In the broader context, there is an urgent need to better characterize of how Short-Lived Climate Forcers (SLCFs), such as aerosol particles and trace gases influence Arctic climate and radiative forcing. Additionally, improved understanding of the key processes influencing the Greenland ice sheet is needed. These improvements will reduce uncertainties in associated feedback mechanisms and will help to quantify threshold conditions or tipping points in the Arctic environment.

- **Research collaboration in the Arctic region highlights the critical importance of cooperation between local communities and Indigenous peoples.**

Future research communities should focus on inclusivity, invest in data-sharing infrastructure, and adapt to new knowledge and findings. Overcoming challenges in funding, institutional support, and fragmentation will be key to promoting effective collaboration across disciplines and borders in the Arctic region. Research depends on relationships. Scientific work should be designed so that communities can use, build on, and benefit from the results for years, ensuring that the research is not only thorough but also relevant, resilient, and responsive to the needs of Arctic peoples and landscapes.

- **There is still an urgent need for observational data and support for the close collaboration between data providers and modelers.**

It is essential to refine parameterizations based on detailed observational data and advance high-resolution modeling techniques. Advancing our understanding requires a close collaboration between observationalists and modelers, establishment and maintenance of multidisciplinary research networks, and integrative analysis of field observations. Given the significant logistical challenges, coordinated efforts—such as those within the International

Polar Year (IPY)—provide an ideal framework for facilitating comprehensive and impactful research.

The establishment of a common language and standardized and harmonized observation methods are crucial to ensure consistency in data collection emphasizing FAIR principles. Similarly, Indigenous leadership and representation are needed to engage with observations ethically and equitably, ensuring that the best available data is incorporated into models and other analyses. This effort will require substantial work in the future.

- **We need to improve and renew our concepts of the Arctic Data systems.**

Improving data sharing is essential. This goes beyond public access to data and extends to making data more usable for researchers and other stakeholders. Achieving this will involve adopting standardized formats and naming conventions to enhance the consistency and usability of shared data. This work must also involve ethical and equitable engagement with Indigenous knowledge systems to ensure that standards, formats, and naming conventions align with and respect Indigenous contributions to global observing systems. The application of AI methods for multi-platform data will need to be addressed in future technological developments.

- **We recommend conducting the necessary research to identify new ideas for effective mitigation solutions.**

Avoiding cryosphere tipping points with planetary consequences at the 1.5°C threshold seems increasingly unlikely, and preventing them at 2°C above pre-industrial temperatures may be challenging. In addition to focus on how to best monitor and observe the collapse of vital components of the cryosphere during the next Polar Year, we could also explore whether anything can be done to avoid the worst threats. This will require massive cross-disciplinary and cross-cultural collaboration. Developing potential ideas to work with nature and enhance its stabilizing feedbacks, which rising temperatures have disturbed, is essential, though the efficacy of these ideas remains uncertain.

"By fostering interdisciplinary dialogue, strengthening cooperation, and embracing innovative research approaches, we can drive forward the solutions needed to safeguard the Arctic and, ultimately, our shared future. For these ambitions to succeed, faced with the forces opposing us, we need unwavering commitment."

HSH Prince Albert II of Monaco

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Acronyms

AASCO	Arena for the Gap Analysis of Existing Arctic Science Co-Operations
AC3	Arctic Amplification: Climate relevant Atmospheric and Surface Processes and Feedback Mechanismin http://www.ac3-tr.de/
AGU	American Geophysical Union
AI	Artificial Intelligence
Cal/Val	Calibration / Validation
AMOC	the Atlantic Meridional Overturning Circulation
AQ	Air Quality
ARCO	format specifications will help establish a common “AI-ready” data specification that supports the system’s interoperability and integration
CAOFA	Central Arctic Ocean Fisheries Agreement, Arctic Science Cooperation Agreement
CARE	Collective Benefit, Authority to Control, Responsibility, and Ethics principles
CC	Climate Change
CubeSats	cubesatellites are a type of nanosatellites defined by the CubeSat Design Specification (CSD)
DSG	The Alliance for Just Deliberation on Solar Geoengineering
EO	Earth Observation
FAIR	Findable, Accessible, Interoperable, and Reusable principles
FAO	Food and Agriculture Organization of the United Nations
GIS	The Greenland Ice Sheet
ICARP	International Conference on Arctic Research Planning
IPY	International Polar Year
LCS	Lagrangian coherent structures – observations
MVP	minimum viable product
NASA	National Aeronautics and Space Administration
NEGIS	The Northeast Greenland Ice Stream
NWP	Numerical weather prediction
PACES	Air Pollution in the Arctic: Climate, Environment and Societies
PEEX	Pan-Eurasian Experiment
ROADS	Roadmap for Arctic Observing and Data Systems
SAON	Sustaining Arctic Observing Networks
SLCFs	short-lived climate forcers
TEK	traditional ecological knowledge
UArctic	University of the Arctic
UNCCD	United Nations Convention to Combat Desertification
UNEP	The United Nations Environment Programme
WMO	World Meteorological Institute

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