ICARP IV Research Priority Team (RPT) 1

Final Report

The Role of the Arctic in the Global Earth System

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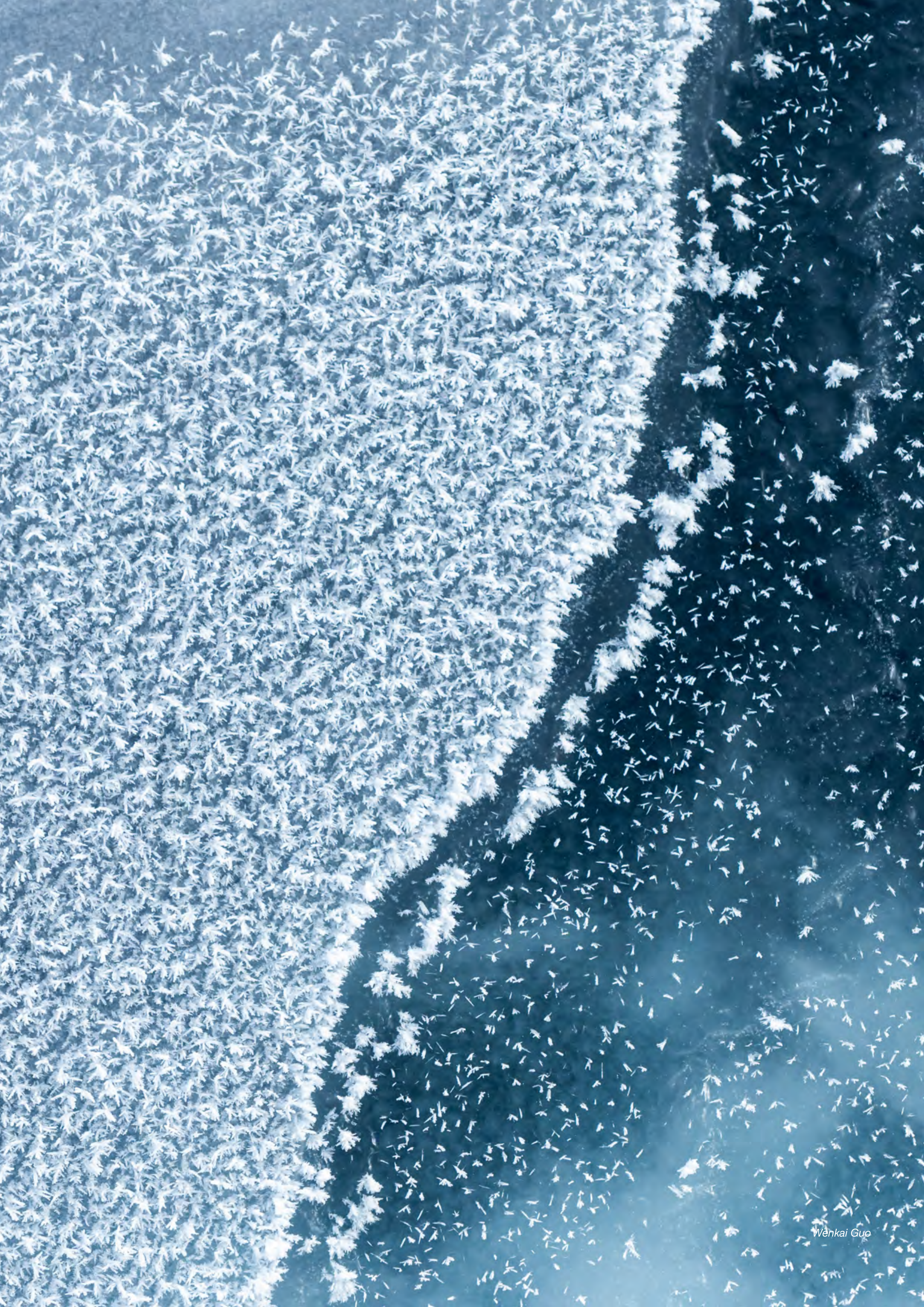

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1. Executive Summary

The overarching goal of the RPT 1 is to identify urgent research needs and priorities and make corresponding recommendations on actionable implementation for improving systematic understanding of variability, changes, and extreme events of the Arctic Earth system, and their two-way interactions with the global system. Due to its nature, the outcome from the RPT 1 provides foundational information to facilitate and collaboratively benefit from other RPTs.

The Arctic Earth, including the atmosphere, ocean, cryosphere, terrestrial systems, ecosystems, and Arctic Indigenous Peoples, has been experiencing dramatic changes across its components during recent decades. These changes are predominantly characterized or driven by the Arctic amplification (AA) with a warming rate of annual mean surface air temperature at 0.63 ºC per decade from 1979-2023 (north of 60ºN), about three and half times the global average (Zhang et al., 2025). Although considerable progress has been made through various competitive projects and internationally coordinated programs (such as IPY 4, YOPP, MOSAiC), new knowledge gaps and grand challenges have emerged, in addition to continually existing and unsolved scientific problems. Outstanding examples include a serious lack of high-resolution and especially winter season observations and associated improvements of model representations (e.g., Yang et al., 2025); short observations records and large model uncertainties in substantiating and understanding the accelerating changes, state shift, and extreme anomalies in the Arctic system and their interactions with the global system (e.g., Screen, et al., 2018; Cohen et al., 2022; Smith et al., 2022; Zhang et al., 2025); under-investigated and under-represented interactive processes between dynamics and biogeochemistry in the shifted physical, biological, wildfire, and permafrost regimes (e.g., Lund et al., 2018; Whaley et al., 2022; Willis et al., 2023). All of these require conducting a comprehensive review and synthesis of the state-of-knowledge, based on which to sharply identify urgent research needs and priorities to address with a recommendation of actionable implementation plans.

To this end and considering the complexity of the highly nonlinear, interactive Arctic and global Earth system, five specific focuses for RPT 1 are identified and defined:

1. Enhancement of high-resolution observations and its integration with model improvements
2. Two-way interactions between the Arctic and global Earth systems
3. Attribution of Arctic Earth system changes
4. Arctic terrestrial system and impacts on local and global hydrological and carbon cycles
5. Governance of Arctic and global politics

Based on the analysis and synthesis from the five focal areas and cross-review of the work in other RPTs, the key takeaways about urgent needs and priorities, as well as implementation recommendations, within the RPT 1 and linked with other RPTs are briefly summarized below:

1. **Enhanced and sustainable three-dimensional high-resolution observational network and km-scale model development**

   The emphasis needs to be on vertical profiles from the upper atmosphere, across the atmosphere, sea ice, ocean, and terrestrial interfaces, and down to the ocean mixed layer and intermediate warm water layers, with a particular focus on the under-observed dark season. This enhanced observation will fill historical and current observational gaps for capturing more complete dynamic and thermodynamic structures and the interactive processes between the system components, especially at high-resolution scales (such as micro-scale aerosol cloud interaction and radiation feedbacks, blowing snow processes, turbulent heat, moisture, momentum, chemical fluxes) and their coupling across the surface. Integration between the enhanced observation and models will help include or improve model representation of high-resolution processes towards km-scale model development, advancing understanding and predicting Arctic Earth system variability, changes and extreme events.

   The enhancement and sustainability of observations can be implemented through internationally coordinated ship observations as fundamental basis in additional to the well-established met station observations, improved satellite sensors and spatial coverage, and model assimilation approaches, mimicking the three-level global sounding observational network (e.g., IGRA, GUAN, and GRUAN) and data assimilation system.

2. **Improved quantitative and predictive understanding of local and remote forcings in driving AA and its Arctic and global consequences**

   Quantitative analysis on two-way interactions between the Arctic and lower-latitudes will be a major focal area. During the last couple of decades, meridionally transformed atmospheric circulation, enhanced poleward atmospheric heat, moisture, and chemical tracers transport and ocean heat and salinity transport have emerged. These changes influence Arctic clouds, radiation, precipitation and its phases, and turbulent fluxes, and, in turn, feedbacks. Meanwhile, the transformed atmospheric circulation pattern and wavier jet streams advect polar cold air mass southward to influence the lower-latitudes weather and climate. However, inconsistencies and large uncertainties continually exist in quantifying these processes, hindering understanding, assessing, and predicting the AA and its Arctic and global consequences.

   This research priority can be implemented through the new CMIP7 and newly designed, internationally coordinated multi-model intercomparison project, following the experience and lessons learned from the PAMIP and/or CMIP6. Novel diagnostic analysis tools and framework will be needed to identify robust signals and feedbacks, which could be facilitated by ML/AI techniques.

3. **Attribution of the Arctic Earth system changes employing integrated, multidisciplinary approaches.**

   This research priority is mainly centered on identifying and distinguishing the externally forced changes and internal variability, as well as local processes and remote influences. The essential part is to define historical baseline climate state and characterize internal variability and extreme events of the Arctic Earth system on various time scales from the past to the present and future. One outstanding extreme event is a shift of baseline state when Earth system change crosses a tipping point through nonlinear dynamics. Because of short records of instrumental observations, information from the paleo-archive will help place the change in a long-term perspective.

   Implementation of this research priority will include an integrated framework of studies encompassing observations, modeling, aggregation, and connecting local, regional (e.g., marginal ice zones), and global changes and development of novel methods to evaluate tipping point of the Earth system and metrics for early warning of the occurrence of baseline state shift. Collection of multidisciplinary paleo proxy datasets will help to infer information to verify paleo model simulations.

4. **Changes in the Arctic terrestrial systems and impacts on Arctic and global hydrological and carbon cycles, as well as biogeochemical transformation**

   The priority focuses on complex interactions between thawing permafrost, changing vegetation, intensifying wildfire regimes, and their impacts and contribution to the Arctic and global hydrological and carbon cycles, as well as biogeochemical transformation. Intensification of the Arctic hydrological cycle has been manifested along with the AA, which influence Arctic Ocean stratification, circulation, and freshwater export to the North Atlantic Ocean, and have significant implications for AMOC. The contributions of thawing permafrost and changing vegetation to the hydrological cycle remain unclear. The same for the carbon cycle and biogeochemical transformation, in particular under the changes in the wildfire regimes. All of these land processes and their interactions need to be quantitatively analyzed.

   Recommended implementation includes a coordination between data and knowledge systems for researchers, government agencies, and stakeholders to access existing datasets related to permafrost changes and biogeochemical transformation. High-resolution observational datasets, standardized formats, and robust metadata to ensure accurate aggregating, coupling, and scaling.

5. **Governance of Arctic and global politics and integration of Indigenous knowledge into Arctic Earth system studies and policy-decision processes**

   A changing Arctic brings new challenges and opportunities and activates both political and security issues at all scales. There is a need to map Arctic actor engagement (states, Indigenous Peoples' organizations, NGOs) in and explore future pathways for Arctic-relevant solutions in global governance bodies relevant to the Arctic (biodiversity, justice/Indigenous rights, pollution, ocean governance, climate mitigation, cryosphere and large-scale atmosphere effects). Many of the processes impacting the Arctic are global in nature, working towards a safe and sustainable Arctic necessitates using global regimes, settings, treaties and soft-law/private initiatives to the extent possible.

   Implementation can be conducted through identifying and pursuing key topics at the global or regional interface, such as security (including human and food security), trade, environmental governance. Dialogue and innovation around transdisciplinary modes of interaction, in particular with Indigenous knowledge-holders, will be needed to inform instrumentally observed and model simulated changes, and research into policy-decisions and governance. This includes actions to prevent the changes of the Earth system from approaching a tipping point, reducing risks of possible cascading effects on negative socioeconomic consequences.

2. Definition of the Focus of RPT 1

The RPT 1 focuses on identifying overarching urgent research needs and priorities, and recommending corresponding actionable implementation plans for improving systematic understanding of variability, changes, and extreme events of the Arctic Earth system, and their two-way interactions with the global system.

The Arctic Earth system has been predominantly characterized by an amplified warming at rate more than three times the global average during the recent decades in annual average (e.g., 0.63 °C dec^{-1} vs. 0.20 °C dec^{-1} from 1979-2023; north of 60ºN; Zhang et al., 2025; Figure 1) based on the latest observational datasets (Lenssen et al., 2019; Rohde and Hausfather 2020; Morice et al, 2021; Vose et al., 2021; Ma et al., 2023). This phenomenon is named the Arctic Amplification (AA). Although already the pioneering model simulation research by Manabe and Wetherald (1975) shows the occurrence of the AA, the AA mainly pronouncedly emerged in observations during recent decades, in particular since the beginning of this century (e.g., Zhang et al., 2008; Serreze et al., 2009). Continuing studies further reveal that the AA accelerates with time (e.g., Huang et al., 2017; Chylek et al., 2022) and the AA increases in the central Arctic region (north of 66°N; Rantanen et al., 2022).

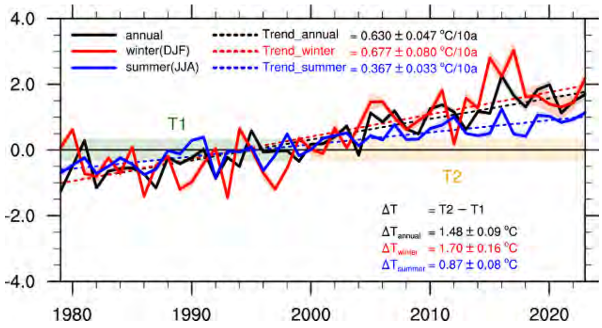

Figure 1. Accelerated Arctic warming rate estimated from multiple observational datasets. Annual (black line), winter (December - February; red line), and summer (June - August; blue line) mean Arctic (north of 60ºN) surface air temperature (SAT) anomalies averaged using multiple in-situ observational datasets from 1979 – 2023 for annual mean and summer mean and 1979/80 – 2023/24 for winter mean. The dashed lines represent the linear trends. The multiple datasets mean long-term trend, the one standard deviation across the datasets, and the multidecadal changes in SAT before and after 2000 (indicated by T1 and T2) are shown in the figure. The Arctic amplification becomes prominent and further strengthened since the beginning of the 21st century, elevating the baseline SAT (adapted from Zhang et al., 2025).

Along with the AA, systematic changes have occurred across all the components in the Arctic system, including drastically declined sea ice cover and reduced sea ice thickness (e.g., Parkinson, 2022; Stroeve and Notz, 2018); pronouncedly warmed ocean surface and intermediate layers (e.g., Steele, M. & Dickinson, 2016; Polyakov et al., 2017; Shu et al. 2022); substantially increased Greenland Ice Sheet melt (e.g., Hanna et al., 2020); largescale thawing of permafrost on land (e.g., Romanovsky et al., 2010; Rasouli, 2017; Biskaborn et al. 2019); intensified hydrological cycle and increased river discharges into the ocean (e.g., Peterson et al., 2002; Rawlins et al., 2009; Zhang et al., 2013; Rasouli et al., 2020); increased liquid freshwater storage and intermittent release to the North Atlantic (Solomon et al., 2021; Holliday et al., 2020) ;increased shrub extension to higher latitudes (Mekonnen et al., 2021), and a regime shift of ocean ecosystem (e.g., Heide-Jørgensen et al., 2022).

In addition to these long-term changes, extreme events are becoming more extreme and more frequent (e.g., Zhang et al., 2025), including heatwaves in both the atmosphere and ocean, rapid sea ice loss, pulses of intense poleward North Atlantic Ocean heat transport, and unprecedented Greenland Ice Sheet melt rate. The changes and extreme events are not constrained within the Arctic system. They can be driven by the mechanisms originating from interaction between the Arctic and lower latitude processes (e.g., Zhang et al., 2008; 2025; Årthun et al., 2012; Dörr et al., 2024). They can also excite teleconnections to influence midlatitude and tropical climate and weather anomalies and extreme events (e.g., Cohen et al., 2020; Screen et al., 2018; Overland et al., 2021; Zhang et al., 2022), as well as the Southern Ocean and the Antarctic (e.g., Chylek et al., 2010; Wang et al., 2015).

Although notable progress has been made during the recent decades, especially through internationally coordinated large-scale field campaigns (such as IPY 4, YOPP, MOSAiC) and model intercomparison projects (such as CMIPs, SIMIP, and PAMIP), obvious knowledge gaps still exist, and new grand challenges have emerged. For example, there is still a severe lack of regular and widespread vertical profile observations of the Arctic atmosphere and ocean, especially during winter and at appropriate spatial coverage (Yang et al., 2025a; b), which hampers the understanding and model representation of complete interactive processes from the upper atmosphere to the air-ice/ocean interface and further down through the ocean mixed layer and intermediate Atlantic and Pacific warm waters layers.

Although it is hypothesized that AA influences large-scale atmospheric circulation dynamics to cause extreme weather and climate events in the midlatitudes, considerable inconsistencies exist across different studies, particularly between models and observations. For example, the composite analysis from the coordinated PAMIP modeling experiments show a much weaker jet stream response than expected from the observations (e.g., Smith et al., 2022), though there exist concerns about the sample size of observational records.

Considering the complexity and nonlinear, multiscale interactive processes in the Arctic and its two-way interaction with the global system, our RPT 1 defined specific focuses organized into five Themes below:

Theme 1: Integration of observations and models to further Arctic process understanding and predictability on weather and climate scales.

Deficiencies in both observations and model representation of Arctic processes, especially at high resolutions and during winter and transition seasons, are limiting our understanding of, and ability to predict, the Arctic system and its links to the global-scale climate system. Reanalysis (e.g. ERA5) is often used as a substitute for observations but remains only weakly constrained by observations especially in the lower troposphere and many aspects of Arctic climate are modelled without support from assimilated observations (e.g. surface energy fluxes and clouds). New methods, tools, and approaches, as well as the recognition and inclusion of different knowledge systems, are needed to better improve the spatial and temporal completeness of observations and integrate observations and models to improve representations of model physics. All of these lays groundwork to enhance our systematic understanding of the coupled Arctic system and its interactions with the global system. This requires an enhanced collaboration between different scientific communities, including between numerical modeling and observational specialists, and between the science community and national and international operational centres. Indigenous Knowledge holders and scientists, and between the climate and weather forecasting communities, i.e. increase our forecast capability at subseasonal to decadal time scales.

Theme 2: Two-way interactions and teleconnections between the Arctic and lower latitudes arising within the Arctic and global coupled Earth system.

In addition to the well-recognized local feedback processes, remote forcing and resultant interactive processes between the Arctic and lower latitudes play essential roles in driving the changes, variability, and extreme events in the Arctic Earth system. The amplified warming and associated climate and environmental changes and deviations in the Arctic, in turn, have wide-reaching impacts on lower latitudes through complex interactions, feedbacks, and teleconnections involving the atmosphere, ocean, cryosphere, and biosphere. Understanding these two-way linkages and being able to represent the underlying physical, biological, and chemical processes in models is critical for robust climate projections, including regional extremes and risks.

Theme 3: Attribution of Arctic system changes, encompassing the atmosphere, ocean, sea ice, glaciers, ice sheet, and biogeochemical components.

Consistent and systematic changes have quantitatively been observed and projected in the Arctic and global Earth system using various metrics, which mainly focus on the thermodynamic states of the interested system component, such as regional or global mean temperature in the atmosphere and ocean, mass balance in cryosphere. However, it is complicated to comprehend the changes solely detected by these thermally-sensitive metrics, because observed and projected changes on various time scales are composed of both externally forced and internally generated nonlinear dynamic processes, as well as their interactions. These processes and interactions have not been explicitly identified, especially considering the short instrumental observations and highly limited paleo records, leading to a continuing, substantial lack of knowledge about the attribution of Arctic Earth system changes.

Theme 4: Changes in Arctic terrestrial systems and associated multidisciplinary interactive processes

The Arctic terrestrial system encompasses complex interactions between thawing permafrost, expanding vegetation, intensifying wildfire regimes, and changing hydrological cycles. These processes control carbon release mechanisms, influence global atmospheric composition through aerosol production, and affect freshwater inputs to the ocean. They might create cascading effects through interactions with atmospheric and oceanic processes to enhance feedbacks and, in turn, accelerate changes in the Arctic Earth system. Arctic terrestrial changes operate across multiple scales—from local thermokarst formation and vegetation shifts to interacting with large-scale atmospheric and oceanic dynamics and chemistry, and even longer, such as the shift from millennia-long carbon sinks to net sources of greenhouse gases. All of these interactive, multiscale processes have not been well understood.

Theme 5: Governance between Arctic regional and global politics.

The specific focus is placed on how Arctic-relevant governance solutions can be pursued at the global level. This includes identifying knowledge gaps and research avenues relating to a) interplay across Arctic-regional politics and security and global politics and security and b) the prospects of and steps needed to achieve progress on Arctic governance challenges (climate change, pollution, Indigenous rights, justice, ocean governance) that require (at least, in part) resolution within global governance settings. Given a strong interest and focus on Arctic politics at the regional scale in Arctic-focused social/political science milieus, these global-regional interconnections have been largely overlooked in circumpolar/Arctic research agendas, despite the longstanding efforts of Arctic political actors, most notably Indigenous Peoples' organizations, at the global level. Connections to local and national scales are outside the scope of this sub-theme. However, working together with other ICARP RPTs, we are able to supplement our focus on global politics and identify research needs across governance scales (supplementing RPT3) and building upon research needs identified relating to Arctic research cooperation and diplomacy in a broader governance setting (RPT4). An essential cross-cutting challenge for Arctic governance and security research, to which this sub-theme contributes, is to analyze interactions and identify pathways for action across scales, from the global to the local.

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3. Priorities and Needs in Arctic Research for the Next Decade

Following the definition of the five focal areas, we have conducted comprehensive review and evolutions of the state-of-knowledge, and then synthesized the evaluation results. Nine urgent needs and nine priorities are identified in the RPT 1 topic area. Meanwhile, three urgent cross-cutting needs and priorities are also identified, which aims to capture the interconnected nature of Arctic system changes and their global implications (Figure 2). The needs and priorities are summarized below.

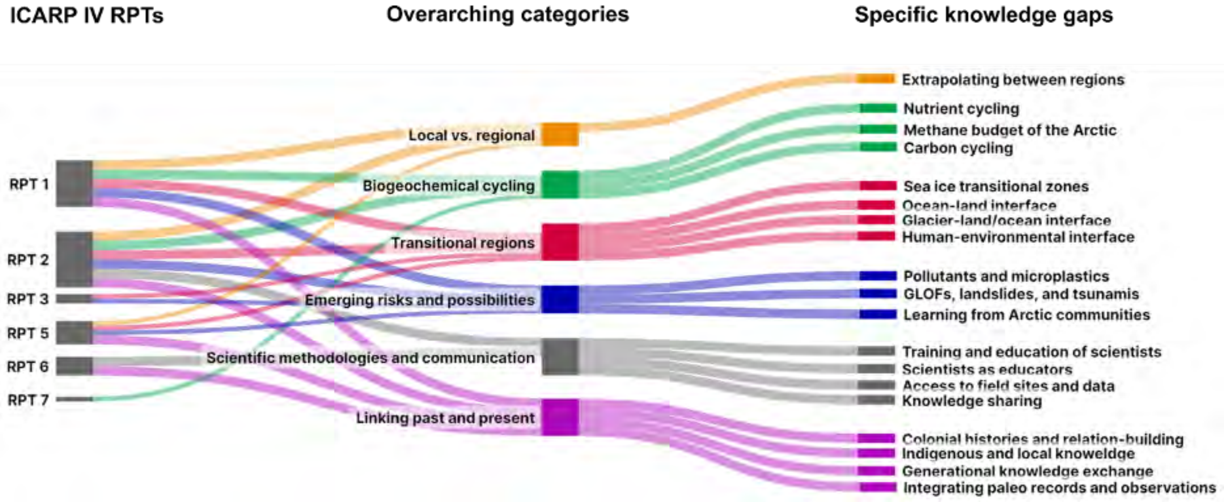

Figure 2. Overview of the relationship between the RPTs of ICARP IV (left) with the identified overarching themes during the IASC FOX ICARP IV 2024 workshop (middle) and the more specific knowledge gaps (right). The graph was created with SankeyArt (Adasheva et al., 2024). Title of the workshop 'Input to the ICARP IV process collaboratively developed by the IASC Fellows'Ongoing X-change (IASC FOX) network'

3.1. Needs and Priorities specific to the RPT 1 topic area

3.1.1. Research Needs for the RPT 1 topic area

Research Need	Description of the Research Need	Rationale why included in this report
1. An observing system for the Arctic Earth system with vertical profile sampling from the upper atmosphere to air-ice/sea interface and the intermediate ocean warm layers, especially for winter conditions, with the aims of improving model representations and assessing the impact of polar winter processes on global climate.	Earth system models have advanced considerably in recent decades. However, substantial uncertainties and biases persist at high latitudes (Sardana et al. 2025; Vignesh et al. 2020), particularly during the polar winter (Wei et al., 2021). Polar winter biases are found in many aspects, from micro-scale aerosol to macro-scale clouds and boundary layer processes, meso-scale storms and ice growth and melt, as well as large-scale atmospheric dynamics (Zhang et al., 2008; Cohen et al., 2020; Notz et al., 2020; Fiddes et al., 2022; Valkonen et al., 2025; Zhang et al., 2025). For climate monitoring, a sustainable observation system is needed that can benefit from already existing observations. This requires improved coupled assimilation of satellite observations supported by field campaigns. To enhance polar winter modeling, it is particularly important to conduct targeted and intensive measurements across various platforms to collect the data necessary for better process understanding, refining model parameterization, and reducing uncertainties, including Indigenous Knowledge and guidance by Indigenous Peoples for effective sampling strategies.	Reanalysis is increasingly utilized for climate monitoring in areas where observations are sparse, but this is also where reanalysis in large parts remains unconstrained by observations. It is imperative that we develop methods to use those observations already available and build a system for observations where different parts support each other. During the winter season, the Arctic experiences substantially different conditions from the rest of the year, including but not limited to reduced solar radiation, isolated air masses, sea ice growth and snow accumulation. The importance of the polar winter climate and processes to the Earth system has been reviewed recently by Yang et al. (submitted). However, the harsh weather conditions and various challenges associated with conducting field campaigns, alongside restrictions on using visible sensors, limit data coverage across the full range of spatial and temporal scales during the polar winter. An enhanced observation capacity can be reached by the Indigenous communities, offering a complementary approach instead of intensive field campaigns. This leads to a significant lack of observations of winter processes and a reliance on summer observational data for analysis and model improvement. Precedents of such expeditions exist, such as N-ICE2015 (Granskog et al., 2017) and MOSAiC (Shupe et al., 2022; Nicolaus et al., 2022; Rabe et al., 2022; Fong et al., 2024) that pose guidance to future campaigns during the Arctic winter, both in the form of implementation as well as scientific findings.
2. Fully coupled regional models of the Arctic Earth system capable of predicting and projecting changes at km-scales	Pan-Arctic modeling systems operating at km-scales that consist of dynamically coupled models of the atmosphere, ocean, and sea ice, with improved representation of processes that underpin the exchange of radiative and momentum fluxes between the systems. This includes unresolved processes such as, ABL turbulence, cloud-aerosol interactions, cloud microphysics, precipitation types, snowpack processes and permafrost. Building on coupled systems also makes possible new coupled assimilation methods that facilitate improved use of already existing observations.	The urgent need to better understand, monitor, and project changes in the Arctic climate system and environment demands a regional modeling system at spatial scales relevant for society, capable of resolving critical processes and interactions in the Arctic climate system that can include multiple knowledge sources. This could be in the form of a purely regional model or an unstructured-mesh global model with regionally enhanced resolution (e.g. Sidorenko et a., 2015; Rackow et al., 2016; Huo et al., 2025).
3. Improved understanding of drivers of, model diversity in, and local and remote consequences of Arctic Amplification (AA).	Polar regions are warming rapidly, with surface air temperatures in the Arctic increasing more than three times faster than the global average (Zhang et al., 2025; Rantanen et al., 2022; Vaughan et al., 2003; Turner et al., 2009; Ma et al., 2025). Notably, the most rapid temperature increases in the Arctic occur during the boreal winter (December–February), about 4.2 times the global average as shown in Figure 1. (Zhang et al., 2025; Ma et al., 2024; Liu et al., 2025), a seasonality that is not captured by current climate models. Moreover, the rate of Arctic amplification has been found to vary over time, giving rise to questions around the role of natural variability and forced response (England 2021;2025). Sweeney et al., (2023) and Zhou et al. (2024) suggest that the forced response of the Arctic Amplification is about 3, while the internal variability amps up the magnitude by 38%. However, the causes of AA, including the interconnectedness of local feedbacks and remote processes, are still not clear. Gaps in our knowledge about AA in turn hampers the ability to robustly project regional climate change and local and remote climate risk, while the coupled nature of processes driving AA across the atmosphere, ice and ocean requires an interdisciplinary approach. For the consequences of polar amplification, while recent studies have advanced the knowledge through theoretical work and coordinated modeling efforts (Smith et al. 2022), it remains unclear what forcing factors associated with the AA (e.g., temperature increase itself vs. sea ice decrease) play an essential role.	The state-of-the-art climate models struggle to accurately simulate polar amplification. For example, the largest biases between the Coupled Model Intercomparison Project phase 6 (CMIP6) simulations and satellite observations of cloud fractions (CF) occur at high latitudes (Vignesh et al., 2020; Sardana et al., 2025), with the greatest model spread of CF during winter (Wei et al., 2021). Several key factors contribute to these uncertainties, including limited understanding of the sources of cloud condensation nuclei and ice-nucleating particles, aerosol-cloud interactions (Kremser et al., 2012) or aerosol-precipitations feedbacks (Swain et al. 2025), the mixed-phase clouds associated with supercooled liquid water (Bodas-Saledo et al., 2019; Tan & Storelvmo, 2019), and surface turbulent fluxes (Taylor et al. 2022). The CMIP models underestimate the observed decline in Arctic sea ice area per degree of global warming. However, the models well represent the rate of Arctic sea ice area loss per degree of local warming. Therefore, the polar amplification is underestimated and likely the driver of the deficiencies in Arctic sea ice loss. For example, the recent Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC; Shupe et al., 2022) campaign revealed a new Arctic amplification process that all climate models have previously overlooked: the production of fine-mode (<200 nm) sea salt aerosols from blowing snow on sea ice (Gong et al., 2023; Zhang et al., 2023; Yang et al., 2019). There is also substantial model diversity and need to quantify and understand the sensitivity of feedback to parameterizations of individual processes (Taylor et al. 2022). A better understanding of forced and internal variability can lead to more accurate process representation in models, ultimately improving predictions from subseasonal to decadal scales.

Research Need	Description of the Research Need	Rationale why included in this report
4. Attribution of Arctic Earth system changes across time, space and domain	Research on the attribution of Arctic changes involves defining climate baseline, its internal variability, and associated extreme events. To achieve this goal, a research framework needs to be established to separate the externally forced and internally generated components on various time scales (i.e. past, present, and future), as well as to distinguish between local processes and remote influences, encompassing reanalysis datasets, observations, data aggregation, and data interoperability. For example, quantitative attribution studies using numerical models require verification through empirical observations. In addition, knowledge needs to be built by integrating well-connected and consistent insights from past, present, and future climate and environmental research (Yoshimori et al., 2025). The involvement of the paleo-archive is necessary as the changes we are facing are expected to be of a similar scale only to the substantial changes seen during the long-term paleo records.	Characterizing the Arctic natural climate baseline, its internal variability, and associated extreme events is beneficial for society at both local and global scales. Their attribution to the causes and factors provides one of the most fundamental bases of knowledge on which mitigation and adaptation strategies can be built. It is also central to the scientific understanding of the Arctic climate and environment in the global system.
5. Improved understanding of impacts of permafrost thaw on biogeochemical transformations, land-ocean-atmosphere interactions, and other processes	• Permafrost carbon dynamics and global impact assessment, including subsea permafrost and thermokarst processes • Arctic mercury and contaminant mobilization from thawing permafrost - including significant mercury releases and elevated dissolved arsenic through bank erosion • Arctic infrastructure vulnerability assessment and early warning development - given widespread infrastructure threats from permafrost thaw • Impacts of permafrost thaw on increased drying and vegetation feedbacks	• Subsea permafrost contains significantly more organic carbon than terrestrial counterparts and higher thawing rates • Thermokarst lagoons show up to 18 times higher greenhouse gas production compared to open lagoons
6. Connecting atmosphere, cryosphere, ocean and Inland science processes and Indigenous Knowledges at the Arctic, regional, and global scales	Earth system models consisting of the atmosphere, cryosphere, ocean, and terrestrial components have been an essential tool to understanding the rapidly changing Arctic. Missing are the connections across scales of changes from local to global and the attention to how Indigenous Knowledge can challenge, support, and shape our understandings of long-term, large-scale change in the Arctic (Inuit Circumpolar Council 2022; Heikkilä, et al 2024; Hætta et al, 2025). What are the most important/immediate ways in which this connection can be ethically and equitably implemented and enhanced? What knowledge about large-scale physical systems can be achieved through co-production of knowledge approaches? How can different forms of knowledge and scales of decision-making best be brought together to address challenges and opportunities at the intersection of rapid natural change (e.g., Siegert et al, 2025; Chitty et al, 2025, Buschman & Sudlovenick 2023)?	This research need is relevant to the report as it relates to growing efforts across the Arctic to use multiple evidence bases to produce knowledge of environmental change and risks. Pathways for doing such co-production in modeling/large-scale/global change natural science remains challenging, with few examples, and thus merits attention in this RPT.
7. Systematic, comparative research identifying possible future avenues for coordinated Arctic-anchored political action (states, Indigenous Peoples' Organizations, NGOs) in seeking to govern at the international level the global drivers shaping the physical and political state of the Arctic region	Governance and environmental outcomes in the Arctic are shaped by extra-regional and global processes. Much of our understanding of the 'global Arctic' thus far has had focus on what is at stake for non-Arctic states and what they can or should contribute in Arctic governance and for the Arctic environment (Woon et al 2020). Too little research attention has been directed to how, in a more aggregate view, this interest and engagement can be harnessed and global governance processes used to ensure good outcomes for a safe and secure Arctic (Dahl et al 2024; Jacobsen and Wilson Rowe, editors, 2026). How can global governance settings - from the UN setting to engagement with private sector organizations be navigated and utilized to secure a sustainable, prosperous and just Arctic? This need emerges in a particularly pressing way when patterns of scientific and political cooperation in Arctic regional settings are disrupted.	This RPT highlights global environmental drivers shaping outcomes in the Arctic region. Similarly, from a governance perspective, several of the key factors driving Arctic change originate outside the region and are governed (or sought governed) at the global level. Addressing this governance research need would thus serve to complement the global scope of this RPT with a social science perspective.

3.1.2. Priorities for Arctic Research for the RPT 1 topic area

Priorities for Research	Reason why this should be an ICARP IV Priority
1. Improve observational capacity and sustain coordinated monitoring in the Arctic, across the cryosphere, ocean and atmosphere, with a strong emphasis on improving vertical profile observations from the upper atmosphere down to sea ice and ocean and across seasons, with a particular focus on the winter season.	A severe lack of scientific observations, especially during winter, and across the vertical profile of the atmosphere and ocean hampers development and improvement of Arctic processes and parameterizations included in models. This results in poor constraint of numerical weather prediction and limits the understanding of climate system processes in the Arctic and hence the credibility of climate scenarios. Particularly, due to severe weather conditions and logistical challenges associated with conducting scientific monitoring winter campaigns, our scientific data coverage at both spatial and temporal scales for the polar winter is especially limited and often based on reanalysis rather than real observations. This means that crucial processes vital to the coupled climate system are still not fully understood.
2. Improve understanding of Arctic processes that underpin the exchange of radiative and turbulent fluxes between the atmosphere, ocean, sea ice, and terrestrial system.	The ongoing fast-paced changes in the Arctic climate system are driving an urgent need to rapidly develop our capacity to monitor, predict, and project these changes within the coming decade. This requires expedited development of regional modeling systems that include models of all components of the Arctic climate system and the interactions between them at km-scales. The interactions between the different components is poorly understood despite their influential role in the Arctic climate.
3. Conduct coordinated model intercomparisons, develop new and advanced process parameterizations, and apply novel frameworks, strategies and tools to advance the understanding of and ability to predict Arctic climate change, including Arctic Amplification, and two-way interactions between the polar and lower latitudes.	Biases and model diversity hampers the ability to project regional climate change. Missing or poorly described, constrained, or understood processes across the atmosphere, land, ocean, and cryosphere, contributes to the uncertainty. This in turn limits our understanding of the impacts and risks to other parts of the world caused by Arctic climate and environmental change, knowledge which is required for adaptation planning at local-to-regional scales. Key steps to close existing knowledge gaps include: • coordinated model intercomparisons to quantify how parameterizations of different physical processes influence model diversity and biases • utilize the existing outputs from the past CMIPs, specifically the PAMIP and SIMIP • coordinated model intercomparisons to simulate the remote impact of polar amplification (beyond polar sea ice decline) • coupled and ensembles of ESM experiments to capture interactions across the Earth system components and teleconnection effects • Development of process parameterizations, with open and collaborative research enabling enhanced data integration, standardization, and interoperability across domains • Exploitation of contemporary ML/AI tools • Novel frameworks (e.g. feedback quantification frameworks) and modeling strategies (e.g. hierarchical approaches encompassing large-eddy simulations, single-column models, nested resolution, topographic differences, inclusion of Indigenous Knowledge in modeling (Gryba et al. 2025))
4. Improve attribution studies of Arctic climate change via an integration of a multi-disciplinary approach	Attribution studies aim to identify and distinguish the roles of external forcing and internal variability in Arctic changes. They are often conducted individually; however, an integrated framework of attribution studies encompassing observations, modeling, aggregation, and connecting local, regional (e.g., marginal ice zones), and global changes has not been established. In addition, information from the paleo-archive will help place the change in a long-term perspective and attribute the projected cause and effect of a changing baseline climate, which is unprecedented and expected to be different from today (e.g., “blue Arctic” characterized by sea ice loss and “green Arctic” characterized by ice and snow retreat on land). The attribution studies must be linked to the non-physical aspect of Arctic change, such as ecosystem and material cycle changes. Also, climate modellers will play an important role in the attribution studies. The same is for observations from meteorological, satellites and local (Indigenous) for the near time perspective. Paleoclimate reconstructions will be needed, including high-resolution data for extreme event attribution , for the long-term context. Creating an Arctic-reanalysis product covering the whole region, building on the Copernicus Arctic Regional Reanalysis (CARRA, Batrak et al. 2024) would be highly useful. Additionally, expertise in impact attribution should be included to quantify the direct societal and economic consequences of climate change. This is necessary to inform on how the acquired information can be relevant for societies and policy making.
5. Improve understanding of permafrost thawing and its impacts on biogeochemical transformations, land-atmosphere interactions, and other processes	Permafrost thawing changes landscape, thermokarst extension, and biogeochemical cycling and represents a fundamental research priority given the profound implications for global carbon dynamics. Arctic permafrost contains an estimated 1,460-1,600 billion metric tons of organic carbon—approximately twice the amount currently in the atmosphere. Recent observations indicate that the Arctic tundra has now shifted from a millennia-long carbon sink to a net source of carbon dioxide and methane. The biogeochemical impacts extend beyond carbon cycling. Thermokarst formation creates direct pathways for permafrost solutes to reach surface water networks, short-circuiting natural soil filtration processes and delivering unprocessed nutrients and carbon directly to aquatic ecosystems. Research has documented dramatic effects on stream chemistry, with some Arctic streams turning orange due to metal mobilization from thawing permafrost, resulting in lower pH, higher turbidity, and elevated concentrations of iron and trace metals. These changes have cascading effects on ecosystem health, including dramatic declines in macroinvertebrate diversity and fish abundance.

Priorities for Research	Reason why this should be an ICARP IV Priority
6. Connect Arctic and global governance processes	There is a need to map Arctic stakeholders (states, Indigenous Peoples' organizations, data repositories, NGO) and identify future pathways for Arctic-relevant solutions in global governance (biodiversity, justice/Indigenous rights, pollution, ocean governance, climate mitigation, cryosphere & atmosphere large-scale scientific and policy processes). Many of the processes impacting the Arctic are global in nature - and working towards a safe and sustainable Arctic necessitates using global regimes, settings, treaties and soft-law/private initiatives to the extent possible. This also necessitates understanding Arctic governance as crossing scales from local to national, regional to global, including the role of non-Arctic states/actors in these processes. As an illustration, food chain interactions impact both Arctic and non-Arctic communities. Extra-regional security challenges and Arctic security tensions wrought by populism, imperial thinking and conflict place some limits on what can be achieved at an Arctic/circumpolar level today (Hoogensen et al, 2020; Friis et al 2023). This requires innovative thinking about how different levels of governance settings can be used to advance security, safety and sustainability in the Arctic. It also requires research on how core Arctic principles forged, through decades of cooperation in more peaceful times and realized imperfectly, can be transferred and pursued in international governance settings as well, including respect for the value and purpose of co-production of knowledge, Indigenous Peoples leading alongside states, and knowledge-driven policymaking (see Dahl et al 2023). This research priority is focused on mapping, analyzing and projecting where and how Arctic and non-Arctic actors can pursue common solutions at the global level, and how core ways of working on Arctic challenges can gain purchase in international governance and scientific processes. A result of research under this priority would be identification of novel and longstanding tools to advance negotiations in key regional and global settings (i.e. Arctic Council, UNCLOS).
7. Governing and managing and managing global risks to Arctic security	The Arctic is facing new governance challenges as the Arctic Ocean turns from white and ice-covered to seasonally blue and open and as permafrost melt and wildland fire change communities, cities, livelihoods, military installations and public infrastructure on land. Furthermore, the global maritime sector and associated regimes are under pressure and order and disorder at sea exist simultaneously, impacting multiple arenas from Arctic shipping routes (i.e. Northern Sea Route) to the collection and sharing of Arctic-relevant research data. Despite challenges facing global multilateralism today, there remains an urgent research need to consider what the next generation of binding and soft-law agreements and mechanisms relevant to the Arctic should be, considering Indigenous sovereignty and the need to recognize Indigenous leadership in conservation and risk management. In particular, the prospects of climate interventions or geo-engineering loom large for the Arctic - a region already facing large-scale environmental changes and surrounded by wealthy states with advanced science and technological capacity. This priority focuses on marshalling legal and political competence, as well as extensive Indigenous Peoples and stakeholder engagement to connect across governance scales from local to global, to identify ambitious yet pragmatic and realizable agreements that could be pursued under even slightly improved conditions for Arctic cooperation and global multilateralism. This research priority would also focus on identifying effectful mechanisms and means to govern a changing Arctic that could be realized in a more modular fashion (between some states and actors, with the aim of promoting these solutions more broadly as political conditions allow). Key examples include supporting and exploring efforts like the Pikialasorsuaq Commission, which responds to the impacts of climate change and the likelihood of changed users and usages of the region by enhancing the responsibility and sovereignty of Inuit communities on either side of the Pikialasorsuaq. A new Arctic brings new challenges and opportunities, and activates both politics and security issues relating to sovereignty and to planetary commons. There is a need to enhance precautionary approaches to governance and to explore options for inclusive governance, adapted to new realities. Scenario exercises to prepare for a diversity of Arctic governance and security futures should be a transdisciplinary priority.

Wenkai Guo

3.2. Cross-Cutting Needs and Priorities

Cross-cutting needs and priorities are defined as not only relevant for one of the RPT topic areas specifically, but instead cutting across several of the seven topic areas:

- RPT 1: The Role of the Arctic in the Global Earth System
- RPT 2: Observing, Reconstructing, and Predicting Future Climate Dynamics and Ecosystem Responses
- RPT 3: Understanding the Dynamics and Resilience of Arctic Social-Ecological Systems to Foster Sustainable Futures
- RPT 4: Arctic Research Cooperation and Diplomacy
- RPT 5: Co-Production and Indigenous-led Arctic Research
- RPT 6: Education and Knowledge-Sharing In and About the Arctic: Research and Practice
- RPT 7: Technology, Infrastructure, Logistics, and Services

3.2.1. Cross-Cutting Research Needs

Research Need	Description of the Research Need	Rationale why included in this report
1. Improve understanding of Arctic freshwater and global ocean circulation	• Arctic Ocean acidification rate acceleration mechanisms - with pH declining, three to four times higher than other ocean basins • Arctic precipitation and freshwater reservoir (e.g., basins and shelves) monitoring - hydrographic profiles from in situ ship-based surveys and autonomous devices (e.g., ice-tethered profiler, ARGO profilers) and satellite altimetry • Arctic Ocean freshwater export pathway quantification - systematic monitoring of changing export routes and their global circulation impacts • Arctic marine ecosystem response to multiple stressor interactions - integrated responses to warming, ice loss, acidification, and freshwater changes, including sediment flux from rivers. • Arctic ocean-sea ice-atmosphere interactions - quantifying relationships and feedbacks between ocean circulation, sea ice loss, and atmospheric forcing and response • Glacier and ice sheet interactions with oceans - quantifying meltwater contribution to global sea level rise and impacts on nutrients and ecosystems	Accelerated Arctic Ocean acidification, changing precipitation and freshwater export, and evolving glacier–ocean interactions are altering ocean chemistry, circulation, and ecosystem dynamics. Research on marine ecosystem responses to multiple stressors and sea ice–atmosphere heat coupling is feasible with expanding observation networks, has high global impact by informing climate and carbon cycle projections, and addresses processes at regional to pan-Arctic scales critical for understanding Arctic–global system feedbacks.
2. Improve understanding of Arctic atmospheric circulation impacts	• Comprehensive Arctic-global atmospheric circulation linkage quantification - understanding ice-albedo and ice-insulation feedback mechanisms • Arctic atmospheric moisture transport and global weather pattern impacts - quantifying relationships between Arctic sea ice-evaporation and global circulation changes • Arctic brown carbon aerosol climate impact assessment - standardized monitoring and impact assessment for different source regions • Arctic microplastic and emerging contaminant tracking - comprehensive tracking systems for global pollutant transport to the Arctic • Arctic renewable energy and climate mitigation potential assessment - systematic assessment of renewable energy resources and environmental interactions	

Research Need	Description of the Research Need	Rationale why included in this report
3. Improve understanding of Arctic wildfire's global atmospheric effects	• Wildfire-aerosol-cloud interaction quantification in Arctic systems - understanding complex aerosol mixtures and their climate effects • Arctic fire emission inventory and real-time monitoring systems - addressing 2-5 times lower emission estimates than other inventories • Arctic industrial impact assessment on environmental systems - systematic assessment of gas flaring and drilling impacts • Arctic Indigenous Knowledge documentation and integration systems - systematic integration of Indigenous fire management knowledge • Arctic community-based monitoring integration and coordination - systematic integration with scientific research networks • Co-produce Indigenous Knowledge- science frameworks/methods and formal frameworks for co-production of knowledge	
4. Enhance understanding of vegetation changes and carbon-fire interactions	We need to focus on understanding how shifts in Arctic plant communities (including shrub expansion) alter fuel loads, snow and soil conditions, and carbon storage and release. This research need also covers quantifying how the vegetation changes modify fire regimes, including fire frequency, intensity, and burn severity, and how post-fire vegetation succession feeds back on permafrost and carbon cycling.	We need to enhance understanding of vegetation changes and carbon-fire interactions because changing fire regimes can rapidly convert long-term carbon sinks into sources, amplifying global climate warming. Improved knowledge of these coupled processes is essential for reliable Earth system modeling, for assessing risks to Arctic communities and ecosystems, and for informing adaptation and fire management strategies in a rapidly warming Arctic.
5. Interdisciplinary work on the prospects for and consequences/ governance of climate interventions	The level of public/policy attention directed towards climate interventions currently outstrips our processes designed to govern the atmosphere and nature, as well as our understanding of the impacts of climate interventions at all scales and time horizons. As the impacts of climate change become ever more visible, climate interventions are rapidly becoming a more mainstream policy idea. RPT1 should contribute with cutting edge knowledge about the impacts, risks, ethical issues and governance options associated with climate interventions, and consider what agreements and mechanisms are needed to govern or limit climate interventions at the global and regional levels.	Work on climate interventions - both their potential impact and their potential governance - is a theme that could tie the natural and political science within this RPT together.
6. Enhanced understanding of relation between land-ocean connection	The relationship between terrestrial and marine environments includes not just ecological factors but also socio-economic and political elements. Recognizing and addressing this interdependence is crucial for preserving ocean health, developing sustainable bolstering, and protecting coastal populations. It is vital that policies are integrated, knowledge-based (Indigenous Knowledge included), and adaptable to climate change and socio-economic transformations / changes (i.e: sea level rise, fisheries, reindeer husbandry). Our global governance mechanisms such as UNCLOS impose a static perspective on the oceans (which are changing) and uphold a strong delineation between land and sea. A cross-cutting theme within ICARP could therefore be focused on the social and natural science needed to appreciate the land-ocean connection, including the impact of human activities on land on the ocean. Such a theme would engage across maritime governance, international relations and the natural sciences. Ice/cryosphere change is a factor in sea level rise, fisheries, Indigenous livelihoods, and security regionally and globally as ice patterns change.	The influence of terrestrial activities on the ocean - and vice versa - is a security-political and sustainability concern, cutting across RPT themes and disciplines.

3.2.2. Cross-Cutting Priorities for Arctic Research

Priorities for Research	Reason why this should be an ICARP IV Priority
1. Improve understanding of Arctic freshwater and global ocean circulation	Understanding how changes in terrestrial water balance affect global oceanic circulations through freshwater inputs addresses critical gaps in Earth system science. The Arctic Ocean serves as a fundamental node in the global hydrological cycle and thermohaline circulation, collecting over 11% of global river discharge despite representing only 1% of ocean volume. Recent research reveals dramatic changes in Arctic freshwater dynamics. The Beaufort Sea has increased its freshwater content by 40% over the past two decades, with implications for both regional marine environments and Atlantic Ocean overturning circulation. Arctic freshwater export pathways have shifted, with increasing transport through the Canadian Archipelago to the Labrador Sea rather than European passages. This freshwater input, being both fresher and nutrient-rich, could significantly impact the Atlantic's conveyor-belt circulation by slowing thermohaline overturning.
2. Evaluate impacts of Arctic atmospheric circulation	Understanding how changes in soil moisture, precipitation, evapotranspiration, and aerosol patterns affect global atmospheric circulations represents a critical knowledge gap. Research demonstrates that atmospheric moisture transport from Arctic Ocean evaporation to Siberia has increased significantly during autumn to early winter periods coinciding with substantial sea ice retreat. Enhanced Arctic moisture transport creates feedback mechanisms that extend far beyond the region. Arctic moisture content reaching western Siberia in September correlates with observed increases in snow cover, while eastern Siberia experiences sharp increases in Arctic moisture during October-December. Model projections indicate that rapid sea ice retreat in the future would intensify summer warming and moistening over high-Arctic lands, especially along the Arctic coast of Siberia (Yang et al., 2025). These patterns influence not only regional weather but also radiation balance through enhanced water vapor acting as a greenhouse gas.
3. Enhance understanding of Arctic wildfire effects on global atmosphere	Understanding how Arctic wildfires affect global atmospheric aerosols, snow melt, and pollution addresses an emerging threat with planetary implications. Arctic wildfires differ fundamentally from lower-latitude fires, with most carbon emissions coming from burned organic soil rather than vegetation. These fires release not only carbon dioxide and methane but also complex aerosol mixtures including brown carbon particles. The global reach of Arctic wildfire impacts is substantial. Brown carbon aerosols from wildfires contribute up to 30% of black carbon's warming effect in the Arctic, while wildfire smoke affects sea ice melt patterns through cloud-aerosol interactions. Research indicates that Arctic sea ice melts more during summers with relatively low fire activity due to reduced aerosol seeding of clouds. Additionally, Arctic wildfire pollution creates large transboundary health impacts, with PM2.5 from Arctic fires affecting air quality across multiple countries.
4. Enhance understanding of vegetation changes and carbon-fire interactions	Understanding vegetation changes, particularly shrubification, and their impacts on carbon cycling and wildfires is essential for predicting Arctic ecosystem trajectories. Arctic shrub expansion has been widely observed across the tundra, with increases in woody plants, particularly tall deciduous shrubs. However, contrary to simple climate-suitability models, research demonstrates that observed shrub expansion during 1984-2014 was not controlled by environmental suitability alone but required consideration of seed dispersal and fire dynamics. The relationship between vegetation change and wildfire creates complex feedback loops. Shrubs affect nutrient cycling, animal populations, and wildfire risk through changes in snow accumulation patterns, soil thermal regimes, and fuel loads (Rasouli et al, 2014, 2019). Post-fire environments show enhanced shrub growth in optimally drained areas, while postfire active layer deepening accelerates nutrient cycling. Climate change is intensifying high-latitude fire regimes, resulting in increased burned area, fire intensity, and carbon emissions that exceed vegetation regrowth capacity.
5. Identify pathways for improving Arctic governance across all scales (connecting local, national, regional, global change and cross-scale solutions) and seek justice/ inclusivity in research and policy processes (Related to RPT3 and RPT4)	Addressing complex challenges impacting the Arctic - such as climate change impacts and rapidly changing security issues - requires governance approaches that operate effectively across all scales: local, national, regional, and global. For instance, community-based adaptation to climate change must be linked to national adaptation plans and supported by international climate finance mechanisms. Connecting governance across scales while seeking justice aligns with RPT3 and RPT4, and builds upon RPT1 research priority themes 8 and 9 above.
6. Conduct interdisciplinarity and cross-cutting topics of different RPTs and foster interdisciplinary conversation across RPTs	Imagining and exploring possible futures is a powerful way to bring together diverse disciplines, perspectives, and knowledge systems. It creates a shared space where complex, cross-cutting issues can be examined not in isolation, but as interconnected challenges. Within the context of the Research Priority Themes (RPTs), future-oriented thinking serves as both a unifying lens and a bridge for interdisciplinary collaboration. Possible futures inherently reflect interdisciplinarity, drawing on insights from natural sciences, social sciences, the humanities, and the arts. Developing possible futures invites collaboration beyond academia, incorporating Indigenous Knowledge systems, community experiences, artistic expressions, and policy expertise. This opens pathways for co-production of knowledge (RPT4), where tools such as participatory scenario planning or visioning exercises can be used to foster dialogue and integrate multiple forms of evidence and values. Engaging with futures can make abstract or long-term challenges more tangible. Importantly, possible futures are not about predicting a single outcome. Rather, they explore a range of trajectories, highlighting trade-offs, tipping points, and feedback loops. It supports the identification of leverage points for intervention, and helps researchers and practitioners engage with uncertainty in constructive ways. It fosters a shared language that respects disciplinary depth while encouraging collaboration across boundaries. By linking imagination with rigorous analysis, and inclusivity with systems thinking, possible futures serve as a vital tool for shaping more sustainable, equitable, and resilient pathways forward.

4. Recommendations to Implement the identified Priorities for Arctic Research

Implementing the identified research priorities for Arctic research requires a multi-faceted approach integrating enhanced monitoring systems, data infrastructure, and international coordination mechanisms. The recommendations span technological deployment, data management protocols, early warning system development, and sustainable funding models to address the complex challenges facing Arctic system science.

- Lack of knowledge of existing and potential political interlinkages between Arctic regional policymaking/ security dynamics and global processes, resulting in lack of knowledge of potential global solutions to Arctic challenges
- More interdisciplinary research Heightened transdisciplinarity/co-creation of knowledge from academia, Indigenous policy actors/organizations and communities on pathways for navigating global politics to secure sustainable Arctic outcomes.
- New opportunities to present better solutions and real actions to put in place at a global/regional levels can happen with more partnerships between research institutions, NGO's, Indigenous organizations and government representatives (sub-theme 5)

4.1. Implementation of the RPT 1-specific Priorities

Priority 1:
Improve observational capacity and sustain coordinated monitoring in the Arctic, across the cryosphere, ocean and atmosphere, with a strong emphasis on improving vertical profile observations from the upper atmosphere down to sea ice and ocean and across seasons, with a particular focus on the winter season.

Spatial scale:	Local to global
Time scale:	For the next 10 years (ramp-up phase and establishment of infrastructure), then ongoing legacy of measurements beyond IPY-5.
Funding requirements and potential sources:	Coordinated or collaborative funding calls from national agencies in the Arctic countries.
Infrastructure needs and requirements:	Instrumentation, facilities (stations, research vessels, aircraft, remote sensing, automated etc.), manpower, advances in satellite retrievals for high latitudes, coordinating data infrastructure to collect and archive datasets and enable interoperability and comparability of datasets.
Data needs and requirements:	Robust data documentation and standardization (relevant to discipline best practices) to leverage interoperability and comparability initiatives.

Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Ensure weather observations are equipped and conducted in a coordinated way, for all research vessels in the Arctic, and recommend an improvement of satellite remote sensing over the Arctic.		IASC, WMO
Build of an international initiative to coordinate existing and foster new Arctic vertical profile measurements	• Work with polar agencies, aircraft measurement facilities, satellite researchers, unmanned vehicle operators, local Arctic communities to develop plans for coordinated measurement activities. • Exploit funding opportunities to facilitate individual measurement components / platform deployments, as well as those targeted at building overarching coordinating logistical and data infrastructure. • Engage with national and international weather institutes to utilize profile data in model development and improved assimilation of e.g. satellite products.	IGAC, IASC, WMO

Priority 1: Improve observational capacity and sustain coordinated monitoring in the Arctic, across the cryosphere, ocean and atmosphere, with a strong emphasis on improving vertical profile observations from the upper atmosphere down to sea ice and ocean and across seasons, with a particular focus on the winter season.		
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Work in partnership with Indigenous Peoples and Knowledge Holders to integrate Indigenous and scientific knowledge systems, ensuring that data infrastructure supports Indigenous ownership of Indigenous research, equitable access, co-stewardship, and respect for Indigenous data governance.		

Priority 2: Improve understanding of Arctic processes that underpin the exchange of radiative and turbulent fluxes between the atmosphere, ocean, sea ice, and terrestrial system.		
Spatial scale:	Local, regional and pan-Arctic	
Time scale:	Urgently needed now and continuously into the next 10 years, development needs in the IPY ramp-up phase, informing IPY agenda, and exploitation of outcomes in the post-IPY phase.	
Funding requirements and potential sources:	Funding calls for model development and infrastructure. National funding agencies, EU, Joint Programming Initiatives.	
Infrastructure needs and requirements:	Regional models of the Atmosphere, regional ocean models, and sea ice models operating at km-scales and capable of using GPUs. High performance computing and storage capabilities.	
Data needs and requirements:	High-resolution observational datasets, standardized formats, robust metadata, and using a regionally refined global model with an unstructured horizontal mesh (e.g. FESOM2, AWI-CM) to ensure accurate aggregating, coupling, and scaling. Transparent version control, sustained data infrastructure, and clear governance on sensitive Arctic data support reproducibility and ethical use.	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Foster improved collaboration between the observing and modeling communities to resolve key km-scale processes in the observations and integrate the observed results into the Earth system development, and develop best practices in process-based model evaluation.	Establish a task force for designing roadmap and coordinating efforts to resolve high-resolution observational processes and integrate the observed results into the system development, including collecting high-resolution data from historical field campaigns; conducting new observational data to fill historical gaps, especially during IPY5; developing a data portal to share the data; and establishing a network for collaboratively developing and verifying km-scale Arctic climate systems.	Modeling centers and groups, IASC

Priority 3: Conduct coordinated model intercomparisons, develop new and advanced process parameterizations, and apply novel frameworks, strategies and tools to advance the understanding of and ability to predict Arctic Earth system changes, with primary focuses on causes and consequences of Arctic Amplification, and two-way interactions between the polar and lower latitudes.		
Spatial scale:	Global, modeling centers and research institutions around the world	
Time scale:	Relevant for the next 10 years, development needs in the IPY ramp-up phase, informing IPY agenda, and exploitation of outcomes in the post-IPY phase.	
Funding requirements and potential sources:	Funding calls for model development and infrastructure. National funding agencies, EU.	
Infrastructure needs and requirements:	Clear governance agreements, ethical use protocols, and transparent repository policies support responsible, long-term collaboration.	
Data needs and requirements:	Data needs to be shareable by utilizing standardized formats, persistent identifiers, and robust metadata to ensure interoperability and reproducibility.	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Establish dedicated, international-level project for coordinating multi-model intercomparison; Ensure better integration of Arctic focused research questions in other MIPs	A committee consisting of lead scientists on the topic to design the intercomparison project, call for participation of international modeling centers/groups, and create protocol for coordinated model simulations and comparisons. Specific work can include: • Assessing the status of knowledge; • Targeted workshops, early actions to influence MIP planning. Inventory key missing/poorly represented processes in existing models, establish/improve diagnostics, metrics and evaluation/benchmarking frameworks; • Integrated community workshops, training and capacity building across disciplines (modelers, observational scientists, data scientists, machine-learning experts).	CLIVAR, CliC, and IASC with Arctic and global Earth system communities.

Priority 4: Improve attribution studies of Arctic climate change via an integration of a multi-disciplinary approach.		
Spatial scale:	Pan-Arctic, global	
Time scale:	10 years	
Funding requirements and potential sources:	National and international funding agencies, IASC	
Infrastructure needs and requirements:	World-wide simulation data archive like Earth System Grid but with high-level analysis capability via remote access (i.e., without downloading massive data locally). Coordinated compilation and assessment of Arctic observations and proxies, with potential efforts directed to include spatial representation of climate proxies.	
Data needs and requirements:	Output data from coordinated and designated numerical experiments for the attribution of Arctic climate and environmental changes from research institutions and modeling centers; Observation data including paleo-reconstructions for model validation at the same platform as the simulation data archive	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Establish a dedicated, international-level project aiming to address attribution of Arctic changes with clear scientific questions, including paleoclimate data and observations (meteorological and Indigenous), model experimental designs and model inter-comparison. Should also address how to use attribution results for policy and society relevant application.	Establish a task force/working group of modelers within the Arctic science community who can lead the initial coordination for designing the research on the priority; Expand the team involving the experts of instrumental/satellite observations and paleo-reconstructions; Expand the team involving experts who can suggest how to use the acquired information to policy and society relevant application.	Modeling community focusing on the Arctic region by collaborating with existing model intercomparison projects such as CMIP, CFMIP, PAMIP, and PMIP etc. It should include biogeochemical cycle modeling and the community should be expanded well beyond the GCM community. Given the impact of Arctic change, the project should embrace an Earth System thinking and include experts from relevant scientific and social disciplines.

Priority 5: Improve understanding of permafrost thawing and its impacts on biogeochemical transformations, land-atmosphere interactions, and other processes.	
Spatial scale:	Local and Global
Time scale:	5 years
Funding requirements and potential sources:	NOAA, USGS, Department of Defense, Horizon Europe
Infrastructure needs and requirements:	Standardized and sustained long-term permafrost and active layer observatories, filling gaps in the large regions currently without data (see IPA - Global Terrestrial Network for Permafrost)
Data needs and requirements:	Coordination between data and knowledge systems for researchers, government agencies, and stakeholders to access existing datasets related to permafrost thawing and biogeochemical transformation. High-resolution observational datasets, standardized formats, and robust metadata to ensure accurate aggregating, coupling, and scaling. Transparent version control, sustained data infrastructure, and clear governance on sensitive Arctic data support reproducibility and ethical use.
Implementation: **Implementation Actions:**	**Who to address the actions**
Deploy comprehensive permafrost monitoring network with CO_2 and methane flux measurements, with at least 50 sites across the Arctic by 2030, including measurements from the snowpack. Existing facilities should be assessed and included when possible for harmonising measurement protocols across the Arctic.0	**Lead:** NOAA, USGS, International Permafrost Association (GTN-P), with Indigenous community partnerships **Funding:** $15M annually through expanded IARPC coordination **Partners:** Russia's Roshydromet, Nordic research institutions
Establish early warning system for thermokarst -related geohazards affecting critical infrastructures and ecosystem services	**Lead:** Department of Defense, USGS, Department of Transportation **Funding:** $8M through existing hazard mitigation programs **Partners:** Alaska Native Corporations, Canadian permafrost researchers, International Permafrost Association, SIKU.
Develop standardized biogeochemical monitoring protocols for thermokarst lagoons and stream	**Lead:** EPA, NOAA, with Indigenous Knowledge Holders **Funding:** $5M annually through environmental monitoring programs Partners: Arctic communities, international research stations, International Permafrost Association

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Priority 6: Connect Arctic and global governance processes.		
Spatial scale:	Pan-Arctic and global	
Time scale:	Now to next 10 years	
Funding requirements and potential sources:	National research councils (Arctic and non-Arctic states), foundations (estimated cost 6 million USD)	
Infrastructure needs and requirements:	Standardized and sustained long-term permafrost and active layer observatories, filling gaps in the large regions currently without data (see IPA - Global Terrestrial Network for Permafrost)	
Data needs and requirements:	Synthesis, document analysis, interviews, and participant observation at global governance settings, use and update of existing data sets (e.g. MARIPOL dataset). To achieve these requirements, data needs to be properly archived, made accessible, and openly available, while including enough contextual information to ensure reproducibility and ethical use.	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Map Arctic actor engagement (states, Indigenous Peoples' organizations, NGOs, IGOs, researchers) in and explore future pathways for Arctic-relevant solutions in global governance bodies (biodiversity, justice/Indigenous rights, pollution, ocean governance, climate mitigation, cryosphere and atmosphere large-scale scientific, and policy processes).	Document analysis, large-scale participant observation with shared protocol, interviews and co-creation exercises with actors engaged in these settings	Researchers, funding bodies
Identify and pursue key topics at the global or regional interface - security (including human and food security), trade, environmental governance	Large-scale workshop to identify the most significant policy global policy fields shaping Arctic governance/sociopolitical outcomes. Subsequently, qualitative and quantitative analysis of these policy fields (document analysis, large-scale participant observation with shared protocol, interviews and co-creation exercises with actors engaged in these key policy fields).	Researchers, funding bodies
Synthesis	Large-scale, capstone synthesis involving research and policy community in and beyond Arctic states to gather and synthesize our knowledge about Arctic presence in and impacts from global institutions and global policy fields.	Policymakers, researchers, funding bodies

Mariasilvia Giamberini

Priority 7: Explore ways to govern and manage global risks to Arctic security		
Spatial scale:	Global / pan-Arctic	
Time scale:	Now to next 10 years	
Funding requirements and potential sources:	National authorities (defense spending budgets), national research councils, private sector actors (shipping, telecommunications) 6 million USD	
Infrastructure needs and requirements:	No significant infrastructure needs beyond financing (primarily field and desk research)	
Data needs and requirements:	Synthesis, document analysis, interviews, and participant observation at security-relevant settings, use and update of existing data sets.	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Conduct updated assessment on threats and sources of risk to Arctic maritime security and safety	Convening major cross-community / pan-Arctic workshop on Arctic maritime security risks, planning and implementing a state of the art research synthesis report	Policy actors, scholars, government officials, private sector
Identify and conduct up-to-date analyses of key sources of risk that require immediate attention (subsea infrastructure/ interconnectivity, great power rivalry, climate change as a threat multiplier/changing patterns of military activity, governance of shipping and tourism). This action will ensure that Indigenous perspectives on security--including food, environmental, cultural, and community security--are explicitly included	Commission studies of these sources of risk, also considering their interplay, Long-term historical reflections and qualitative/quantitative measures of change in these fields.	Research community
Identify pathways for action - scenario and policy option development	Large scale, transdisciplinary scenario work on risks to Arctic safety and stability primarily originating from outside the region and identification of policy options that can mitigate such risks (in multiple scenarios)	Policy actors, Indigenous leaders/diplomats, scholars, government officials, private sector
Develop a synthesis of scenarios and research	Update the baseline assessment on global risks to Arctic security and safety. Use the scenarios to identify a suite of policy options that can mitigate risk across multiple scenarios (including different levels of environmental change)	

Sarah Evans

4.2. Implementation of the Cross-Cutting Priorities

Priority 1: Improve understanding of Arctic freshwater and global ocean circulation.		
Spatial scale:	Pan-Arctic and global	
Time scale:	Next 10 years	
Funding requirements and potential sources:	National and international funding agencies	
Infrastructure needs and requirements:	Meteorological and hydrological observational network in the Arctic terrestrial system; mooring, buoy, and ship based ocean hydrographic observations; and satellite remote sensing; Earth system models with a high-resolution representation of Arctic atmospheric, hydrological, and oceanic processes	
Data needs and requirements:	High-resolution meteorological, hydrological, and ocean hydrographic observations, especially in the ungauged watershed areas and Greenland Ice Sheet runoff, as well as upper ocean mixing	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
An international-level project to coordinate observations and modeling experiments on the budgets, pathways, and oceanic impacts of Arctic freshwater.	Establish a working group to lead the project and organize project workshops; update and assess the observational network in the Arctic watersheds; identify observational gaps, especially in undermeasured areas; coordinate international organizations and national agencies to enhance observations and fill observational gaps in the atmosphere, land, and ocean; coordinate ocean or Earth system modeling experiments to investigate and evaluate the impacts of freshwater on ocean properties and dynamics.	WMO, IASC, CliC, national meteorological and hydrological operational agencies, and scientific communities.

Priority 2: Evaluate impacts of Arctic atmospheric circulation.		
Spatial scale:	Regional, pan-Arctic, and global	
Time scale:	Next 10 years	
Funding requirements and potential sources:	National funding agencies	
Infrastructure needs and requirements:	Spatially and temporally well covered observational network from the upper ocean to the stratosphere.	
Data needs and requirements:	Vertical profiles of the atmosphere and upper ocean and interface energy fluxes between air, ice, and sea are needed. Year-round observations are required to capture a complete seasonal cycle.	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Evaluate leading modes and key systems of multiscale atmospheric circulation and their changes under global warming forcing; Assess and explore mechanisms of corresponding changes or anomalies of sea ice, ocean, and land surface properties under different phases of atmospheric circulation leading modes or associated with different circulation systems.	Coordinate pan-Arctic vertical profile observations in the atmosphere from the surface to the stratosphere to capture atmospheric circulation dynamic processes; Coordinate pan-Arctic observations of surface energy fluxes between atmosphere and sea ice/ocean/land and vertical profiles of the upper ocean; Coordinate Earth system modeling experiments to investigate the responses and associated processes of sea ice, ocean, and land under atmospheric circulation forcing.	CLIVAR, IASC, and climate research community

Priority 3: Enhance understanding of Arctic wildfire effects on global atmosphere.	
Spatial scale:	Local and global
Time scale:	Now to next 10 years
Funding requirements and potential sources:	NASA, ESA, EPA, Health Canada, Nordic environmental agencies
Infrastructure needs and requirements:	Observational network of satellites and ground-based monitoring stations to measure aerosols and air quality
Data needs and requirements:	Coordination between data and knowledge systems for researchers, government agencies, and stakeholders to access existing datasets related to smoke, aerosols, and dust. High-resolution observational datasets, standardized formats, and robust metadata to ensure accurate aggregating, coupling, and scaling. Transparent version control, sustained data infrastructure, and clear governance on sensitive Arctic data support reproducibility and ethical use.
Implementation: **Implementation Actions:**	**Who to address the actions**
Launch dedicated Arctic wildfire monitoring satellite constellation with aerosol and emissions tracking capability	**Lead:** NASA, ESA, with private sector partnerships **Funding:** $150M international collaborative investment **Partners:** Wildfire management agencies, atmospheric research institutions
Establish transboundary wildfire impact monitoring network tracking air quality and health effects	**Lead:** EPA, Health Canada, Nordic environmental agencies **Funding:** $20M through international health cooperation agreements **Partners:** Indigenous health organizations, Arctic medical centers

Priority 4: Enhance understanding of vegetation changes and carbon-fire interactions.	
Spatial scale:	Local and regional
Time scale:	10 years
Funding requirements and potential sources:	NASA, ESA, Canadian Space Agency
Infrastructure needs and requirements:	Satellite network to collect data on vegetation coverage; ground-based monitoring network for measurement of wildfire-vegetation-carbon interactions
Data needs and requirements:	Coordination between data and knowledge systems for researchers, government agencies, and stakeholders to access existing datasets related to wildfire and vegetation dynamics. High-resolution observational datasets, standardized formats, and robust metadata to ensure accurate aggregating, coupling, and scaling. Transparent version control, sustained data infrastructure, and clear governance on sensitive Arctic data support reproducibility and ethical use.
Implementation: **Implementation Actions:**	**Who to address the actions**
Launch pan-Arctic vegetation monitoring satellite mission with annual coverage capability	**Lead:** NASA, ESA, Canadian Space Agency **Funding:** $200M joint international investment **Partners:** Nordic satellite agencies, private sector technology providers
Establish integrated wildfire-vegetation-carbon monitoring networks at 25 key locations and key representative sites	**Lead:** U.S. Forest Service, Natural Resources Canada **Funding:** $12M annually through wildfire management programs **Partners:** Indigenous fire management practitioners, academic institutions
Develop predictive models linking shrubification to wildfire risk with community-relevant scales	**Lead:** Academic consortiums, Indigenous research organizations **Funding:** $6M through NSF and international collaborative funding **Partners:** Local fire management authorities, subsistence communities

Priority 5: Identify pathways for improving Arctic governance and security across all scales (connecting local, national, regional, global change and cross-scale solutions) and seek justice/inclusivity in research and policy processes.		
Spatial scale:	Local to global	
Time scale:	Next 10 years, emphasis on years 7-10 as this task builds upon foundational research supported in this RPT and, especially, RPTs 3 and 4.	
Funding requirements and potential sources:	See implementation plans for RPT priority 6 and priority 7 above for foundational research needs seen from the perspective of RPT1, and other RPTs for funding requirements for foundational research relating to Arctic governance. These funds would need to be supplemented by funding for workshops, travel and salary/honorarium for knowledge-holders to participate in transdisciplinary/co-production activities. Minimum 1.5 million USD.	
Infrastructure needs and requirements:	This proposed cross-cutting priority would be focused on integration of findings across research initiated within all RPTs relating to governance, particularly in cooperation with RPTs 3 and 4. As such there are no novel data needs.	
Data needs and requirements:	High-resolution meteorological, hydrological, and ocean hydrographic observations, especially in the ungauged watershed areas and Greenland Ice Sheet runoff, as well as upper ocean mixing	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Series of inclusive/relatively large-scale workshops to identify interlinkages between global, regional, national and local governance challenges and mechanisms.	Multi-year process of scoping, synthesis and recommendations. Synthesis and recommendations may be usefully supported by some limited scenario/foresight exercises.	Researchers, policy actors (states, Indigenous leaders/organizations, private sector, NGOs)

Priority 6: Conduct interdisciplinarity and cross-cutting topics of different RPTs and foster interdisciplinary conversation across RPTs.		
Spatial scale:	Pan-Arctic, global	
Time scale:	Next 10 years	
Funding requirements and potential sources:	National funding agencies, EU, IASC, CliC	
Infrastructure needs and requirements:	Online communication and information sharing platform, in-person meeting rooms for organizing workshops	
Data needs and requirements:	Update of research progresses on the identified priorities in each RPT focus area.	
Implementation: **Implementation Actions:**	**How to implement the actions:**	**Who to address the actions:**
Organize online discussions meetings regularly or as needed to communicate and share information of research progress of the priorities identified in each RPTs; Organize an in-person workshop annually at ASSW to summarize the research progress on the identified priorities, identify existing challenges and problems, and provide recommendations for the follow-up research.	Create an interdisciplinary working group based on the RPTs to plan and lead the online meetings and in-person workshops	IASC

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5. Recommendations on how to track the Implementation of the ICARP IV Outcomes over the next decade?

Implementation Action	How to track?	Who to track?	How to include in the IPY-5 planning?
Improve attribution studies of Arctic climate change via integration of multi-disciplinary approaches	Track through peer-reviewed publications; Annual reporting at ASSW; Comprehensive review at ASSW 2030 joint IASC-SCAR Conference	IASC Secretariat; National ICARP IV Implementation Coordinators; WCRP Climate and Cryosphere (CliC) project	Establish IPY attribution science cluster incorporating paleoclimate, observations, and modeling; Require attribution framework in IPY project proposals
Improve observational capacity and sustain coordinated monitoring across cryosphere, ocean and atmosphere	Monitor deployment of new observational infrastructure; Track data availability and accessibility through international repositories; Assess winter season and vertical profile data coverage improvements biannually at ASSW	WMO Global Cryosphere Watch; NOAA, Environment Canada, Nordic meteorological services; Indigenous Peoples' Coordination Group	Designate as core IPY infrastructure priority; Establish IPY monitoring network building on ICARP IV deployments; Coordinate bipolar observation systems
Conduct coordinated model intercomparisons and develop advanced process parameterizations	Track participation in coordinated model intercomparison projects (MIPs); Monitor publications on new parameterizations; Assess improvement in model skill scores at ASSW sessions	WCRP Coupled Model Intercomparison Project (CMIP); National modeling centers; IASC modeling working groups	Establish IPY modeling grand challenge building on ICARP IV model improvements; Require CMIP participation for IPY modeling projects
Improve understanding of interactions between ice sheets and ocean circulation	Monitor ice sheet mass balance observations; Track seawater oxygen isotope measurement network expansion; Assess ice sheet-ocean coupled model development through publications and ASSW presentations	International Ice Sheet Mass Balance Committee; IASC Cryosphere Working Group; SCAR ice sheet initiatives	Create joint Arctic-Antarctic IPY ice sheet-ocean interaction research cluster; Coordinate bipolar isotope monitoring networks
Improve understanding of Arctic processes underpinning radiative and momentum flux exchanges	Track development and deployment of regional km-scale coupled Arctic models; Monitor flux measurement network expansion; Assess publications on atmosphere-ocean-ice-land coupling	National weather and climate modeling centers; University Arctic modeling consortia; IARPC Collaboration Teams	Establish IPY process understanding cluster focused on coupled system interactions; Require km-scale modeling capacity for IPY prediction projects
Detect impacts of permafrost thawing on biogeochemical transformations	Monitor permafrost monitoring network expansion to 50+ sites; Track methane and carbon flux measurements; Assess thermokarst and biogeochemical publications; Review infrastructure early warning system deployment	NOAA, USGS, Roshydromet; International Permafrost Association; Indigenous community monitoring networks	Create IPY permafrost-carbon cluster with bipolar permafrost comparison; Establish IPY carbon flux measurement standards building on ICARP IV protocols
Connect Arctic and global governance processes	Track Arctic stakeholder engagement in global governance forums (UNFCCC, CBD, UNCLOS processes); Monitor Indigenous Peoples' organizations participation in global settings; Assess policy-relevant publications and briefs	Arctic Council; Indigenous Peoples' organizations (ICC, Saami Council); IASC-IPY governance working group	Establish IPY governance and diplomacy cluster; Require policy engagement pathways in IPY project proposals; Create IPY policy-science interface mechanisms

Implementation Action	How to track?	Who to track?	How to include in the IPY-5 planning?
Cross-cutting: Arctic freshwater and global ocean circulation	Monitor freshwater flux measurement systems across Arctic rivers; Track Arctic Ocean freshwater content observations; Assess global ocean model incorporation of Arctic freshwater processes	NOAA, Fisheries and Oceans Canada; International Arctic Ocean observing systems; IASC Marine Working Group	Create IPY bipolar freshwater-ocean circulation cluster; Coordinate Arctic-Antarctic freshwater monitoring; Establish IPY sea level contribution tracking
Cross-cutting: Arctic atmospheric circulation impacts	Track atmospheric monitoring network deployment; Monitor moisture transport and aerosol measurements; Assess teleconnection research publications; Review Arctic-midlatitude linkage modeling improvements	WMO; NOAA, Environment Canada; European atmospheric research networks; WCRP atmospheric circulation working groups	Establish IPY atmosphere-climate teleconnection cluster; Require bipolar atmospheric circulation research; Create IPY extreme weather attribution framework
Cross-cutting: Arctic wildfire global atmospheric effects	Monitor Arctic wildfire satellite constellation deployment; Track fire emission inventories and real-time monitoring capabilities; Assess wildfire-aerosol-climate publications; Review transboundary air quality monitoring	NASA, ESA; National wildfire agencies; Arctic air quality monitoring networks; Indigenous fire management organizations	Create IPY wildfire-climate cluster; Establish IPY fire emission monitoring standards; Coordinate bipolar fire regime change research; Integrate Indigenous fire knowledge

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References

Adasheva E., Burson A., Dayal A., Detlef H., Singh N., Soleymani A., Walch D., Wells G. (2023) 'Input to the ICARP IV process collaboratively developed by the IASC Fellows' Ongoing X-change (IASC FOX) network.' *all contributed equally

Biskaborn, B.K., Smith, S.L., Noetzli, J. *et al.* Permafrost is warming at a global scale. *Nat Commun* **10**, 264 (2019). https://doi.org/10.1038/s41467-018-08240-4

Bodas-Salcedo, A., K. D. Williams, P. R. Field, and A. P. Lock, 2012: The surface downwelling solar radiation surplus over the Southern Ocean in the Met Office model: The role of midlatitude cyclone clouds. *J. Climate*, 25, 7467–7486, https://doi.org/10.1175/JCLI-D-11-00702.1.

Chitty, Odessa , Justin Barnes, Elizabeth Hanlon, Jennifer Spence and Tessa Varvares. "Workshop Report: The Governance of Arctic Climate Interventions." *Belfer Center for Science and International Affairs*, August 11, 2025. https://www.belfercenter.org/sites/default/files/2025-07/Chitty%20et%20al_Climate%20Intervention%20Workshop%20Report_20250731.pdf

Chylek, P., Folland, C., Klett, J. D., Wang, M., Hengartner, N., Lesins, G., & Dubey, M. K. (2022). Annual Mean Arctic Amplification 1970–2020: Observed and Simulated by CMIP6 Climate Models. Geophysical Research Letters, 49(13), e2022GL099371. https://doi.org/10.1029/2022GL099371.

Dahl, J. et al. (2024). Empowering Arctic Indigenous Peoples Celebrating 50 Years of Indigenous Diplomacy. IWGIA, ICC, Saami Council. https://www.iwgia.org/en/resources/publications/5547-empowering_arctic_indigenous_peoples_50_years_diplomacy.html.

Dörr, J., Årthun, M., Eldevik, T. and Sandø, A.B., 2024. Expanding influence of Atlantic and Pacific Ocean heat transport on winter sea-ice variability in a warming Arctic. Journal of Geophysical Research: Oceans, 129(2), p.e2023JC019900. https://doi.org/10.1029/2023JC019900.

Hoogensen G. et al., eds. (2020). Routledge Handbook of Arctic Security. London ; New York: Routledge/Taylor & Francis Group.

Fiddes, S. L., A. Protat, M. D. Mallet, S. P. Alexander, and M. T. Woodhouse, 2022: Southern Ocean cloud and shortwave radiation biases in a nudged climate model simulation: does the model ever get it right? *Atmos. Chem. Phys.*, 22, 14603–14630, https://doi.org/10.5194/acp-22-14603-2022.

Fong, AA and Coauthors, RR. 2024. Overview of the MOSAiC expedition: Ecosystem. Elementa: Science of the Anthropocene 12(1). DOI:10.1525/elementa.2023.00135.

Friis, K. et al. (2023). Navigating Breakup: Security Realities of Freezing Politics and Thawing Landscapes in the Arctic. Norwegian Institute of International Affairs and Wilson Center. https://www.nupi.no/en/publications/cristin-pub/navigating-breakup-security-realities-of-freezing-politics-and-thawing-landscapes-in-the-arctic.

Gong, X., and Coauthors, 2023: Arctic warming by abundant fine sea salt aerosols from blowing snow. *Nat. Geosci.*, 16, 768-774, https://doi.org/10.1038/s41561-023-01254-8.

Granskog, MA, Fer, I, Rinke, A, Steen, H. 2018. Atmosphere-ice-ocean-ecosystem processes in a thinner Arctic sea ice regime: The Norwegian young sea ICE (N-ICE2015) expedition. Journal of Geophysical Research: Oceans 123(3): 1586–1594. http://dx.doi.org/10.1002/2017JC013328.

Gryba, R., Von Duyke, A., Huntington, H.P., Adams, B., Frantz, B., Gatten, J., Harcharek, Q., Sarren, R., Henry, G. and Auger-Méthé, M., 2025. Indigenous Knowledge as a sole data source in habitat selection functions. Proceedings of the National Academy of Sciences, 122(15), p.e2411946122. https://www.pnas.org/doi/10.1073/pnas.2411946122.

Holliday NP, Bersch M, Berx B, Chafik L, Cunningham S, Florindo-López C, Hátún H, Johns W, Josey SA, Larsen KMH, et al. 2020. Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. Nat Commun 11(1): 585. doi: 10.1038/s41467-020-14474-y

Heikkilä, Lydia, Rauna Kuokkanen, Veli-Pekka Lehtola, Päivi Magga, Sigga-Maria Magga, Janne Näkkäläjärv, Sanna Valkonen, and Pirjo Kristiina Virtanen. 2024. *Ethical Guidelines for Research Involving the Sámi People in Finland*. https://oulurepo.oulu.fi/bitstream/handle/10024/50

Heatta, M.J., Hausner, V.H. & Utsi, T.A. The use of multiple evidence base methods to enrich climate change research and knowledge in the Arctic. *Ambio* 54, 603–617 (2025). https://doi.org/10.1007/s13280-024-02093-6115/nbnfioulu-202405294076.pdf?sequence=1&isAllowed=y.

Inuit Circumpolar Council. 2022. *Circumpolar Inuit Protocols for Equitable and Ethical Engagement.* Inuit Circumpolar Council.

Jacobsen, Marc, and Elana Wilson Rowe, editors. 2026. *Research Agenda for Arctic Security and Governance*.Edward Elgar Publishing.

Kim, H., Timmermann, A., 2024. Seawater oxygen isotopes as a tool for monitoring future meltwater from the Antarctic ice-sheet. Commun Earth Environ 5, 343. https://doi.org/10.1038/s43247-024-01514-4

Kremser, S., and Coauthors, 2021: Southern Ocean cloud and aerosol data: a compilation of measurements from the 2018 Southern Ocean Ross Sea Marine Ecosystems and Environment voyage. *Earth Syst. Sci. Data*, 13, 3115–3153, https://doi.org/10.5194/essd-13-3115-2021.

Lenssen, N. J. L. et al. Improvements in the GISTEMP uncertainty model. J. Geophys. Res. Atmos. 124, 6307–6326 (2019).

Liu, Z., C. Risi, F. Codron, G. Gastineau, X. Huan, H. Lan, W. Xu, and G. J. Bowen, 2025: Anthropogenic intensification of Arctic anticyclonic circulation. *Sci. Adv.*, 11, eads4508, https://doi.org/10.1126/sciadv.ads4508.

Ma, W., H. Wang, G. Chen, Y. Qian, I. Baxter, Y. Huo, and M. W. Seefeldt, 2024: Wintertime extreme warming events in the high Arctic: characteristics, drivers, trends, and the role of atmospheric rivers. *Atmos. Chem. Phys.*, 24, 4451–4472, https://doi.org/10.5194/acp-24-4451-2024.

Ma, Z. et al. Newly reconstructed Arctic surface air temperatures for 1979-2021 with deep learning method. Sci. Data. 10, (2023).

Mekonnen, Z. A., Riley, W. J., Berner, L. T., Bouskill, N. J., Torn, M. S., Iwahana, G., ... & Grant, R. F. (2021). Arctic tundra shrubification: a review of mechanisms and impacts on ecosystem carbon balance. Environmental Research Letters, 16(5), https://doi.org/10.1088/1748-9326/abf28b.

Morice, C. P. et al. An updated assessment of Near-Surface temperature change from 1850: the HadCRUT5 data set. J. Geophys. Res. Atmos. 126, (2021).

Nicolaus, M, Perovich, DK, et al. 2022. Overview of the MOSAiC expedition: Snow and sea ice. Elementa: Science of the Anthropocene 10(1). https://doi.org/10.1525/elementa.2021.000046.

Notz, D., and Coauthors, 2020: Arctic sea ice in CMIP6. *Geophys. Res. Lett.*, 47, e2019GL086749, https://doi.org/10.1029/2019GL086749.

Peterson, B. J. et al. Increasing river discharge to the Arctic Ocean. Science 298, 2171–2173 (2002)

Rabe, B, Heuze , C, Regnery, J, et al.. 2022. Overview of the MOSAiC expedition: Physical oceanography. Elementa: Science of the Anthropocene, 10(1). https://doi.org/10.1525/elementa.2021.00062.

Rackow, T., Goessling, H.F., Jung, T., Sidorenko, D., Semmler, T., Barbi, D. and Handorf, D., 2016. Towards multi-resolution global climate modeling with ECHAM6-FESOM. Part II: climate variability. Climate Dynamics, pp.1-26.

Rantanen, M., A. Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen, 2022: The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.*, 3, 168, https://doi.org/10.1038/s43247-022-00498-3.

Rasouli, K. (2017). Sensitivity analysis of mountain hydrology to changing climate (Doctoral dissertation, University of Saskatchewan), Saskatoon, Canada

Rasouli, K., Pomeroy, J. W., Janowicz, J. R., Carey, S. K., & Williams, T. J. (2014). Hydrological sensitivity of a northern mountain basin to climate change. *Hydrological Processes*, 28(14), 4191-4208. https://doi.org/10.1002/hyp.10244.

Rasouli, K., Pomeroy, J. W., & Whitfield, P. H. (2019). Are the effects of vegetation and soil changes as important as climate change impacts on hydrological processes?. *Hydrology and Earth System Sciences*, 23(12), 4933-4954. https://doi.org/10.5194/hess-23-4933-2019.

Rasouli, K., Nasri, B. R., Soleymani, A., Mahmood, T. H., Hori, M., & Haghighi, A. T. (2020). Forecast of streamflows to the Arctic Ocean by a Bayesian neural network model with snowcover and climate inputs. *Hydrology Research*, 51(3), 541-561. https://doi.org/10.2166/nh.2020.164.

Rawlins M Aet al 2009 Diagnosis of the record discharge of Arctic-draining Eurasian rivers in 2007. Environ. Res. Lett. 4 045011

Rohde, R. A. & Hausfather, Z. The berkeley earth Land/Ocean temperature record. Earth Syst. Sci. Data 12, 3469–3479 (2020).

Sardana, D., S. Kulkarni, and A. Agarwal, 2025: Evaluation and Projection of Arctic sea ice concentration under various emission scenarios using CMIP6 models. *Climate Dyn.*, **63**, 172, https://doi.org/10.1007/s00382-025-07646-3.

Serreze, M. C., Barrett, A. P., Stroeve, J. C., Kindig, D. N., and Holland, M. M.: The emergence of surface-based Arctic amplification, The Cryosphere, 3, 11–19, https://doi.org/10.5194/tc-3-11-2009, 2009.

Shu, Q., Wang, Q., Årthun, M., Wang, S., Song, Z., Zhang, M., & Qiao, F. (2022). Arctic Ocean Amplification in a warming climate in CMIP6 models. Science advances, 8(30), eabn9755

Shupe, M.D., and Coauthors, 2022: Overview of the MOSAiC expedition: Atmosphere. *Elem. Sci. Anth.,* 10, 00060, https://doi.org/10.1525/elementa.2021.00060.

Shupe, MD, Rex, M, et al. 2022. Overview of the MOSAiC expedition—Atmosphere. Elementa: Science of the Anthropocene 10(1). https://doi.org/10.1525/elementa.2021.00060.

Sidorenko, D., Rackow, T., Jung, T., Semmler, T., Barbi ,D., Danilov, S., Dethloff ,K., Dorn, W., Fieg, K., Goessling, H. F., Handorf, D., Harig, S., Hiller, W., Juricke, S., Losch, M., Schröter, J., Sein, D. V., Wang, Q. 2015. Towards multi-resolution global climate modeling with ECHAM6–FESOM. Part I: model formulation and mean climate. Climate Dynamics, 44(3-4), pp.757-780.

Solomon, A., Heuzé, C., Rabe, B., Bacon, S., Bertino, L., Heimbach, P., Inoue, J., Iovino, D., Mottram, R., Zhang, X., Aksenov, Y., McAdam, R., Nguyen, A., Raj, R. P., and Tang, H.: Freshwater in the Arctic Ocean 2010–2019, Ocean Sci., 17, 1081–1102, https://doi.org/10.5194/os-17-1081-2021, 2021.

Siegert, Martin, Heïdi Sevestre, Michael J. Bentley, et al. 2025. “Safeguarding the Polar Regions from Dangerous Geoengineering: A Critical Assessment of Proposed Concepts and Future Prospects.” *Frontiers in Science* 3 (September): 1527393. https://doi.org/10.3389/fsci.2025.1527393.

Swain, B., Vountas, M., Singh, A., Anchan, N.L., Malasani, C.R., Mallick, D., Deroubaix, A., Lelli, L., Patel, N., Alawode, R. and Gunthe, S.S., 2025. Insights of aerosol-precipitation nexus in the central Arctic through CMIP6 climate models. npj Climate and Atmospheric Science, 8(1), p.103. https://doi.org/10.1038/s41612-025-00957-6.

Sweeney, A. J., Fu, Q., Po-Chedley, S., Wang, H., & Wang, M. (2023). Internal Variability Increased Arctic Amplification During 1980–2022. Geophysical Research Letters, 50(24), e2023GL106060. https://doi.org/10.1029/2023GL106060.

Tan, I., and T. Storelvmo, 2019: Evidence of strong contributions from mixed-phase clouds to Arctic climate change. *Geophys. Res. Lett.*, 46, 2894–2902, https://doi.org/10.1029/2018GL081871.

Turner, J., and Coauthors, 2009: *Antarctic climate change and the environment*. Scientific Committee on Antarctic Research, Scott Polar Research Institute, UK, 526 pp.

Valkonen, E., Cassano, J., Cassano, E., Seefeldt, M., & Parker, C. (2025). CMIP6 representation of declining sea ice and Arctic cyclones in the current climate. *Journal of Geophysical Research: Atmospheres*, 130, e2024JD042388. https://doi.org/10.1029/2024JD042388

Vaughan, D. G., and Coauthors, 2003: Recent rapid regional climate warming on the Antarctic peninsula. *Climatic Change*, 60, 243–274, https://doi.org/10.1023/A:1026021217991.

Vignesh, P. P., J. H. Jiang, P. Kishore, H. Su, T. Smay, N. Brighton, and I. Velicogna, 2020: Assessment of CMIP6 cloud fraction and comparison with satellite observations. *Earth Space Sci.*, **7**, e2019EA000975, https://doi.org/10.1029/2019EA000975.

Vose, R. S. et al. Implementing full spatial coverage in NOAA’s global temperature analysis. Geophys. Res. Lett. 48, (2021).

Wei, J., Z. Wang, M. Gu, J.-J. Luo, and Y. Wang, 2021: An evaluation of the Arctic clouds and surface radiative fluxes in CMIP6 models. *Acta Oceanol. Sin.*, 40, 85–102, https://doi.org/10.1007/s13131-021-1705-6.

Woon, C. et al., eds. (2020). “Observing” the Arctic: Asia in the Arctic Council and Beyond. Northampton: Edward Elgar Publishing.

Yang, J., Dou, T., Han, W., Du, Z., Li, S., & Xiao, C. (2025). Intensified warm and moist Arctic coast in summer due to future sea ice retreat. Geophysical Research Letters, 52, e2025GL118052. https://doi.org/10.1029/2025GL118052

Yang, X., Zhang, X. et al., Polar winter climate: an under-represented research focus within the coupled Earth system. To be submitted to BAMS.

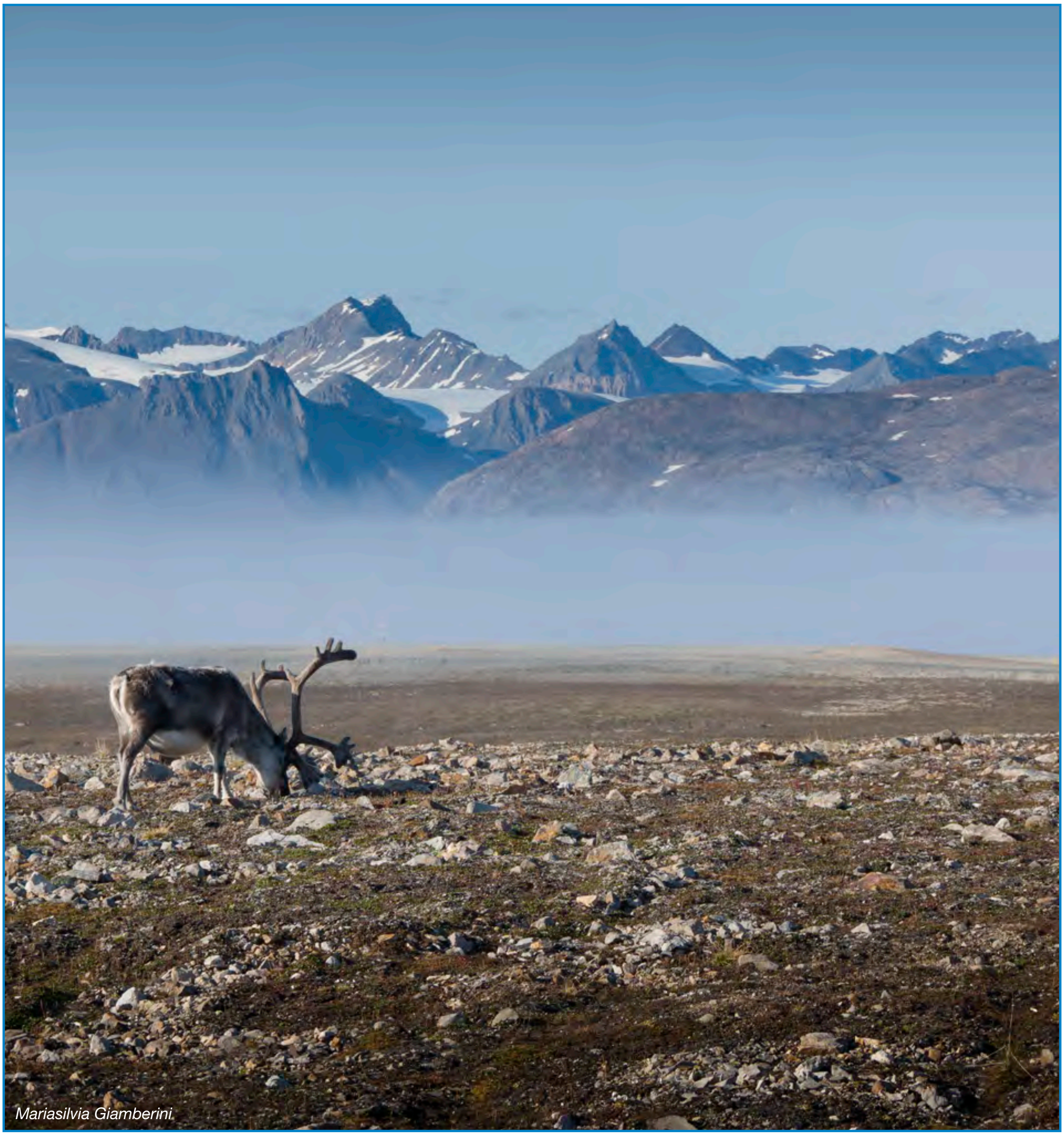
Yang, X., and Coauthors, 2019: Sea salt aerosol production via sublimating wind-blown saline snow particles over sea ice: parameterizations and relevant microphysical mechanisms. *Atmos. Chem. Phys.*, 19, 8407–8424, https://doi.org/10.5194/acp-19-8407-2019.

Yoshimori, M., T. Kawasaki, A. Abe-Ouchi, and H. Hasumi (2025): Arctic amplification in the past, present, and future: A review for the challenge to the integrative understanding of its mechanism. *J. Meteor. Soc. Japan*, 103, 523-558. https://doi.org/10.2151/jmsj.2025-027

Zhang, J., Weijer, W., Steele, M., Cheng, W., Verma, T., & Veneziani, M. (2021). Labrador Sea freshening linked to Beaufort Gyre freshwater release. *Nature Communications*, 12(1), 1229. https://doi.org/10.1038/s41467-021-21470-3.

Zhang, X., et al., 2025: Weather and climate extremes in a changing Arctic. Nature Reviews Earth & Environment, 6, 691-711. https://doi.org/10.1038/s43017-025-00724-4

Zhang, X., Sorteberg, A., Zhang, J., Gerdes, R. & Comiso, J. C. Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system. Geophys. Res. Lett. 35, (2008).



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Appendix: About RPT 1

1.1. Approaches / Methods used to complete the RPT 1 tasks

The topic of the RPT 1 covers the entire, interactive natural components of the Arctic Earth system in the context of the global system, and the impacts of their variability and changes on socioeconomic securities and policy decision-making. Considering the broad coverage and the complex nature of this topic, we employed a grouping and integrating approach among the team to complete the RPT 1 tasks. We began with identifying the most challenging scientific questions and problems in the key Arctic system components and their interactions with the global system based on the state-of-knowledge and new findings from recently completed/ongoing major research projects worldwide. Following the identified grand challenges and through comprehensive discussions, we grouped the team into five themes, as described in Chapter 2, to conduct further in-depth analysis, respectively, using both qualitative and quantitative methods.

We then followed the logics in the flow chart as shown in Figure 3 to work on the final report. We carefully conducted detailed literature reviews for each thematic area. The key review results were presented by invited team members and followed by thorough examinations and discussions during our team's kick-off workshop during the 2024 ASSW and the business meeting during the 2025 ASSW/ICARP IV Summit, along with our regular monthly meetings online. Through the examination and discussions, we refined which research findings are solid, where uncertainties exist, and what are the continually existing challenges. During this process, we have also incorporated input through engaging the broad communities through the 2025 ASSW/ICARP IV town hall and open science sessions, and the open call for comments on the ICARP IV website. Finally, we integrated and synthesized the analysis results to identify urgent needs and priorities and provided corresponding recommendations for implementation plans.

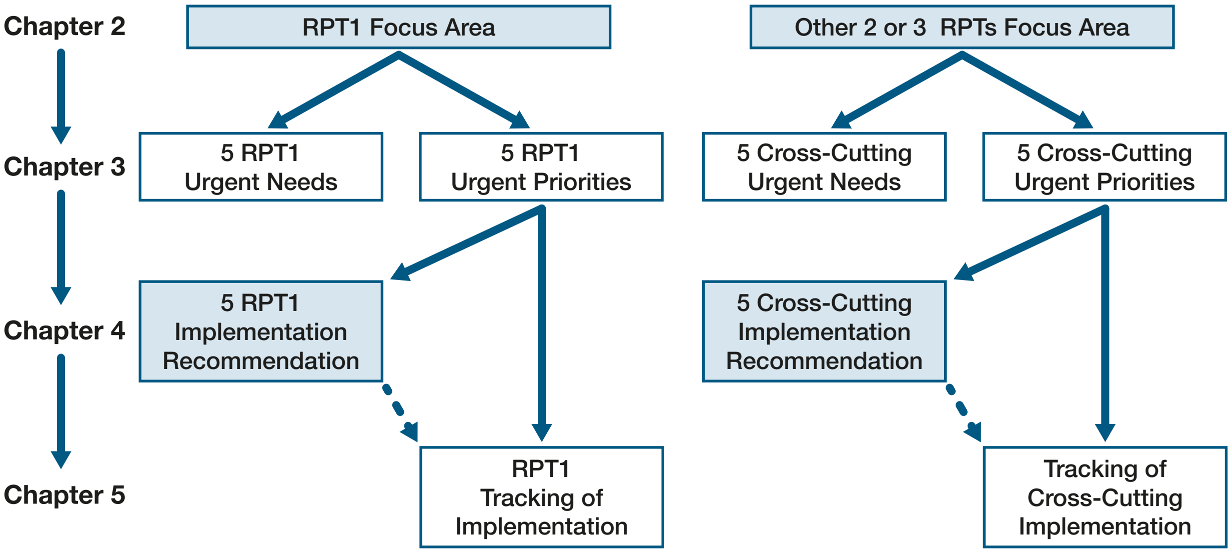

Figure 3. Flow chart for preparing Chapter 2-5.

1.2. Overlaps and Synergies with other RPTs

The topic in RPT 1 provides baseline information about variability, evolution, and changes of the Arctic nature system in the context of interactions with the global system, serving as a foundation for other RPTs. Specific synergies with other RPTs include the enhanced observations and high-resolution model improvement in Theme 1 in RPT 1, which can complement and lay groundwork for Arctic data reconstruction and Arctic climate projections in RPT 2. Governance and security research in Theme 5 of our RPT 1, focused on global settings, also has significant synergies with RPTs 3 and 4.

1.3. RPT 1 Membership

The RPT 1 members include internationally-renown senior scientists and promising early-career scientists from 12 countries. Their expertise and research areas covers the Arctic and global atmospheric dynamics and chemistry, meteorology, physical and biogeochemical oceanography, sea ice, physical and biogeochemical terrestrial processes, Greenland Ice Sheet, and social impacts.

Name	**Affiliation**	**Country**
Co-Chairs		
Xiangdong Zhang	North Carolina State University	United States
Kabir Rasouli	Desert Research Institute	United States
Secretaries		
Armina Soleymani	University of Waterloo	Canada
Greta Wells	University of Iceland	Iceland
Theme Co-Leads		
Steve Arnold *Theme 1*	University of Leeds	United Kingdom
Priscilla Mooney *Theme 1*	NORCE, Bjerknes Centre for Climate Research	Norway
Marianne Tronstad Lund *Theme 2*	CICERO Center for International Climate Research	Norway
Hans Linderholm *Theme 3*	University of Gothenburg	Sweden
Masakazu Yoshimori *Theme 3*	Atmosphere and Ocean Research Institute, The University of Tokyo	Japan
Hotaek Park *Theme 4*	Japan Agency for Marine-Earth Science and Technology	Japan
Céline Rodrigues *Theme 5*	Nova University of Lisbon, FCSH, IPRI-NOVA, Portugal	Portugal
Elana Wilson Rowe *Theme 5*	Norwegian University of the Life Sciences	Norway
Members		
Marius Årthusn	University of Bergen & Bjerknes Centre for Climate Research	Norway
Ed Blockley	Met Office	United Kingdom
Archana Dayal	University of North Texas	United States
Markus Frey	UKRI - British Antarctic Survey	United Kingdom
Stefania Gilardoni	Institute of Polar Sciences - National Research Council	Italy
Mats Granskog	Norwegian Polar Institute	Norway
Maret Hætta	Saami Council	Norway
Joo-Hong Kim	Korean Polar Research Institute	Republic of Korea

Name	Affiliation	Country
Members *continued*		
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Will Kochtitzky	University of New England	United States
Malte Müller	Norwegian Meteorological Institute and University of Oslo	Norway
Giovanni Muscari	Istituto Nazionale di Geofisica e Vulcanologia	Italy
Erika Roesler	Sandia National Laboratories	United States
Margit Hildegard Simon	Norwegian Research Centre	Norway
Tommaso Tesi	Institute of Polar Sciences - CNR	Italy
Michael Tjernström	Swedish Polar Research Secretariat	Sweden
Claire Waelbroeck	LOCEAN (Sorbonne Université, CNRS, IRD, MNHN)	France
Yutian Wu	LDEO/Columbia University	United States
Xin Yang	UKRI - British Antarctic Survey	United Kingdom

Wenkai Guo

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INTERNATIONAL CONFERENCE ON
ARCTIC RESEARCH PLANNING

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