

# Advancing the Understanding and Quantification of Arctic Climate Feedbacks to Improve Climate Models and Inform Decision-Making: Insights from the AASCO Project (2020–2022)

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*A better understanding of land-atmosphere-ocean feedbacks and interactions is essential for developing effective strategies for sustainable development of the Arctic region. Further, this understanding is crucial for improving mitigation and adaptation plans and transforming them into actionable services for Arctic stakeholders and Indigenous communities. In this paper, we highlight key topics in Arctic research from atmospheric, oceanic, and cryospheric perspectives and offer insights into the latest research on interactions and feedback mechanisms in the Arctic region, particularly from the natural sciences perspective. Our approach synthesizes insights from the Arena for the Gap Analysis of Existing Arctic Science Co-Operations (AASCO-1) project (2020–2022), which calls for further development of integrated observation systems and the fusion of data from diverse sources, extending beyond traditional scientific boundaries.*

## Introduction

The Arctic faces immense pressure from rapid environmental, economic and cultural changes, as the complex dynamics of globalization has positioned it as a region of high influence in global geopolitics (e.g., Hartfield et al., 2018; Ford et al., 2015; Petäjä et al., 2020; Heininen, 2018). The role of the Arctic in the global climate system, Arctic ecosystems, and the development of Arctic societies are challenged by global megatrends, including rising concentrations of greenhouse gases (GHG, all acronyms defined in Appendix A-1), resource extraction, urbanization as well as local and long-range pollution (Smith 2011; Overland et al., 2019; Farré et al., 2014; Meinander et al., 2021). The changing Arctic has placed its fragile environment and its population, especially Indigenous Peoples, in a vulnerable position (e.g., Holland & Stroeve 2011; Arnold et al., 2016;

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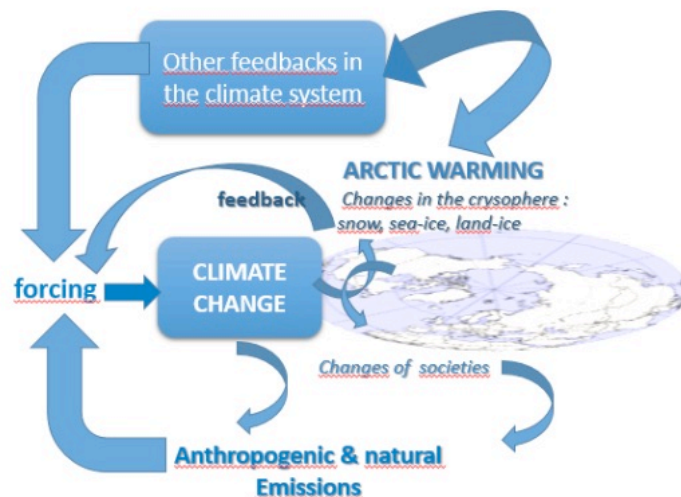
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Kulmala et al., 2015; Kumpula et al., 2011; Post et al., 2009 & 2019; Destouni et al., 2021; Ezhova et al., 2021).

The observed Arctic climate change is a consequence of the increased anthropogenic GHG emissions causing global warming and the local and remotely driven feedback processes amplifying warming in the Arctic (e.g., Rantanen et al. 2022). Climate change in the Arctic is affected by complex land-ocean-cryosphere-atmosphere feedback mechanisms linking higher and lower latitudes and acting on time scales from weeks to decades (however, geological and glaciological feedback mechanisms with longer time scales are beyond the scope of this paper). Due to the apparent rapid changes observed in the Arctic, there are simultaneous needs for both domain-specific scientific advances, e.g., in ecology, atmospheric, and cryosphere sciences, as well as for more in-depth integration of the research from these fields to better understand the interconnected system as a cohesive whole. A quantitative feedback analysis requires special attention so that the detailed, process-level knowledge can be elevated to a system-wide understanding of causes and effects and how actions mitigating the effects of climate change are best placed (Lappalainen et al. 2016, Kulmala et al. 2004).

There are still several critical knowledge gaps (Boy et al., 2019) in the Arctic environment. For example, ecological research on disentangling and quantifying Arctic processes and their drivers across the appropriate temporal scales is challenged by a lack of understanding of the detailed coupling within the Earth system including the relevant feedback mechanisms (e.g. Heffernan et al., 2014). Such combined system understanding is required to meet the complex environmental challenges in the Arctic. In addition to improved system understanding, the fundamental evaluation of the feedbacks and interactions will provide a foundation for necessary improvements of climate models and for required services benefiting Arctic residents and other stakeholders in the region (e.g., Starkweather et al., 2022).

The international Arctic research community has addressed the complexity of Arctic changes in several recent activities. The need for a deeper understanding was recognized by the IASC State of Arctic Science Report (2021) underlining the role of the Arctic in the global system and listed eleven relevant topics in this context, including “Improving understanding of Arctic amplification and Arctic climate feedbacks”. The NCoE-CRAICC provided several scientific legacies for deeper Arctic gap analyses and feedback interaction studies and analyzed new or improved existing feedback loops in ESMs that are crucial for accurate representation of the Arctic cryosphere-biosphere-atmosphere interactions (Boy et al., 2019) (Fig. 1). Now research projects like CRiceS, PolarRES, PROTECT and the Horizon Europe GREENFEEDBACK are continuing in this direction.



**Figure. 1.** The feedbacks related to the Arctic region and climate change are a key research topic of global importance. Figure adopted and modified from Boy et al. (2019) doi.org/10.5194/acp-19-2015-2019.

A general framework representing the complexity of feedbacks is not sufficient to find solutions for the critical issues, as quantification of feedbacks is needed to make progress. Comprehensive observational data with adequate geographical coverage and temporal sampling are the foundation for such a feedback analysis so that it is fit to support decision making in the Arctic. Some of the essential variables for monitoring the state of the Arctic environment are already available (e.g. Petäjä et al., 2020; Noe et al., 2022) and the development of Arctic observational infrastructure is a critical step in this process (Uttal et al., 2016; Petäjä et al., 2020; IASC 2021; Starkweather et al., 2022). Towards this end, the strategical planning and implementation of basic research together with an integrated Arctic Research Infrastructure (RI) is underway (e.g. Starkweather et al., 2022), where different national and international activities have provided critical support (SIOS 2018- ; IASC-SAON; WMO). Also, several European Union projects e.g. INTAROS 2016-2022, Arctic PASSION 2021-2025, iCUPE 2017-2021, EU-PolarNet 2, and GEM 1995- (Pirazzini et al., 2020; Noe et al., 2022) provide novel data and process management to integrate and combine Arctic data sets. However, these infrastructure projects and the modelling of Polar climate and weather largely separate activities, and gaps emerge in lieu of explicit links.

Beyond observational data collection and processing, the link between observations and models is crucial for turning process understanding into Arctic wide and for global monitoring and prediction capabilities. Here, the WMO's PPP project, the YOPP (Jung et al., 2016; Goessling et al., 2016) and the EU funded APPLICATE project (e.g. Sandu et al., 2021) have been important milestones for creating a new methodological Arctic focus covering the range from weather to climate timescales. YOPP is followed by the new the WMO project PCAPS, more strongly oriented towards development of services for societies. Also, Preparations for the International Polar Year (IPY) 2032–2033 are underway, coordinated by the International Conference on Arctic Research Planning (ICARP) with the seven Research Priority Teams (RPTs). Ultimately, science must support societal and political agreements, fostering social acceptance and active engagement. This is increasingly recognized as a fundamental asset for enabling the implementation of these plans (Berkmann et al., 2017, ARCTIC OPTIONS).

Here we introduce the scientific contributions obtained from the “Arena gap analysis of the existing Arctic science co-operations” AASCO project (2020-2022) funded by the Prince Albert II of Monaco Foundation. AASCO complements the IASC report (2021) with a specific focus on the Arctic feedbacks and interactions framework, the related Research Infrastructures (RIs) and data needs. Further, AASCO contributes to the ICARP process for the IPY.

## Methods

The AASCO project spans two periods: 2020–2022 (AASCO-1, Contract No. 2858) and 2023–2025 (AASCO-2, Contract No. 2858). It is coordinated by the Institute for Atmospheric and Earth System Research (INAR) at the University of Helsinki. The primary goal of AASCO-1 was to establish the AASCO collaborative process, focusing on understanding land-ocean-atmosphere feedbacks and interactions within the Arctic-boreal context. The project analyzed research gaps in Arctic-boreal studies, specifically addressing unresolved problems identified in existing research. A key method involved organizing two interactive workshops for Arctic experts in the field. Due to COVID-19, we conducted online workshops in November 2020 (over 200 participants) and December 2022 (with over 200 participants). The abstracts submitted by participants and reports generated from the discussions during AASCO-1 were utilized for this paper's overview.

First, we briefly introduce the current capacity of Arctic research infrastructure and outline future data needs. Next, we synthesize discussions on existing knowledge gaps, particularly concerning system feedbacks and process interactions. Although the societal component was not included in AASCO-1, it remains a crucial aspect for future analysis in AASCO-2.

The AASCO process contributes to Arctic research and observation planning in preparation for the International Polar Year (IPY) 2032–2033, particularly regarding the following ICARP research priorities: RPT 1 "The Role of the Arctic in the Global System," RPT 2 "Observing, Reconstructing, and Predicting Future Climate Dynamics and Ecosystem Responses," and RPT 4 "Arctic Research Cooperation & Diplomacy."

## The Arctic research infrastructure and data - current and future approaches

Understanding of Arctic processes and feedbacks is the key to provide a scientifically sound basis for policy making. To this end, there is need for systematic observations from different domains, such as the physical Earth system, biodiversity, ecosystem structure and functionality, and the global and regional environmental drivers changing the system. The current networks of monitoring and research are unevenly spread across the Arctic region, which largely reflects the reality of difficulties with working in remote areas, inequality of resources and limited human presence causing limited observational coverage at the Earth surface. In support of surface-based observations, the remote sensing from satellites and aircraft can provide data with a high spatial and temporal resolution, distributed with a remarkable speed and cost-effectiveness governed by internationally agreed protocols and infrastructures. The availability of harmonized data is crucial not only for monitoring changes as they occur, but also to forecast future conditions and to combine the environmental data with socio-economic data, such as health data.

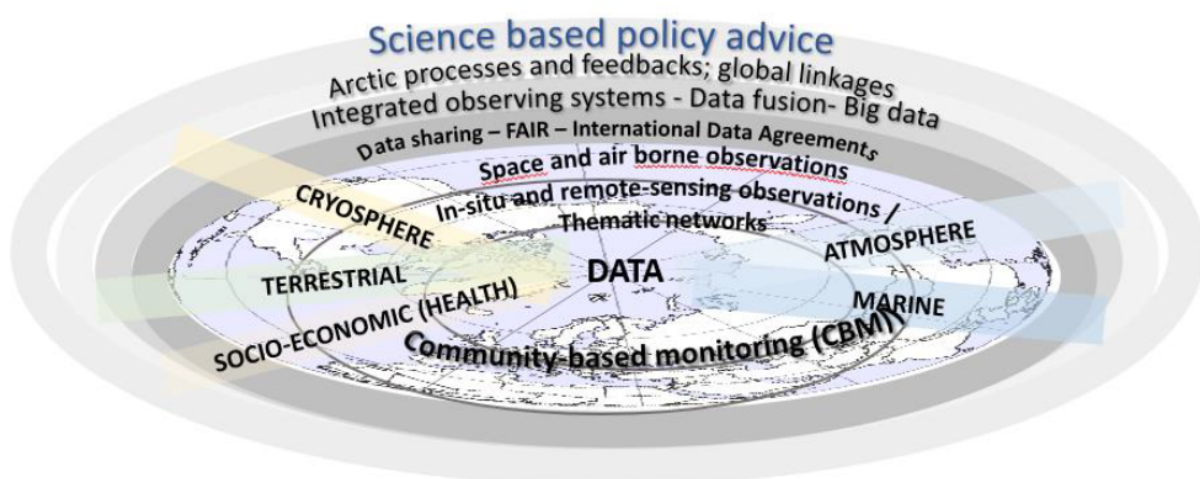
Russia's invasion of Ukraine on February 24, 2022, marked a significant turning point for pan-Arctic research and data collaboration. In response, the European Union and several individual countries, such as the United States, Canada, Norway, and Iceland took decisive actions, with research organizations and communities following suit by suspending cooperative efforts with

Russia. For example, on March 4, 2022, the Arctic Council announced that it would "temporarily pause the work of the Arctic Council and its subsidiary bodies until further notice". Since then, access to environmental data from Russia has become much more difficult, and in some cases, impossible. However, the World Meteorological Organization (WMO) continues to collaborate with Russia, ensuring access to meteorological data from the region.

The use existing of data is becoming more efficient due to the fast development of artificial intelligence-based solutions. Stevens et al. (2023) introduced Artificial Intelligence-based "Earth Virtualization Engines" (EVE) which are generating novel and fundamentally improved sources of information that has the potential to catalyze changes towards a new generation of data ecosystem and services.

Global and regional re-analyses form the best available databases of physical variables in the atmosphere and ocean over the past decades because they exploit most of the existing ground-based and space-borne observations (Hersbach et al., 2020; Bromwich et al., 2018). Re-analyses combine such observations with numerical models through data assimilation methods to produce a physically consistent, three-dimensional record of the coupled atmosphere-ocean system at the highest affordable resolution. The numerical models fill observational gaps in space and time but also permit insights into processes and cause-effect relationships. However, our limited understanding of process details and feedbacks in the Arctic also requires dedicated modelling efforts that must be supported by observations and campaigns (Shupe et al., 2022).

At the moment, the observational data product streams covering the Arctic are based on numerous atmospheric, cryospheric, oceanic and terrestrial observing systems (Fig. 2). The linkages between observational RIs and data management are implemented through topical projects and programs (see Appendix A-1 for details) while the planning, implementation, and production of data in the Arctic takes place in many different communities at global, regional, national and local scales.



**Figure 2.** Arctic data are multidimensional and consist of atmosphere, marine, cryosphere, terrestrial ecosystem and socio-economic datasets. Observations are made as in situ and remote based measurements and by community based monitoring. The long-term goal is open data for everyone. In the best case we have the so-called "big data", which we need as a basis for science-based political decision-making.

### **In situ Research Infrastructures (RIs) and thematic networks for the Arctic**

The European and national RIs for the observation of climate are based on physical structures and on logistics such as satellites, terrestrial stations, aircraft, ships and ocean/sea ice platforms. European infrastructures ([roadmap2018.esfri.eu/](http://roadmap2018.esfri.eu/)) are partly represented in Arctic areas or they plan to extend their observational capacities into the Arctic. Some are already established as legal entities, such as the ICOS-ERIC and ACTRIS-ERIC, or are public, limited companies (e.g., SIOS Svalbard AS), while others are yet in the process of establishing their legal status to ensure that the observing system has a sustainable organization. Most of the in-situ observations are funded through European or national research infrastructure programs. They provide high-quality, standardized data on GHG concentrations and fluxes (ICOS), short-lived trace gases and aerosols (ACTRIS), as well as on biodiversity and ecosystems (eLTER and EU INTERACT). Global networks relevant to the Arctic include, e.g., the GAW and the BSRN observation networks of the WMO.

Some thematic observing systems (focusing on, e.g., ice sheets, snow, hydrology, permafrost, and sea ice) are not developed through formal RIs but operate as part of research projects and are organized in networks, programs or as formal organizations, such as the GCW network of the WMO. In a few cases, governmental funding is involved but most of their efforts are driven by research projects without long-term funding. In some cases, they are developed into formal RIs, such as the International Arctic Buoy Program. In addition, the locally generated data from community-based monitoring (CBM) activities provide environmental and climate data as decided by the contributors. The evolution of such local observing systems plays an increasingly important role. Many CBMs are designed to support science in addition to community needs, and sometimes are lacking community involvement in design. The AMAP marine mammal monitoring generated by CBMs is an example how the CBM systems represent important information to the science systems (Appendix A-1).

The recent AMAP report (2021) on human health in the Arctic highlights effects of environmental contaminants on health, diets, lifestyles, and other circumstances of the Indigenous Peoples and leads to an assignment of different risk levels and health impacts between regions. Connecting the environmental data with health data is in progress, and is currently implemented in different large-scale projects, such as the EU Horizon-2020 Nunataryuk project and the NordForsk Nordic Centre of Excellence CLINF on epidemics of infectious diseases (Appendix A-1).

### **Space and airborne Research Infrastructures (RIs) in the Arctic**

The global observing programs initiated under the UN, e.g., WMO and IOC, which include the polar regions, often use satellites as the backbone observing system. The European Union space program's Earth observation component Copernicus, launched in 2014, became the largest open and free satellite data provider with seven currently operational so-called Sentinel missions (Plummer et al., 2017). The Arctic component measurements (CIMR, CRISTAL, ROSE-1), combined with Sentinel-1 instruments, can measure dry snow depths, soil moisture and vegetation characteristics. ESA now also has its own polar projects, which adds a layer of complexity when identifying the gaps. In addition to Europe and USA, Chinese satellite systems are actively developing their remote sensing capacity in the Arctic.

The space-borne observing systems are growing and produce an increasing amount of data in the polar regions. The largest impact of this data is produced by offering free and open data access of the entire circumpolar Arctic on a weekly basis at high spatial resolution and a sub-daily basis at medium resolution. This is already achievable with European and American data, which are facilitated by the GEOSS programs (Qiu et al., 2016 & 2017). However, high-quality, long-term in-situ and airborne observations, which are particularly important in the Arctic, are typically not included in such space programs. There are a number of specific airborne campaigns in the Arctic (e.g. Wendisch et al., 2024). These types of measurements help to investigate specific research questions, such as the role of clouds in the Arctic climate system.

### ***Data sharing and international agreements***

A common data management and open data distribution policy is an important part of the operating principles for these programs, and data from thematic observing systems are often complementary to space-based observing systems. Data from any observational activity are broadly used by the scientific community only if the data are supplemented by transparent metadata and follows the FAIR principles (<http://www.go-fair.org/fair-principles/>). This is extremely important for widely shared datasets to ensure maximum value generation but also to ensure that the scientists operating in the Arctic and collecting the data are properly credited.

An integrated Arctic observing system needs to provide access to ground- and space-based data at the same time. Currently, there is a combination of data systems that are specific to the Arctic or include the Arctic as part of a global or regional system and are operated by individual research organizations, national data centres, data infrastructures, and thematical observing programs. With many data systems that have evolved largely independently, a major challenge is that they offer different access mechanisms, and support different metadata, vocabularies and data formats. This makes it hard to integrate data from multiple systems, requiring a complex technical implementation to make interoperability work in practice.

So far, the efforts to strategically improve the Arctic observing systems have been hampered by the lack of a consistent, equitable and holistic planning mechanism and direct coordination at a high level from international funding agencies. Vihma et al. (2019) presented a comprehensive overview and formulated views on a future Arctic marine and terrestrial observing system. Recently, SAON has taken an active role and delivered a ROADS roadmap for Arctic RI (Starkweather et al., 2022). ROADS aims at improving linkages across independently funded efforts, proposes a holistic concept, building from the societal benefit-based approach of the IDA, and presents a roadmap to improve the most important Arctic observing elements accessed through interoperable data systems. The concept of SAVs is central to the ROADS and is linked to the essential harmonization of variables in broad, global networks (e.g., GCOS, GOOS, and GAW) (Starkweather et al., 2022).

A similar approach for the identification of the essential climate variables has been addressed in the frame of the R&B Initiative by China, by the EOST and by the Big Earth Data (BED). In addition to research, SAVs are serving an increasing socio-economic need, such as the Climate and Environmental Services in the Arctic (Baklanov et al., 2018; Grimmond et al., 2020). On one hand, climate variables from other parts of the World are important for understanding and predicting the changes in the Arctic (Karpechko et al., 2024). On the other hand, the High Latitude Cold Regions, especially the Arctic Ocean, and the High-Altitude Mountain Cold Regions of Asia have a profound

influence on the northern hemisphere weather and climate, through which they further determine global changes (You et al., 2021). From the perspective of the Earth's climate system, there is a need for continuous, long-term observations of these areas, as well as for the development of new methodologies to better characterize the evolution of the ecosystems, atmosphere, and cryosphere.

One of the major challenges is the gap between data collectors producing new datasets and data managers tasked with ensuring long-term storage and open access. A mediator role between these two communities of scientists and technical experts needs to be established, enabling competence building in FAIR data management (FAIR, 2016) and providing support in documenting and formatting datasets. For example, the Data Catalogue developed by INTAROS (<https://catalog-intaros.nersc.no/>) is an attempt to integrate and provide access to data from different scientific disciplines (Sandven et al., 2022). In addition to the technical organization of the data products and their availability, agreements are needed to allow on international cooperation (like COPENICUS) for studies addressing complex observations, basic science, multidisciplinary analysis and predictions, social dimension and policy mechanisms. The Agreement on Enhancing International Arctic Scientific Cooperation (signed in 2017 [www.arctic.gov/agreement-on-enhancing-international-arctic-scientific-cooperation/](http://www.arctic.gov/agreement-on-enhancing-international-arctic-scientific-cooperation/)) serves as an example, which aims to promote cooperation and prevent conflict with an international, interdisciplinary and inclusive implementation “for the benefit of all on Earth across generations” (Berkman et al., 2017). The agreement is also a science diplomacy asset, which improves collaboration and the dialogue between the Arctic actors (Berkmann et al., 2017; Evengård et al., 2021; Lappalainen et al., 2022).

### ***Integrated observation system and big data***

An integrated observing system for the Arctic needs to be established at different levels ranging from better formalized co-operations between institutions and countries to the practical integration of sensors and platforms and the development of interoperability between data systems. We have successful examples going in these directions. The regional observing system SIOS is an example of an integrated, in-situ observing system where scientists work together by sharing observing methods, knowledge, and logistics in an interdisciplinary manner over the entire Svalbard region (van den Heuvel- Greve et al., 2020; Moreno-Ibáñez et al., 2021). Another example is the SMEAR concept, which was originally developed for the high-latitude, boreal forest environment but can now be applied to various environments and conditions from the tropics to the Arctic, from rural regions to megacities (Kulmala 2018, Hari et al. 2016). The SMEAR concept is providing big data and enabling analysis of the atmospheric feedbacks, interactions and processes in and between the atmosphere and different land surface types (Hari et al., 2016; Kulmala et al., 2004 & 2014; Lappalainen et al. 2016, Vihma et al., 2019; Kulmala et al. 2021).

As new, advanced satellite observing systems emerge based on advanced hyperspectral radiometer and active lidar-radar instruments complemented by ground-based sensor networks and the internet of things, and as numerical models reach much finer scales also integrating impact sector models, the way big data are generated, analysed and workflows managed will evolve towards so-called digital twins. Digital twins will not only allow to observe and simulate the complex Earth system more accurately, also bridging between the physical and human world, but such an information system also allows a much more interactive way to work for scientists, service providers and decision makers (Bauer et al. 2021 a, b). Particularly for the Arctic, digital twin

capabilities will create new opportunities for preparing climate change adaptation measures and preparing Arctic societies for the future.

Existing and future actions for the further development of Arctic RIs and the role of big data are not only important for the services and for the verification of the sustainable development, but also for research, e.g., feedback analysis (e.g. Kulmala 2018; Kulmala et al., 2021; Guo et al. 2018). While the global climate modelling and numerical weather prediction communities have driven this macro-level data gathering and merging approach in the past, increased attention to the Arctic only emerged recently triggered by the decline of sea-ice, glaciers, and the Greenland ice sheet, as well as by the complex process interaction during weather regime transitions affecting mid latitudes. Still, in the consolidation phase of YOPP and an early stage of PCAPS, both weather and climate prediction require more polar focus and a dedicated RI to fill this gap.

Different observing systems must be seen as complementary to each other. In situ observations provide validation data for models and remote sensing observations, particularly important in the data-sparse Arctic region. Without standardization of data structures, formats, access and analysis capabilities, the data will not provide sufficient understanding of the complex natural and societal interactions or improve predictions of future changes. There is an urgent need to collaborate across communities, across local and global scales and across methods of modeling and observations. Progress in one area is impossible without progress in the others. To meet these challenges, Arctic observing programmes have been at the forefront of filling the gap over the last decades (e.g. AOS 2020 summit). However, better ways of coordinating observations are only one element of this agenda.

### **Arctic processes and their broader context - science-based rationale**

Altogether 13 key fields of research relevant to feedbacks in different Arctic main domains are introduced in Table A-2 (Appendix 2). These key areas call for comprehensive data, a multidisciplinary approach, and dedicated funding to better understand all these interconnections and feedbacks (Schuster et al., 2018).

To better predict and mitigate the rapid changes in the Arctic environment, there is a strong need to better understand numerous local and large-scale processes in the Arctic atmosphere, cryosphere, hydrosphere, biosphere, and within Arctic societies. The Arctic Amplification and understanding the atmospheric process and changes in the cryosphere in the Arctic are key issues (e.g. Pithan and Mauritsen, 2014, Wendisch et al., 2023). Practical issues in the hydrosphere include warming, salinity changes, and acidification in the Arctic Ocean and its marginal seas. Changes in the Arctic cryosphere are seen as reductions in the mass of sea ice (in particular, multi-year ice), lake ice, terrestrial snow, the Greenland ice sheet, and numerous Arctic glaciers, as well as in the thawing of terrestrial and submarine permafrost (Meredith et al., 2019). The cryospheric changes are mostly driven by the atmosphere and ocean, providing feedback to both. The sea-ice decline also allows stronger impacts of the open ocean on the coastal zone, seen above all in coastal erosion (Ogorodov et al., 2020). The above-mentioned changes both affect and are affected by the socio-economic evolution in the terrestrial and marine Arctic. The key socio-economic issues include e.g. pollution of the environment (Schmale et al., 2018), environmental health (Evengård et al., 2021), urban climate (Esau et al., 2021a, b), as well as socio-economic effects of extreme weather and climate events (Walsh et al., 2020). Both terrestrial and marine systems are strongly dependent on

atmospheric (temperature, precipitation), cryospheric (water availability, snow and ice cover, permafrost), and socio-economic trends (land cover, land use, and offshore activities).

Considering the atmosphere, the active transport of heat, moisture, greenhouse gases, trace gases and aerosols occurs between the marine Arctic and northern continents, and the source regions are often located in mid-latitudes (Hirdman et al., 2010; Backman et al., 2021; Schmale et al., 2021). In particular, the moisture transport is critical for the state of the Arctic climate system, as it distributes atmospheric water vapor and thereby impacts cloud formation, radiative transfer through the atmosphere, precipitation (Vihma et al., 2016), and consequently the ocean hydrography (Carmack et al., 2016) and terrestrial hydrology (Bring et al., 2016). The Arctic climate system is further modified by variable concentrations of natural and anthropogenic aerosols which directly interact with the radiation and take part in the complex dynamic processes modifying the properties and lifecycle of clouds (Schmale et al., 2021). Analogously in the ocean, heat and salt are transported poleward above all in the Atlantic sector, whereas freshwater is transported to the Arctic Ocean by rivers, the major ones having their origins in the Eurasian continent and North American mid-latitudes (Carmack et al., 2016), and by the relatively fresh oceanic flow from the Pacific and from melting ice (Solomon et al. 2021). Over recent decades, a large part of this freshwater has been accumulated in the Beaufort Gyre, but if it gets released relatively fast, as a response to large-scale atmospheric circulation, and transported to the North Atlantic, it might impact the oceanic meridional overturning circulation (Zhang et al., 2021). In addition to mid-latitude effects on the Arctic, conditions in the Arctic affect mid-latitudes. Due to the strong Arctic warming, cold-air outbreaks originating from the Arctic have become less cold (Screen et al., 2015). However, simultaneously with the warming of the marine Arctic, decadal-scale cooling trends and the increased occurrence of cold, snow-rich winters have been observed in parts of Eurasia and North America. These may represent natural climate variability or the forced response to Arctic warming, or, most likely, be a combined effect of both (Cohen et al., 2020).

Considering the Arctic cryosphere and biosphere, on the one hand, the situation is simpler in the sense that the variations and trends are controlled by local-to-regional processes in the Arctic (although the atmospheric and oceanic boundary conditions are partly remotely driven). On the other hand, the processes are very complex. The cryospheric ones involve both atmospheric and oceanic forcings, as well as thermodynamics and dynamics of sea ice, glaciers, and ice sheets, the dynamic components of glaciers and ice sheets being the least well-known ones (Meredith et al., 2019). The terrestrial biospheric processes in the Arctic are closely controlled by the availability of heat, water, and nutrients, which determine the ecosystem structure and productivity. The impacts on Arctic biodiversity are partly driven by local factors (depending on land cover and management), and partly by regional or even global ones (e.g. migrating birds and mammals).

Analogously to the atmosphere and hydrosphere, also the socio-economic component of the Arctic system is strongly externally driven, as both in large private companies as well as in the public sector in national and international levels the key decisions are made outside of the Arctic (Hanacek et al., 2022). In addition, the socio-economic interactions between the marine and terrestrial Arctic are strong (Radushinsky et al., 2017; Huskey et al., 2014), e.g. the shipping along the Northern Sea Route requires improved port infrastructure. Urbanization is accelerating globally but also in Northern high latitudes. This trend causes transformation in the geosphere, biosphere, pedosphere, atmosphere, and hydrosphere, affecting the human-environment system over both short- and long-term timescales. Cities represent a complex and highly dynamic interface between the Earth system

(atmosphere, land, water, etc.) and societal factors (health, social equity, life quality, economy, etc.) (Orttung et al., 2021). At the same time, cities are very sensitive to climate change. This vulnerability is strongly pronounced in the North, especially in the Arctic, where the warming rate since 1979 has been nearly four times the global average (Rantanen et al., 2022). This has direct and indirect impacts on the local livelihoods, infrastructure, water resources, ecology and air quality (e.g. Esau et al., 2020 & 2021a, b; Varentsov et al. 2023).

When the examination is extended beyond the pure natural sciences to the living environments and the effects on people, Urban Arctic climate and environmental health is widely recognized as an important topic (e.g. Schmale et al. 2018). Arctic is home for more than 5 million people living in >100 cities (Arnold et al., 2016). Rapid Arctic warming challenges people, infrastructures, and sustainability of the Arctic settlements (Hjort et al., 2018; Ramage et al., 2021; Sharma et al., 2019; Orttung et al., 2021). Poor knowledge of urban climate anomalies, their feedbacks and implications to socio-environmental interactions impede the progress towards more resilient and sustainable Arctic settlements e.g. proper mitigation and adaptation actions (Esau et al., 2020; Esau et al 2021; Streletskiy et al., 2019). The warming causes e.g., release of mercury (Hg), infectious agents, anthrax, from permafrost (Schester et al., 2018; Revich et al., 2021; Timofeev et al., 2019; Ezhova et al., 2021). Arctic air pollution has negative health effects on Arctic residents and the environment (AMAP, 2021; Schmale et al., 2018). There are a number of nuclear risk sites located in the Arctic (Mahura et al., 2005; Baklanov et al., 2006) causing potential hazards related to unintended release of nuclear waste.

In these challenges, the contributions of the cold climate conditions, stable-stratified turbulent exchange, and intense anthropogenic fluxes of heat and pollutants need to be better understood. High-resolution data from both ground-based and satellite observations are required for quantification of changes in the environment. Strategic plans for food and water security and living conditions influenced by thawing permafrost need to be developed in close collaboration with local stakeholders and researchers (Callaghan et al., 2020). Projects on quantifying nuclear risk sites in the Arctic are needed. Overall, a new view of One Health (World Health Organization, <https://www.who.int/news-room/questions-and-answers/item/one-health>) is needed to tackle the challenges in health of the environment, wild-life, and humans. Open and inclusive collaboration between the different disciplines and experts in research and practical work are needed to make steps forward.

## Conclusions

The Arctic climate is changing much faster than the global average (Hartfield et al., 2018; Meredith et al., 2019; Rantanen et al., 2022) and the permafrost and multi-year sea ice are disappearing rapidly (Onarheim et al., 2018; Kwok 2018; Ricker et al., 2017). Our existing in-situ observational networks and space-borne instruments together with strategical plans (Starkweather et al., 2022) provide us a basis to create a new Arctic focus.

Arctic research on meteorology and sea-ice physics are relatively well established because of the investments made by operational forecasting services and the associated scientific research programs, their good international collaboration, and well-coordinated development of in-situ and satellite observation networks. Increasingly, the global climate modelling community also identifies the Arctic as a key area of interest but struggles with the scales and complexity of the important processes, their interactions and their effects on the large scale. Regarding the primary scientific

challenges, we have introduced 13 key topics on Arctic feedbacks and interactions (Appendix 2) and call for a new coordinated framework from multi-disciplinary perspectives to address them.

While the observations from different systems are currently often performed in isolation, the critical global challenges call upon a multidisciplinary approach, stronger integration, improved information and data flows, and a capacity to draw science-based synthesis and predictions from the existing information through single platforms and data services. Without a coordinated, systematic observation system the science-based approach for the mitigation of environmental threats in the Arctic will be impossible to achieve, and we risk the failure of adaptation measures for Arctic societies.

Moreover, we are still missing full description of polar processes in the models. To be able to add these descriptions we need new, improved polar observations to increase the process level understanding in the Arctic environment. However, the approach has to be extended beyond the physical world with a much-enhanced data-model fusion including impact sectors relevant to societies. In-situ and remote sensing data as well as citizen science and Indigenous knowledges need to be included to form the so-called big Earth data and digital twin capabilities specifically for the Arctic. The important role of the Arctic in the global system and the acceleration of the change seen in the Arctic require these capabilities to be developed at the highest speed.

The collaboration of national and international organizations is of great importance to achieve these goals. The accelerated and amplified urban warming opens a unique opportunity for gap-filling field studies, where the analyses cover the physical, biological, and societal processes in the already warmed and altered environment. Hence, the organization of multi-disciplinary field work in and around the Arctic cities would be beneficial for the environmental protection and better climate projections alike.

For the societies affected by rapid changes and experiencing increasing threats, we urgently need new information systems with foci across basic process and feedback research and bridging between science and society. As changes are evolving fast, these information systems and their scientific input need to be as agile as possible. Based on the Analyzing Global Funding Trends project and the UArctic's funding database, the research funding targeted to the Arctic is only 1% of all global research funding. "Earth Sciences" is the largest proportion of the Arctic research funding and is especially attributed to oceanography. This concretizes the need for enhanced resources for multi- and cross-disciplinary Arctic research (Osipov et al., 2016). AASCO calls for further actions towards achieving this goal by creating a big data framework enabling comprehensive research (program) on land – atmosphere – ocean interactions and feedbacks. This will benefit Arctic stakeholders from local to global communities to address climate change and fulfil UN SDGs in the Arctic context.

The paper has been conceptualized with a joint contribution of all the Authors.

### **Declaration of Competing Interest**

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this paper.

### **Data availability**

No data was used for the research described in the article.

## Notes

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## Appendix 1

**Table A-1.** Explanation of the acronyms.

Acronym	Full name	Scope	Website
AASCO	Arena gap analysis of the existing Arctic science co-operations	Prince Albert Foundation feedback research	<a href="https://www.atm.helsinki.fi/peex/index.php/aasco/">https://www.atm.helsinki.fi/peex/index.php/aasco/</a>
(AC) <sup>3</sup>	Arctic Amplification: Climate Relevant Atmospheric and Surface Processes, and Feedback Mechanisms	Transregional Collaborative Research Centre funded by German Science Foundation (Deutsche Forschungsgemeinschaft, DFG)	<a href="http://ac3-tr.de/">http://ac3-tr.de/</a>
ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure	European RI atmospheric sciences	<a href="https://www.actris.eu">https://www.actris.eu</a>
AMAP	Arctic Monitoring & Assessment Programme - a Working Group of the Arctic Council  AMAP Assessment 2021: Human Health in the Arctic	Arctic Council health research	<a href="https://www.amap.no/documents/doc/amap-assessment-2021-human-health-in-the-arctic-pre-print/3593">https://www.amap.no/documents/doc/amap-assessment-2021-human-health-in-the-arctic-pre-print/3593</a>
AOS	The Arctic Observing Summit	conference	<a href="https://arcticobservingsummit.org/summits/aos-2020/">https://arcticobservingsummit.org/summits/aos-2020/</a>
APPLICATE	Advanced Prediction in Polar Region and Beyond	European Union's Horizon 2020	<a href="https://applicate-h2020.eu/">https://applicate-h2020.eu/</a>
ARCTIC OPTIONS	Arctic Options / Pan-Arctic Options projects (both on Holistic Integration for Arctic Coastal-Marine Sustainability) – funded through ()	the Belmont Forum with Canada, China, France, Norway, Russia and the US from 2013-2022 – which evolved into the Science Diplomacy Center™	<a href="https://scidiplo.org/">https://scidiplo.org/</a>
Arctic PASSION	Pan-Arctic Observing System of Systems - project	EU Horizon2020 RI	<a href="https://arcticpassion.eu">https://arcticpassion.eu</a>
BED	Big Earth Data		

BSRN-WMO	Baseline Surface Radiation Network of the World Meteorological Organization	United Nations' organization	<a href="https://hal.archives-ouvertes.fr/hal-03658664/document">https://hal.archives-ouvertes.fr/hal-03658664/document</a>
CBM	Community-based monitoring		<a href="https://mkp28.wixsite.com/cbm-best-practice">https://mkp28.wixsite.com/cbm-best-practice</a>
CIMR	The Copernicus Imaging Microwave Radiometer (CIMR) Expansion mission	EU Earth observation programme COPERNICUS	<a href="https://atpi.eventsair.com/cimr-mission-2021/">https://atpi.eventsair.com/cimr-mission-2021/</a>
CLINF	Climate-change effects on the epidemiology of infectious diseases and the impacts on Northern societies	Nordic Center of Excellence funded by Nordforsk feedback research	<a href="https://clinf.org">https://clinf.org</a>
CRAICC	Cryosphere–Atmosphere Interactions in a Changing Arctic Climate, Nordic Centre of Excellence	Nordic Center of Excellence funded by Nordforsk feedback research	<a href="https://researchportal.helsinki.fi/en/projects/craicc">https://researchportal.helsinki.fi/en/projects/craicc</a>
CRiceS	Climate Relevant interactions and feedbacks: the key role of sea ice and Snow in the polar and global climate system - project	EU Horizon2020 feedbacks research	<a href="https://www.crices-h2020.eu/">https://www.crices-h2020.eu/</a>
CRISTAL	The Copernicus Polar Ice and Snow Topography Altimeter Mission in COPERNICUS, launch planned in 2027	EU Earth observation programme COPERNICUS	<a href="https://www.copernicus.eu/en">https://www.copernicus.eu/en</a>
eLTER	Integrated European Long-Term Ecosystem, critical zone and socio-ecology Research infrastructure	European RI ecosystem research	<a href="https://elter-ri.eu">https://elter-ri.eu</a>
EOST	Earth Observation Science and Technology	other	<a href="https://le.ac.uk/earth-observation-science">https://le.ac.uk/earth-observation-science</a>
EPOS	European Plate Observing System	European RI	<a href="https://www.epos-eu.org">https://www.epos-eu.org</a>
ERIC	European Research Infrastructure Consortium	a specific legal form that facilitates the establishment and operation of Research Infrastructures with European interest	<a href="https://ec.europa.eu/info/research-and-innovation/strategy/strategy-2020-2024/our-digital-future/european-research-infrastructures/eric_en">https://ec.europa.eu/info/research-and-innovation/strategy/strategy-2020-2024/our-digital-future/european-research-infrastructures/eric_en</a>
ESM	Earth System Models	other	
EVE	Earth Virtualization Engines	<i>interactive data access layer that allows simple navigation, extraction, and application of the climate simulation data</i>	<a href="https://eve4climate.org/">https://eve4climate.org/</a>

EU-POLARNET	European network to co-develop and advance European Polar Research	EU Horizon2020 feedback research	<a href="https://eu-polarnet.eu">https://eu-polarnet.eu</a>
Euro-ARGO	European Research Infrastructure consortium for observing the Ocean	European RI ocean	<a href="https://www.euro-argo.eu">https://www.euro-argo.eu</a>
FAIR	Findability, Accessibility, Interoperability, and Reusability	other	<a href="https://www.go-fair.org/fair-principles/">https://www.go-fair.org/fair-principles/</a>
Gaofen	Gaofen series	a series of Chinese high-resolution Earth imaging satellites for the China High-resolution Earth Observation System (CHEOS) program	<a href="https://directory.eoportal.org/web/eoportal/satellite-missions/g/gaofen-1">https://directory.eoportal.org/web/eoportal/satellite-missions/g/gaofen-1</a>
GAW-WMO	Global Atmosphere Watch of the World Meteorological Organization	United Nations organizations	
GCOS	Global Climate Observing System		<a href="https://gcos.wmo.int/en/home">https://gcos.wmo.int/en/home</a>
GCW	Global Cryospheric Watch (GCW) of the World Meteorological Organization	United Nations organizations	
GEM	Greenland Ecosystem Monitoring	Other research infrastructure(s)	<a href="https://g-e-m.dk">https://g-e-m.dk</a>
GEOSS	Global Earth Observation System of Systems		<a href="https://earthobservations.org/geoss.php">https://earthobservations.org/geoss.php</a>
GHG	Greenhouse gases	other	
GOOS	Global Ocean Observing System	Arctic research infrastructure	<a href="https://www.goosocean.org/">https://www.goosocean.org/</a>
IABP	the International Arctic Buoy Program	Other research infrastructure(s)	<a href="http://abp.apl.washington.edu/overview_principles.html">http://abp.apl.washington.edu/overview_principles.html</a>
IASC	International Arctic Science Committee	International bodies Scientific Associate of International Council for Science (ICSU)	<a href="https://iasc.info">https://iasc.info</a>
ICOS	Integrated Carbon Observation System	European RI atmospheric sciences	<a href="https://www.icos-cp.eu">https://www.icos-cp.eu</a>
iCUPE	Integrative and Comprehensive Understanding on Polar Environments – project	EU Horizon2020 feedbacks research	<a href="https://www.atm.helsinki.fi/icupe">https://www.atm.helsinki.fi/icupe</a>
IDA	The International Development Association		<a href="https://www.worldbank.org/en/news/factsheet/2019/12/13/fact-sheet-the-">https://www.worldbank.org/en/news/factsheet/2019/12/13/fact-sheet-the-</a>

			international-development-association-ida
IMBIE	Ice Sheet Mass Balance Inter-comparison Exercise	project	<a href="https://web-isardsat.vercel.app/project/imbie2">https://web-isardsat.vercel.app/project/imbie2</a>
INTAROS	Integrated Arctic observation system	EU Horizon2020 RIA	<a href="https://www.intaros.eu">https://www.intaros.eu</a>
INTERACT		European RI project	<a href="https://eu-interact.org/project/">https://eu-interact.org/project/</a>
IOC	Intergovernmental Oceanic Commission	International bodies UNESCO	<a href="https://ioc.unesco.org/node/2">https://ioc.unesco.org/node/2</a>
NCoE	Nordic Centre of Excellence	a NordForsk funded Nordic Centre of Excellence (NCoE) promoting Nordic cooperation between outstanding researchers and research institutions	<a href="https://www.nordforsk.org/nordic-centre-excellence">https://www.nordforsk.org/nordic-centre-excellence</a>
NUNATARYUK	Project combines permafrost research with modelling and socio-economic analysis and includes stakeholders from all over the Arctic	EU Horizon 2020 feedback research	<a href="https://nunataryuk.org">https://nunataryuk.org</a>
PCAPS	Polar Coupled Analysis and Prediction for Services further develops numerical weather prediction and utilization of its results in operational services for societies.	WMO project as a follow-up of YOPP	<a href="https://www.wwrp-pcaps.net/">https://www.wwrp-pcaps.net/</a>
PolarRES	PolarRES studies the <b>interactions between the atmosphere, oceans, and sea ice in the Arctic and Antarctic</b>	PolarRES is a multi-partner project, and a member of the <a href="#">EU Polar Cluster</a> .	<a href="https://polarres.eu/">https://polarres.eu/</a>
PPP	Polar Prediction Project	a 10-year (2013–2022) endeavour of the World Meteorological Organization’s (WMO) World Weather Research Programme (WWRP)	<a href="https://www.polarprediction.net/">https://www.polarprediction.net/</a>
R&B	Belt and Road Initiative		<a href="https://www.mfa.gov.cn/ce/cegv/eng/zywjyjh/t1675564.htm">https://www.mfa.gov.cn/ce/cegv/eng/zywjyjh/t1675564.htm</a>
PROTECT	PROjecting sEa-level rise : from iCe sheets to local implicaTions	EU Horizon 2020 project	<a href="https://cordis.europa.eu/project/id/869304">https://cordis.europa.eu/project/id/869304</a>

RI	Research Infrastructure	large-scale, integrated, in situ observation system	-
ROADS	Roadmap for Arctic Observing and Data Systems	SAON coordinated activity	<a href="http://www.arcticobserving.org/news/378-guidelines-for-contributing-to-saon-s-roadmap-for-arctic-observing-and-data-systems-roads">http://www.arcticobserving.org/news/378-guidelines-for-contributing-to-saon-s-roadmap-for-arctic-observing-and-data-systems-roads</a>
SAON	Sustaining Arctic Observing Networks	Arctic Council research RI network	<a href="http://www.arctic-council.org/projects/saon/">www.arctic-council.org/projects/saon/</a>
SAVs	Shared Arctic Variables	-	-
SDGs	Sustainable Development Goals	set up in 2015 by the United Nations General Assembly (UN-GA) and are intended to be achieved by 2030	<a href="https://sdgs.un.org/goals">https://sdgs.un.org/goals</a>
SIOS	Svalbard Integrated Arctic Earth Observing System (SIOS)	Other research infrastructure(s)	<a href="https://us.sios.com">https://us.sios.com</a>
SIOS	Svalbard Integrated Arctic Earth Observing System	large-scale, integrated, in situ observation system	<a href="https://sios-svalbard.org/">https://sios-svalbard.org/</a>
SMEAR	Stations for Measuring Earth surface – Atmosphere Relations (SMEAR)	research infrastructure(s) coordinated by the University Helsinki, FI	<a href="https://www.atm.helsinki.fi/SMEAR/index.php">https://www.atm.helsinki.fi/SMEAR/index.php</a>
UN	United Nations	international organization	<a href="https://www.un.org/en/?">https://www.un.org/en/?</a>
YOPP	Year of Polar Prediction	other	<a href="https://www.polarprediction.net/">https://www.polarprediction.net/</a>

## Appendix 2

**Table A-2.** The list of the 13 domain based Key topics, the existing knowledge and the areas where we need a better understanding of the Arctic feedbacks and interactions. The content of the table is based on the contributions e.g. submitted abstracts to the AASCO events in 2021 and 2020.

**Table 1. (D= Domain KT = Key Topic)**

Domain / Key Topic

**AA = Arctic Amplification:** Key Topic 1 Feedbacks  
Key Topic 2 Trends  
Key Topic 3 Extreme events

**AT = Atmosphere:** Key Topic 4 Atmospheric processes in the Arctic

Key Topic 5 Atmospheric circulation and transports between the Arctic and mid-latitudes

**MA= Marine**

Key Topic 6 Arctic Ocean and its ice cover

Key Topic 7 Ocean environment and socio-economic feedbacks

Key Topic 8 Ocean Acidification & Arctic marine freshening

**CR = Cryosphere**

Key Topic 9 Greenland Ice Sheet mass loss and its impact

Key Topic 10 Interactions of the Arctic permafrost, soil active layer, and atmosphere

**TE = Terrestrial**

Key Topic 11 River transports and coastal erosion

Key Topic 12 Changing pollution load, change of previous feedbacks within the Arctic

Key Topic 13 Continental Biosphere-Aerosol-Cloud-Climate feedbacks



EXISTING KNOWLEDGE	CRITICAL KNOWLEDGE GAPS AND RESEARCH NEEDS
ARCTIC AMPLIFICATION (1-2-3) feedbacks-trends-extreme events	
<p><b>The Arctic Amplification</b> – The mechanisms</p> <ul style="list-style-type: none"> <li>❖ Behind the enhanced response of the Arctic climate system to global warming are generally referred to as Arctic amplification (<i>Serreze and Francis 2006; Serreze and Barry, 2011; Davy et al., 2018; Davy and Outten, 2020; Dai et al., 2019; Previdi et al., 2021; Wendisch et al., 2022</i>). Two prominent indications of Arctic amplification are the dramatic decline of sea ice in the Arctic Ocean (<i>Olonscheck et al. 2019; Screen 2021</i>), and the accelerated increase of the Arctic near-surface air temperature (<i>Rantanen et al, 2022</i>).</li> <li>❖ Clarification of the Amplification mechanisms, feedbacks and impacts in progress (<i>Goosse et al., 2018; Duncan et al., 2020; Feldl and Merlis, 2021; Wendisch et al., 2022</i>).</li> <li>❖ Extreme events related to numerous variables in the coupled Arctic climate system (<i>Bullard et al., 2016; Meinander et al. 2021</i>).</li> </ul>	<ul style="list-style-type: none"> <li>✓ <b>Synthesis of the AA studies</b> are needed to identify and describe multi-scale and multi-process contributions to the phenomenon. Developing this solid background, future projections and implications of the Arctic Amplifications can be prospected and attributed. reanalysis.</li> <li>✓ <b>In the case of extremes</b>, such drought, flooding and cyclones, the future changes are not well known. High priority for: enhancement of observation systems to detect extreme events; application of high-resolution models; more research on the impacts of climate extremes on ecosystems and humans (<i>Walsh et al., 2020; Ezibova et al., 2021</i>).</li> <li>✓ Extreme events may also provide positive feedback to climate change, if critical thresholds or tipping points are passed due extreme events</li> </ul>
ATMOSPHERE (4) Atmospheric processes in the Arctic	

<ul style="list-style-type: none"> <li>❖ <b>Numerous interactive physical and chemical processes</b> act in the Arctic atmosphere (<i>Goosse et al., 2018; Devasthale et al., 2020</i>).</li> <li>❖ <b>Local</b> processes in the Arctic atmosphere that are clearly different from those in <b>mid latitudes</b> include atmospheric boundary layer (ABL) physics and Arctic clouds (<i>Davy et al., 2017; Chernokulsky and Esau, 2019</i>).</li> <li>✓ Atmosphere-cryosphere interactions are important for the arctic radiative balance due to highly reflecting surfaces (<i>Boy et al., 2019; Petäjä et al. 2020</i>)</li> </ul>	<ul style="list-style-type: none"> <li>✓ Understanding of interactions and feedbacks between processes and their presentation in <b>numerical weather prediction and climate models</b> are needed (<i>Vihma et al., 2014, Petäjä et al. 2020</i>).</li> <li>✓ <b>Processes controlling low level clouds formation are unclear.</b> Improved descriptions of aerosol precursor emissions and their influence on the polar aerosol lifecycle, including parameterizations of biologically driven sea-ice DMS production and emission, physical and biogeochemical drivers of NH<sub>3</sub> emissions, and controls on organic aerosol emissions and formation, with a focus on N-containing organic aerosols, are needed.</li> <li>✓ Cloud microphysical processes in mix-phased and ice clouds are poorly understood</li> <li>✓ More insights and improved parametrizations on absorbing aerosol impact on snow albedo and melting (<i>Svensson et al, 2018</i>)</li> </ul>
<p><b>ATMOSPHERE (5) Atmospheric circulation and transports between the Arctic and mid latitudes</b></p>	
<ul style="list-style-type: none"> <li>❖ Atmospheric circulation is of critical importance for climate in the circumpolar Arctic. A vast majority of the energy transport to the Arctic is carried out in the atmosphere. Transport across the Arctic Circle, the role of the atmosphere is 5 to 6 times larger than that of the ocean (<i>Trenberth and Fasullo, 2017</i>).</li> <li>❖ Key physical processes related to atmospheric circulation and transport between the Arctic and mid-latitudes include: on planetary scale, the stratospheric Polar Vortex and the upper-tropospheric Polar front jet stream have a major role in controlling the cyclone tracks (<i>Kidston et al, 2015</i>). In the lower troposphere, warm-air intrusions are characterized by complex interactions of heat and moisture advection, subsidence, cloud and fog formation, turbulence in the atmospheric boundary-layer and clouds, radiative transfer, as well as sea ice thermodynamics and dynamics (<i>Pitban et al., 2018</i>).</li> </ul>	<p>Need for a better understanding:</p> <ul style="list-style-type: none"> <li>✓ Impact of the Arctic amplification on the <b>properties of the jet stream</b> (<i>Coben et al., 2020</i>), and related changes in the occurrence and strength of warm-air intrusions and cold-air outbreaks</li> <li>✓ Relative importance of warm-air intrusions and local arctic processes on the Arctic amplification in the past and future</li> <li>✓ Compensating effects of a warmer Arctic (resulting in higher temperatures during cold-air outbreaks) and conditions that possibly favor increasing occurrence of cold-air outbreaks from the Arctic</li> <li>✓ Modelling capabilities of <b>air-mass transformation</b> and related interactive processes during warm-air intrusions and cold-air outbreaks</li> <li>✓ Measurement campaigns are needed to provide appropriate data to construct test cases, which may help to evaluate and improve models (<i>Wendisch et al. 2019</i>)</li> </ul>
<p><b>MARINE (6) Arctic Ocean and its ice cover</b></p>	
<ul style="list-style-type: none"> <li>❖ An important phenomenon of the regulation is the <b>deep-water formation in the vicinity of sea ice</b> (<i>Bindoff et al., 2019</i>).</li> <li>❖ Oceanic heat transport to the Arctic Ocean from the Atlantic is increasing due to increasing ocean temperatures and changing circulation (<i>Tsubouchi et al., 2021; Trenberth et al., 2019; Oldenburg et al., 2018</i>).</li> <li>❖ <b>Volume transport from the Pacific through the Bering Strait, river runoff and melting ice and snow</b> have increased the fresh water in the Arctic Ocean thus strengthening its stratification, in particular in the Beaufort Gyre. This trend is also affecting the dynamic sea-level and circulation patterns (<i>Couldrey et al., 2021</i>). In some regions such as the Eurasian basin, the reduced sea-ice cover may promote oceanic convection and the eradication of the halocline.</li> </ul>	<ul style="list-style-type: none"> <li>✓ To <b>resolve the volume transports</b>, e.g. from the Pacific, is to resolve currents through the narrow and shallow Arctic passages, e.g. Bering Strait, which require accurate resolution, typically not yet implemented in standard CMIP category ocean climate models.</li> <li>✓ <b>Global ocean – sea-ice models</b> cannot be expected to resolve all relevant scales, such as the sub-mesoscale, due to the issues related to oceanic predictions before the availability of quantum computers. The <b>increasing resolution</b> may also require updating the atmosphere-ocean coupling due to stronger oceanic impacts (<i>Small et al., 2019</i>). However, processes such as sea-level rise and hydrological cycle, could already be addressed probabilistically by deploying model ensemble hierarchies that include, in addition to global models, ocean reanalyses</li> </ul>

<ul style="list-style-type: none"> <li>❖ There is an increased <b>risk of relatively sudden discharge of the Arctic freshwater reservoir</b> to the North Atlantic with impacts on the oceanic meridional circulation (<i>Zhang et al., 2021</i>).</li> <li>❖ <b>Global hydrodynamic models</b>, prognostically reproducing the transports and hydrography of the ocean – sea-ice system, rely on parameterization of meso- and small-scale phenomena, such as ocean eddies, tides and air-sea interaction, due to their insufficient resolution (<i>Fox-Kemper et al., 2019</i>).</li> <li>❖ <b>Arctic sea ice regime</b> (<i>SROCC, 2019; Perovich et al., 2020</i>) with different sea ice properties, ice types, thermodynamical and dynamical conditions (<i>Spren et al., 2020</i>), and changes in snow cover (<i>Webster et al., 2018</i>), may lead to new processes and feedbacks (<i>Graham et al., 2019</i>).</li> </ul>	<p>and high-resolution regional models, and emulators (<i>Lambert et al., 2018; Uotila et al., 2019</i>).</p> <ul style="list-style-type: none"> <li>✓ Knowledge about status and process understanding of the <b>Arctic sea-ice system</b> is key for assessing impacts quantitatively, and for improved projections of future scenarios. Since the current observation system still has crucial gaps when it comes to spatial and temporal coverage of the Arctic sea-ice system (e.g. <i>Gerland et al., 2019</i>), improved observations systems (e.g. <i>Lee et al., 2019</i>) and more (international) coordination and collaboration across disciplines and working groups are necessary.</li> <li>✓ <b>Representing relevant sea ice and snow cover features in numerical models</b> is further challenged because of the limited ability to include increased complexity and sub-grid scale processes (e.g. ice type, leads and melt ponds) in large scale climate models. Further research improvements require utilization of existing and emerging satellite and in-situ observations of sea ice, including sea ice age, thickness, leads, melt ponds, ridges, and ice type, and under ice radiation (driving biological activity). These will provide <b>improved data sets for validation of models and serve as the basis for improved understanding of the processes that govern sea ice.</b></li> <li>✓ <b>Ongoing shift of sea ice age</b> and type from multi-year ice to first-year ice in the Arctic results in changes of properties of the ice pack. The processes that control sea ice and its interaction with atmosphere and ocean have unresolved critical gaps and uncertainties</li> </ul>
<b>MARINE (7) Ocean environment and socio-economic feedbacks</b>	
<ul style="list-style-type: none"> <li>❖ Arctic <b>net primary production</b> increased in ice-free waters, spring phytoplankton blooms occurring earlier in the year in response to sea ice change and nutrient availability with spatially variable consequences for marine ecosystems (<i>IPCC, 2019</i>).</li> <li>❖ <b>Boreal zooplankton and fish</b> are expanding into more Arctic areas (<i>Dalpadado et al., 2016; Fruiner et al., 2017</i>) and Arctic fish are under pressure (<i>Christiansen, 2017; Meredith et al., 2019</i>).</li> <li>❖ <b>Increasing stratification and decreasing nutrients</b> will likely dominate in the Arctic environment, but land derived inputs may have already sustained primary production.</li> </ul>	<ul style="list-style-type: none"> <li>✓ Urgent need to <b>improve sea-ice biogeochemistry models</b> in both hemispheres, focusing on the nutrient buffering role of sea ice and its effect on primary production and carbon export.</li> <li>✓ Understanding the climate change <b>driven risks to food provision through fisheries, transport and access to non-renewable resources are of great importance.</b> Adding to uncertainty in human choice related to climate change is the interaction of climate with other forces for change, such as globalization and land and sea-use change. These interactions necessitate that responses to climate change consider cumulative effects and context-specific pathways for building resilience (<i>ARR, 2016; Meredith et al., 2019</i>).</li> </ul>
<b>MARINE (8) Ocean Acidification &amp; Arctic marine freshening</b>	
<ul style="list-style-type: none"> <li>❖ <i>Terhaar et al. (2020)</i> estimated an increase of regional anthropogenic carbon storage and <b>ocean acidification</b>. Furthermore they predict increasing probability for undersaturation to calcite of the mesopelagic Arctic Ocean by the end of the century. This increased rate of Arctic Ocean acidification together with changing physical and biogeochemical Arctic conditions deepens climate change impact on Arctic marine ecosystems (<i>Terhaar et al. 2020</i>).</li> <li>❖ <b>Arctic marine freshening</b> as an important process: warming and freshening of the surface waters in the coastal and polar regions due to increasing freshwater input (e.g., melting of sea ice and glaciers, river discharge, lateral transport of biogeochemical variables,</li> </ul>	<ul style="list-style-type: none"> <li>✓ The main challenge for the <b>ocean acidification</b> research is to assimilate the knowledge of different research branches into an integrated assessment. The assessment should include short and long-term responses to multiple drivers and their underlying mechanisms at the different scales: organisms, populations, communities and ecosystems. (<i>Riebesell and Gattuso, 2015, see also Pörtner et al., 2019</i>)</li> <li>✓ A need for generalized pan-Arctic representation of the impacts of <b>freshwater on the upper Arctic Ocean</b>. Many biological and geochemical interactions occur in this part. Knowledge on the regional and seasonal variability is</li> </ul>

<p>including carbon) will change the chemistry of the surface waters affecting the GHG uptake/release (<i>Woosley and Millero, 2020</i>),</p>	<p>addressed to gain a pan-Arctic perspective on the physical-geochemical-biological state of the upper Arctic Ocean (<i>Brown et al. 2020</i>)</p>
<b>CRYOSPHERE (9) Greenland Ice Sheet mass loss and its impact</b>	
<ul style="list-style-type: none"> <li>❖ <b>Greenland Ice Sheet mass loss</b> is an urgent topic, given that even by reaching the Paris Agreement goals, Greenland is experiencing 3-4°C warming (<i>Rückamp et al., 2019</i>). Satellite observations provide essential information to quantify the current contribution of the ice sheet to sea level change (e.g. <i>Helm et al., 2014; IMBIE2 team 2020</i>).</li> <li>❖ About half of the <b>mass loss</b> is due to accelerating glaciers, while the other half a consequence of changes in surface mass balance. Surface melt water is either transported via surface rivers into supraglacial lakes, or direct surface run-off. Another fraction of it is penetrating into the firn and may either refreeze (<i>Machguth et al., 2016</i>), releasing latent heat, or may form subsurface aquifers (<i>Miller et al., 2020</i>).</li> <li>❖ Calving of tidewater glaciers in Greenland is linked to subglacial water discharge (<i>Slater et al., 2019</i>). This demonstrates the <b>feedback between glacier dynamics and ice sheet hydrology</b>. Projections are underestimating the mass loss of the Greenland Ice Sheet massively – only about 1/3 of the observed mass loss is represented in simulations (<i>Rückamp et al., 2019</i>) - and this is mainly due to underestimating glacier acceleration.</li> </ul>	<ul style="list-style-type: none"> <li>✓ To understand the <b>processed of ice sheet hydrology</b> and running coupled <b>simulations of ice flow and hydrology</b>. For increasing the process understanding, modelling and satellite remote sensing informed in-situ observations are required (<i>Petäjä et al., 2020; Humbert et al., 2020</i>). This comprises a wide range of different type of observations, radar observations, GPS stations close to supraglacial lakes, pumping tests in firn and model experiments.</li> <li>✓ <b>Coupled ice-ocean models</b> with boundary conditions accounting for physical processes in the boundary layer at the ice-ocean interface (including, e.g., subglacial discharge, <i>Straneo and Cenedese, 2015</i>), improved melting parameterizations.</li> <li>✓ Run-off in crevasse zones and supraglacial lake drainage (e.g. <i>Schröder et al., 2020</i>) are then delivering water to the base of the outlet glaciers, leading to seasonal acceleration (e.g. <i>Neckel et al., 2020</i>) and freshwater discharge into the ocean. All those processes are contributing to the ice sheet hydrology, and they are poorly constrained at the moment.</li> <li>✓ <b>Interdisciplinary approaches are needed to boost process understanding</b>. It is important to attract scientists with continuum mechanical background, researchers from hydromechanics, applied mathematicians and computer scientists, to jointly to derive mathematical models and incorporate the missing processes into exascale-ready simulation codes. (<i>Box et al., 2019; AMAP SWIPA update report 2021 in press</i>).</li> <li>✓ Better projections are needed for the mass loss of the Greenland Ice Sheet (<i>Rückamp et al., 2019</i>).</li> <li>✓ <b>New logistic hubs</b>, supporting operation of monitoring networks on the ice sheet, are crucial. Support of autonomously operating instruments and sample retrieval, will highly benefit from such hubs.</li> </ul>
<b>CRYOSPHERE (10) Interactions of the Arctic permafrost, active layer, and atmosphere</b>	
<ul style="list-style-type: none"> <li>❖ The northern circumpolar permafrost region stores large amounts of <b>soil organic carbon (SOC)</b>, ~1300 Pg C (<i>Hugelius et al., 2014</i>).</li> <li>❖ <b>Carbon based feedbacks connecting Arctic land-atmosphere interactions to thawing permafrost</b>: permafrost thaw makes previously immobile carbon available for microbial decomposition, depending on the oxygen availability, CH<sub>4</sub> or CO<sub>2</sub> is formed and released from the soil; emitted GHGs can amplify warming and further enhance permafrost thawing (<i>Schnur et al., 2015</i>).</li> <li>❖ <b>Abrupt thaw resulting in ground collapse</b> (thermokarst), a process contributing to extensive carbon losses both in lowland and upland terrain (<i>Olefeldt et al., 2016; Turetsky et al., 2020</i>).</li> <li>❖ <b>Future carbon emissions</b> have been estimated under different climate scenarios (<i>McGuire et al., 2018</i>).</li> <li>❖ Increased emissions of nitrous oxide have been observed from thawing Arctic permafrost peatlands, acting as a <b>non-carbon climate feedback</b> (<i>Voigt et al., 2017</i>).</li> </ul>	<ul style="list-style-type: none"> <li>✓ Better <b>process understanding</b> of the complex interactions between climate, permafrost and hydrology is needed for accurate projections of future GHG exchange.</li> <li>✓ More <b>field and satellite based data</b> on soil organic carbon content, vegetation, landforms and GHG emissions in the permafrost region required for better upscaling and incorporation in models.</li> <li>✓ Extent and rate of <b>abrupt permafrost thaw</b> (thermokarst) needs to be better understood and included in ESMs projecting future carbon exchange.</li> <li>✓ Better quantification of CH<sub>4</sub> storage and future carbon lability and release from <b>subsea permafrost</b>.</li> <li>✓ Assessment of the impact of considerable <b>volatile organic compound (VOC)</b> emissions from the thawing permafrost <b>on atmospheric chemistry, aerosol formation or terrestrial biosphere – atmosphere interactions</b> (<i>Li et al., 2020</i>).</li> </ul>

	<ul style="list-style-type: none"> <li>✓ Need to <b>relate reanalysis model data sets with high resolution optical and radar satellite observations</b>. This information would also provide <b>necessary constraints on modelling results</b>.</li> <li>✓ Modelling results for <b>vegetation response</b> (NPP and respiration) to <b>climatic scenarios</b> with strong increasing temperature trends are poorly constrained. Challenges in representing vegetation in the Arctic zone (<i>Birch et al., 2021</i>).</li> <li>✓ <b>Knowledge gaps: landscape dynamics</b> and changes as a result of permafrost thaw; <b>interactions between plants, soils and microbes</b> under changing climatic conditions; integrated analysis of <b>carbon and nitrogen compounds</b> released from the permafrost and their net impacts on the feedback</li> <li>✓ Effects of permafrost thaw on forests (<i>Baltzer et al. 2014</i>), soil microfauna and hydrology (<i>Walvoord and Kurylyk, 2016</i>).</li> </ul>
<b>TERRESTRIAL (11)</b>	
<ul style="list-style-type: none"> <li>❖ <b>Increased nutrient transport via rivers, primary production</b> in the Arctic coastal oceans is expected to increase. The river discharge is a component of the carbon cycle and also affects storm surges and coastal erosion (<i>Wicks and Atkinson, 2017; Shakhova and Semiletov 2007</i>).</li> <li>❖ Valuable datasets on riverine transports are available from the Lena, Ob, and Amur rivers (<i>Savenko, 2006; Bagard et al., 2011; Pokrovsky et al., 2015</i>), but also these datasets suffer from sampling infrequency and uncertainties resulting to underestimation of fluxes (<i>Chalov et al., 2018</i>).</li> </ul>	<ul style="list-style-type: none"> <li>✓ Mechanical and thermal erosion of the coast results in permafrost thaw/ground collapse and removal of the no-longer frozen sediments by water (<i>Lantuit et al., 2012</i>) favoring large-scale release of CO<sub>2</sub>, methane, and other volatile substances from thawing permafrost (<i>Overduin et al., 2016</i>). <b>Quantitative data on these important processes is limited</b>. The average rate of erosion along the Arctic coastline is 0.5 m year<sup>-1</sup>. Spatial variations are, however, large both in local and regional scales with peak values exceeding 3 m year<sup>-1</sup> in the Laptev, East Siberian, and Beaufort Seas (<i>Lantuit et al., 2012</i>). <b>Knowledge gaps remain on submarine permafrost distribution, its thermal state, and release rates of greenhouse gases</b> (<i>Ping et al., 2011</i>).</li> <li>✓ <b>Better knowledge of biogeochemical processes combined with improved model representations of ocean-land interactions</b> are essential to accurately predict the development of arctic ecosystems and associated climate feedbacks.</li> </ul>
<b>TERRESTRIAL (12)</b>	
<ul style="list-style-type: none"> <li>❖ Human activities (wild fires) have an impact on the Arctic environment by increasing quantities:             <ul style="list-style-type: none"> <li>○ <b>pollutants:</b> plastic, heavy metals and other trace elements (<i>Barbante et al., 2001</i>) / <b>radioactive nuclides</b> (<i>Ezerinkis et al., 2014</i>) / <b>synthesized organic compounds</b> (<i>Hermanson et al., 2010; Xie et al., 2007</i>) / <b>artificial light</b> at night (<i>Hölker et al., 2010</i>) / <b>black carbon, carbon-containing compounds</b> (CO, CO<sub>2</sub>) <b>trace gases and greenhouse gases</b> (<i>Garrett and Zhao, 2006; Hienola et al., 2013</i>)</li> </ul> <p>With the global climate changes of recent decades, strong regional temperature, circulation, and hydrological anomalies are manifested. They cause, among other things, extensive fires (<i>Bondur et al., 2020</i>).</p> </li> </ul>	<ul style="list-style-type: none"> <li>✓ Knowledge on the <b>source contribution of pollution</b> to settle mitigation strategies (<i>Law et al., 2014</i>)</li> <li>✓ <b>more measurement of short-lived climate pollutants, and their precursors</b> for evaluating the impacts of natural resource extraction and shipping in Arctic environments (<i>Dekhtyareva et al., 2016</i>).</li> </ul>
<b>TERRESTRIAL (13)</b>	
<ul style="list-style-type: none"> <li>❖ Arctic is home to more than <b>21,000 known species</b> of highly cold-adapted mammals, birds, fish, invertebrates, plants and fungi and microbe species (<i>ACIA, 2005</i>).</li> </ul>	<ul style="list-style-type: none"> <li>✓ <b>Knowledge gaps:</b> <ul style="list-style-type: none"> <li>○ landscape dynamics and changes as a result of permafrost thaw</li> <li>○ interactions between plants, soils and microbes under changing climatic conditions</li> </ul> </li> </ul>

<ul style="list-style-type: none"> <li>❖ Long-term warming and its most dramatic effects and changes in Arctic ecosystems <b>through local extreme events</b> relating to temperature, precipitation and snow (<i>Christensen et al., 2021</i>)</li> <li>❖ Arctic terrestrial ecosystems possess <b>feedbacks and critical tipping points</b>: <ul style="list-style-type: none"> <li>○ <b>wildfires</b> turning the permafrost tundra to bushland or forest with different functioning. (<i>Köster et al., 2018; Sizov et al., 2021</i>)</li> <li>○ local <b>nutrient availability effecting carbon flux</b> magnitudes between otherwise comparable ecosystems (<i>López-Blanco et al., 2020</i>)</li> <li>○ <b>herbivory changing</b> the overall carbon balance via changes on plant composition, energy balance, nutrient availability (<i>Väisänen et al., 2014; Metcalfe and Olofsson, 2015; Stark and Ylänne, 2015</i>).</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>○ integrated analysis of carbon and nitrogen compounds released from the thawing permafrost and their net impacts on the feedback mechanisms.</li> <li>✓ <b>More ground based and remote GHG observations</b> needed on the local and regional levels to improve understanding on land-atmosphere feedbacks, the knowledge on the rate of GHG emissions and contribution from different soils and landforms.</li> <li>✓ <b>More data</b> on the dynamics of thermal structure and thickness of the seasonally thawed layer of permafrost determining the intensity of geomorphological processes and the physical and mechanical properties of soils. <b>(assessment of the geocryological consequences)</b></li> </ul>
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