ICARP IV Research Priority Team (RPT) 2

Final Report

Observing, Reconstructing, and Predicting Future Climate Dynamics and Ecosystem Responses

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1. Executive Summary

Our Research Priority Team (RPT) report describes key knowledge gaps and research priorities in Arctic observing for the period 2025-35, including recommendations for implementing our identified research priorities. We hope that it will be a guide for policymakers, funding agencies and scientists. However, a resource for such a diverse group of users is necessarily broad. Similarly, in order to make our recommendations durable for the next ten years, some more specific research gaps are not featured here. This does not deny their relevance.

Discipline Specific Research Needs (these are not in order of priority)

1. Increase data collection in the central Arctic Ocean and develop better understanding of climate linkages with the surrounding seas
2. Enhance understanding of environmental disturbances and ecosystem stability under climate warming at different scales
3. Develop more comprehensive understanding of interactions at the interfaces between different environmental spheres
4. Advance research on the impact of changes in the Arctic atmosphere's energy budget and precipitation patterns
5. Couple models and observations of atmospheric circulation patterns over different spatial scales

Discipline Specific Research Priorities

1. Co-develop integrated monitoring and management frameworks with Arctic Indigenous Peoples
2. Research Arctic Ocean circulation regulation and its interactions with marine biogeochemical cycles and ecosystem functioning, using contemporary observation data and long-term reconstructions
3. Comprehensively monitor and model Arctic disturbances and ecosystem stability under global change
4. Enhance integrated cryosphere/atmosphere monitoring and modeling
5. Investigate interactive processes at the interface between spheres

Cross-Cutting Research Needs

1. Elevate Indigenous Leadership in Arctic research
2. Increase and improve data collection across the Arctic, with a focus on filling gaps with regard to geography, time, and subject matter. Continue to strive to make data FAIR (Findable, Accessible, Interoperable and Reusable)
3. Improve modeling capabilities for hindcasting and future projections of ecosystem responses
4. Integrate diverse knowledge systems and research techniques

Cross-Cutting Research Priorities

1. Strengthen Indigenous-led governance and decision-making in Arctic research
2. Foster partnerships between scientists and Indigenous Peoples and their communities
3. Fund long-term data collection programs and emphasize cross-boundary data sharing
4. Improve modeling capabilities for: Arctic terrestrial ecosystems, and carbon source/sink assessments in inland water ecosystems, marine ecosystems, and for the atmosphere, to better represent cryospheric and transport processes

Common Themes for Research Priority Implementation:

1. Co-production of knowledge
2. Long-term monitoring and data collection
3. Interdisciplinary and cross-boundary collaboration
4. Enhanced computer modelling
5. Funding and infrastructure for remote sensing, ship-time, field stations and computational resources, enhanced international cooperation in capability building
6. Capacity-building and training, particularly pertaining to those that do not have a grasp of Indigenous Peoples and Indigenous Knowledge as well as Indigenous Peoples' networks

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2. Defining the Focus of RPT 2

Our Research Priority Team's (RPT) given title was "Observing, Reconstructing, and Predicting Future Climate Dynamics and Ecosystem Responses" (shortened to 'RPT 2' therein).

Approximately **40 scientists and practitioners** shared wide-ranging scientific expertise, spanning atmosphere, cryosphere, terrestrial and freshwater systems, marine science, biogeochemistry, modelling, reconstructing climate, environment and dynamics of past ecosystems, remote sensing, and methodology. We worked in sub-groups, **synthesised relevant literature,** and incorporated community input via the **central ICARP online questionnaire**. Preliminary priorities were iterated in sub-group meetings coordinated by the co-chairs and refined during a **public town hall** at the ICARP summit in **Boulder, Colorado, USA (March 2025)**.

Where overlaps with other RPTs occurred (e.g., RPT 1 on the Arctic in the global system; RPT 5 on co-production and Indigenous-led methodologies), RPT 2 incorporated these dimensions, focusing on ecosystem responses within observing–prediction pipelines, ensuring complementarity rather than duplication.

We made best efforts to include diverse Arctic voices by (i) recognizing the stakeholders for Arctic observing and including their published recommendations, (ii) reviewing all questionnaire submissions and (iii) openly debating priorities at the Boulder town hall. Nevertheless, limitations remained, including: **team composition** and **seasonal time constraints during field seasons**. Readers should view this focus as a **living, consensus-seeking synthesis**—it reflects broad input but cannot exhaust every viewpoint or sub-discipline within the scope and timeline.

The work was organized along discipline-specific lines (we will return to this in Section 6): four discipline-specific subgroups addressed the cryosphere, hydrosphere/marine, terrestrial ecosystems, and atmosphere. A subgroup was also formed to address the key issue of involving Indigenous Peoples, both in terms of contributing knowledge and engaging in activities. Finally, a subgroup was organized to address the processes linking the four domains of the climate system listed above. These groups were tasked with examining the issues in their breadth and complexity, ultimately identifying a single overarching research need and a priority. For each priority, we identified elements deemed important for its implementation over the next 10 years.


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

3.1. Needs and Priorities specific to the RPT 2 topic area

3.1.1. Research Needs (Gaps) for the RPT 2 topic area

Longer narratives including more details and context are in Appendix 2.

Research need	Description of the research need	Rationale why included in this report
1. Data gaps in the central Arctic Ocean and knowledge gaps on climate linkages along the Arctic land-shelf-basin continuum and subarctic oceans	Sustained observations and reconstruction on changes in ocean circulation, dense water production, ecosystem functioning and biogeochemical cycles along the Arctic land-shelf-basin continuum, including the central Arctic Ocean where data remain limited, related to global warming (e.g. sea ice reduction, permafrost thaw, increased fluvial input, coastal erosion).	These changes in the Arctic Ocean impact subarctic oceans, Arctic Indigenous Peoples and their communities, and other human activities (e.g. shipping and fisheries).
2. Knowledge gaps in understanding environmental disturbances and ecosystem stability under climate warming at different spatial and temporal scales.	Impacts of climate warming on ecosystems are complex. We lack understanding of how these myriad impacts, both gradual (e.g. vegetation composition change) and acute (e.g. disturbances such as wildfires), interact with each other. These interactions are important because they can establish feedback loops or tipping points, and influence how Arctic species respond and adapt to ongoing change.	Both disturbance and more gradual changes have the potential to create feedback loops that could either accelerate or mitigate the effects of climate change, which will have serious socio-ecological impacts (e.g. food security, water, and cultural practices).
3. Knowledge gaps in the interactions at the interfaces between different spheres shape Arctic climate feedback mechanisms and Arctic ecosystems responses.	The need for a holistic Arctic system approach to natural and anthropogenic stressors and interactive processes across the spheres (atmosphere, hydrosphere, cryosphere, lithosphere, biosphere, pedosphere, and anthroposphere) in order to predict tipping points in the socio-ecological system and effects of climate change.	Interactive processes (e.g., atmospheric interconnection, carbon fluxes, change in fauna migrations and populations, contaminant sources, distribution and impacts, human exploitation, invasive species, tipping points, ocean productivity) are often overlooked but can have substantial impact, and it is here put forward as an important knowledge gap covering local to global and Pan-Arctic scales.
4. Observe and understand the impact of changes in the Arctic atmosphere's energy budget and precipitation patterns, as well as transport of moisture, aerosols and trace gases, including contaminants, on ecosystems and populations.	Despite Arctic Amplification being a fundamental feature of past, present, and modelled future climate, the causes and consequences of this "amplification" are not fully understood. There is a need to better understand the relevance of local within-Arctic processes vs. external forces, as well as to deepen representation in climate regional models of the complex interconnection.	The Atmosphere largely determines the input of mass, momentum and heat to all other spheres, connecting all of them, and having large impacts to the Arctic and global environments, ecosystems, and societies.
5. Coupling models and observations of atmospheric circulation patterns over different spatial scales, from historical trends, current patterns to future predictions to better understand current state of knowledge and gaps.	Atmospheric changes affect extreme weather, sea ice behavior, and biosphere interactions, which urgently need to be understood to mitigate the adverse impacts of these changes. For the Arctic, a specific aspect is that climate change impacts sources, pathways, and the fate of some Contaminants of Emerging Arctic Concern (CEACs) to and in the Arctic.	These predictions will influence everything from weather awareness to extreme events preparedness, crucial for Arctic communities. Society urgently needs regionally relevant predictions of how changes in atmospheric dynamics impact their everyday lives.

3.1.2. Priorities for Arctic Research for the RPT 2 topic area

Longer narratives including more details and context are in Appendix 2.

Priorities for research	Reason why this should be an ICARP IV Priority
1. Co-developing integrated monitoring and management frameworks with Arctic Indigenous Peoples	Co-developing integrated monitoring and management frameworks with Arctic Indigenous Peoples ensures that Indigenous Knowledge Systems are equally valued alongside scientific methods, leading to more holistic and effective solutions to environmental challenges. This approach supports Indigenous rights, sovereignty, governance, and self-determination through equitable partnerships, while delivering actionable research related to urgent climate change impacts such as permafrost thaw, coastal erosion, access to potable drinking water and food security.
2. Enhance integrated cryosphere monitoring and modeling	The rapid pace of cryospheric change outstrips current modeling capabilities, leading to uncertainties in predicting climate dynamics and cryosphere and ecosystem responses. Enhanced monitoring is critical to capture nonlinear climate feedbacks (e.g. permafrost greenhouse gas emissions and albedo changes) and identify hazards and evaluate potential landscape change for adaptation and mitigation planning. Integrating Indigenous Knowledge adds important socio-ecological insights, such as habitat shifts and water quality impacts, often overlooked by the academic scientific community.
3. Assess present and past Arctic Ocean circulation, characterizing Arctic land-shelf-basin and Arctic-Subarctic Ocean interactions, and their relations with marine biogeochemical cycles and ecosystem functioning	Under the new scenarios of global warming with changes in the Arctic Ocean circulation, dense water production, reductions in sea ice, and export of both (fresh) water and carbon/nutrients to the Subarctic Ocean, there is a need to sustain and implement long-term observations (with shared international initiatives) in the following key areas: 1. Elucidating the impact of changes in Arctic Ocean circulation on marine biogeochemical cycles and ecosystems in the Arctic and other ocean basins is an urgent priority to further advance the studies on point 2 below. 2. Investigate the impact of permafrost thaw in the catchments of Arctic river systems on land-shelf-ocean transport of organic carbon, nutrients, and trace metals. Investigate the capacity of the Arctic Ocean to sequester atmospheric carbon (via solubility pump, biological pump, and alkalinity pump). Low oxygen and acidified water that may impact the marine ecosystem, previously observed only in coastal areas, has been discovered in the central Arctic Ocean due to the change in the Arctic Ocean circulation (e.g. Atlantification); and changes in land-shelf-basin transports of nutrients, organic carbon, and trace metals could influence the nature, time evolution, abundance, distribution, and qualities of phytoplankton, ice algae, and macroalgae. Moreover, currently we do not know what (micro-)nutrient will limit summer primary productivity in the future ice-free Arctic Ocean, leading to large uncertainties about future productivity and biological carbon uptake, in addition to uncertainty about other carbon uptake pathways. 3. Reconstruction from the central Arctic Ocean (and circum Arctic terrestrial locations) to inform expected future changes. 4. Better detect changes in biodiversity and ecosystem functioning, as well as an improved knowledge of ecological patterns and processes are key to supporting environmental management and conservation.
4. Understanding the effects of Arctic ecological disturbance and ecosystem stability under climate change	Research priorities for Arctic ecosystems should focus on comprehensive, long-term monitoring of ecological disturbances (including paleoenvironmental and paleoecological reconstructions). Identifying potential ecological tipping points is crucial for predicting and potentially mitigating irreversible ecosystem and carbon transformations. Experimental, observational, and paleoecological studies should investigate the collective influence of factors (e.g. climate, disturbance, herbivory, belowground processes, and species interactions) on Arctic ecosystem dynamics. Furthermore, research efforts should examine how individual species in the Arctic respond and potentially adapt to changing environmental conditions, including phenological shifts, range expansions or contractions, and physiological adaptations. Studies should also explore the impact of global change (e.g., climate change, pollution, species invasions) and disturbances on biogeochemical cycling, and Arctic biodiversity and functioning. Lastly, research should prioritize identifying factors that contribute to ecosystem resilience and stability in the face of rapid climate change.
5. Identifying and understanding the underlying key interactive processes at the interface between spheres to enable prediction of larger-scale impacts and responses through the integration of reconstructions, observations, and modeling approaches.	The coupling between spheres of the Arctic system are changing. To cover interactive processes at the interfaces between spheres, it is a priority to integrate observational, modeling, and reconstruction approaches. Particular emphasis should be placed on feedback loops. Important feedbacks include, e.g., decreasing albedo in the Arctic, increasing greenhouse gas emissions to the atmosphere, reductions in permafrost, perturbations of the energy budget and glacier and ice sheets surface mass balance, changes in freshwater runoff and cloud properties, which are all key elements in the coupled Arctic climate system. Further, attention should be paid to cascading effects and linkages across Arctic systems, such as changes in marine, terrestrial and freshwater biological productivity resulting from warming effects on atmospheric pollution, cryosphere dynamics, precipitation patterns, and weathering rates.

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

Longer narratives including more details and context are in Appendix 2.

Research need	Description of the research need	Rationale why included in this report
1. Indigenous leadership in Arctic research	1. How Arctic research, including Arctic observations, reconstruction, and prediction, are actionable for Indigenous self-determination and supporting Indigenous rights and sovereignty, and 2. Consideration of ethics and actions for Arctic research, including past environmental data collection, without free, prior, and informed consent, and lack of support for Indigenous data sovereignty.	Regional research recommendations from Arctic Indigenous groups have common themes of research relevant to Arctic Indigenous communities, increased participation of Arctic Indigenous Peoples, scientific and Indigenous knowledge being utilized by policy decision-makers, and co-production of knowledge and decolonial methodologies. These groups, including but not limited to Inuit Circumpolar Council, Inuit Tapiriit Kanatami, Naalakkersuitsut, and Sami Council, have put forth guidelines on how they and their communities want to interact with scientists/researchers and funding agencies.
2. The status of shared data collection across the Arctic: geographic, temporal, and subject matter coverage	Arctic science has a decades long history of data collection and sharing. However, most data collection has historically been performed in an ad hoc manner resulting in data that is collected for specific projects, often over short time periods, and regularly in an opportunistic manner resulting in data “hotspots” around field stations, roads, and other infrastructure with geographic gaps elsewhere. Additionally, although community-wide data repositories do exist, data are not always publicly archived or shared between nations, research organizations, government agencies, academic institutions and/or disciplines.	Due to the current lack of knowledge on the status of data collection across the Arctic, the Arctic science community risks duplicating efforts collecting data that might already exist. Furthermore, this knowledge can enable proactive mitigation of data gaps due to geopolitical barriers to international collaboration, changes in financing, and changes in staff. To explore changes over longer time periods, it is essential to provide access and share knowledge about older data sets through digitisation and making them easy to find and access.
3. Enhance modeling capabilities for hindcasting and future projections of terrestrial ecosystem responses	The current generation of process-based models, from site-level, to global-scale land surface models contained within Earth system models, contain longstanding and well-documented limitations for terrestrial ecosystems. These limitations are particularly acute with regards to: interactions between the terrestrial environment and permafrost thaw, including dynamic thermokarst processes; nutrient cycling; herbivory; changing vegetation composition and ranges; interactions with disturbances; and snow and soil moisture dynamics. Hindcasting models under previous paleoclimates is not frequently done, but can be beneficial for understanding paleo environments, establishing baseline conditions (especially with regard to disturbance), and validating model response under different climates.	Process-based models remain the best, and often only, way of projecting future Arctic terrestrial ecosystem responses and feedback to climate change.
4. Integration of diverse knowledge systems and research techniques for understanding terrestrial and inland water ecosystems and cryosphere research in the Arctic	While Indigenous communities possess extensive, long-term observations of terrestrial and inland water ecosystem changes, including ecosystem dynamics, seasonal variations, and species behaviour, these insights are often undervalued or disconnected from scientific research that predominantly relies on field data, remote sensing technologies, and experiments. Cryosphere monitoring and climate modeling would be enhanced with Indigenous Knowledges, e.g., permafrost thaw effects on wildlife, water quality, hazards, and ecosystems. This gap is further compounded by challenges in reconciling different temporal and spatial scales. Filling this gap requires developing frameworks that prioritize equitable collaboration with Indigenous communities, encourage co-production of knowledge, and combine diverse research methodologies to yield more holistic insights into the functioning and sustainability of Arctic terrestrial and freshwater ecosystems.	The lack of integration of diverse knowledge systems means that critical insights into the resilience and tipping points of ecosystems, particularly under the pressures of climate change, may be missed or underutilized. This need enhances research relevance and accuracy across RPTs (e.g., ecosystems, human dimensions) by adding local perspectives to scientific data. It’s feasible via existing community networks and has high impact for policy and adaptation, justifying its urgency for 2025–2035.

3.2.2. Cross-Cutting Priorities for Arctic Research

Longer narratives including more details and context are in Appendix 2.

Priorities for research	Reason why this should be an ICARP IV Priority
1. Strengthening Indigenous-led governance and decision-making in Arctic research	Strengthening Indigenous-led governance in Arctic research is critical for ensuring that research practices are equitable, inclusive, and aligned with the needs and rights of Indigenous communities. This priority addresses historical inequities, supports self-determination, and fosters long-term partnerships that enhance the relevance and impact of Arctic research. By prioritizing Indigenous-led governance, ICARP IV can set a global standard for ethical and impactful research (e.g. protocols, data sovereignty, and trust) that benefits both Indigenous communities and the broader scientific community.
2. Foster partnerships between scientists and Indigenous communities	Integrating Indigenous Knowledge into cryosphere and biosphere research addresses gaps in understanding socio-ecological impacts (e.g., habitat loss, water quality) that complement physical science. This priority is urgent as cryospheric changes disrupt Indigenous livelihoods, requiring adaptive strategies informed by both science and Indigenous Knowledge. Indigenous communities need to build capacity first through supporting Indigenous-led monitoring programs. For fostering partnerships, there needs to be co-designed research programs, project/program examples set, more publications and training sessions on participatory approaches, developing culturally-inclusive data sharing, and more outputs directed towards policy decision-making.
3. Fund long-term data collection programs and emphasize cross-boundary data sharing	Although data have been collected across the Arctic for decades, these data are not always publicly available, oftentimes not standardized, and not necessarily suitable for establishing the long-term records of change needed to assess climate change impacts across the region. A concerted effort is needed to assess the status of data collection across the Arctic, aggregate data from disparate sources, and, where possible, make existing data publicly available. This will allow researchers to truly assess where data gaps exist, both geographically, temporally and across disciplines. Strengthening cooperation among international research organizations, government agencies, research institutions, Indigenous communities, and policymakers will be crucial to this process. Looking forward there is a need for long-term, funded, monitoring programs to collect baseline data for various ecosystems and track environmental change. Continuous monitoring of vegetation, permafrost, biodiversity, terrestrial carbon flux, inland waters and ecosystem dynamics is crucial to building a complete understanding of Arctic ecosystems and how they are likely to change as the climate warms. This should include the establishment of a common data framework, permanent networks, standardized protocols, experiments, and regular assessments to track changes over time. This should also include enhancing observation systems, leveraging experiments, advancing technologies, and incorporating Indigenous Knowledge to increase the geographical and temporal scope of data collection across the region through international and cross-discipline cooperation. These needs are acute across the terrestrial, marine, and atmospheric domains, because field stations and ships are often operated at the national level and international collaboration can be challenging. Existing efforts such as the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS), the international tundra experiment (ITEX), INTERACT research stations, the U.S. National Science Foundation's National Ecological Observatory Network (NEON), the Integrated Carbon Observation System (ICOS), the Global Terrestrial Network for Permafrost (GTN-P) and the Circumpolar Active Layer Monitoring network (CALM) are models that can either be expanded or used as examples for future networks.
4. Improving modeling capabilities for Arctic terrestrial ecosystems, inland water ecosystems, marine ecosystems, and for the atmosphere, to better represent cryospheric and transport processes	Addressing this gap will require a concerted effort among modelers, data providers, and funders. Modeling gaps have been identified; what's needed now is a multi-national effort to fund model development and coordinate developments among modeling groups. Typical funding structures, especially from government agencies, do not prioritize model development, and therefore progress in addressing modeling gaps has been relatively slow. Additionally, process-based terrestrial ecosystem modeling groups have historically not coordinated developments. A closer coordination could speed progress, especially with new mechanisms for code modularity, sharing, and interoperability. Increased communication between modeling and empirical research communities, as well as local communities, would help prioritize and address dataset development needed for modeling.
5. Funding system transformation (PECWS 2025)	From Polar Early Career World Summit (2025): "Current funding structures are inadequate for supporting the collaborative, relationship-based research that polar science requires. There is a strong consensus around the need to more justly distribute funding across diverse communities and groups and to better distribute long-term funding that encourages collaborative resource sharing. Multiple priority statements call for funding cycles that support relationship building, reduce barriers to international collaboration, and eliminate unpaid labor in research. This transformation should reduce institutional gatekeeping in research processes, enabling direct community funding mechanisms."

4. Recommendations to Implement the identified Priorities for Arctic Research

4.1. Implementation of the RPT 2-specific Priorities

Longer narratives including more details and context are in *Appendix 2.*

Priority 1: Co-develop integrated monitoring and management frameworks with Arctic Indigenous Peoples.	
Spatial scale:	At the local and regional levels, while also developing a community of practice at the global, pan-Arctic level.
Time scale:	Relevant now for development and refinement. Long-term relevance (next 5 years) for integrating findings into scientific assessments and policy uptake processes.
Funding requirements and potential sources:	Sustained support for community-based monitoring networks will require both national and international funding. Philanthropic organizations can play a key role by providing seed and infrastructure funding to help establish these networks.
Infrastructure needs and requirements:	Community-run sensors and kits (automatic weather stations (AWS) + time-lapse + river/ice gauges), satellite and data connectivity, lab and office space, including internet connectivity, professional certificates (flying drones, boat safety, scientific protocols), OCAP/CARE-compliant data stewardship, and training to support these activities. Supersites for observation. Ideally, these should be built through international cooperation under certain criteria, such as WMO (GCOS, GCW, etc) Template MOUs (co-PI, data sovereignty clauses), training bursaries, and travel funds.
Data needs and requirements:	Integrating Indigenous Knowledge Systems with scientific observations, ensuring ethical data collection practices, and supporting Indigenous data sovereignty.

Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Developing co-produced research agendas with Indigenous communities	Address specific challenges in terrestrial and freshwater ecosystems. This includes (co-)identifying key research questions, methodologies, and outcomes that align with Indigenous priorities and values.	Local governments and Indigenous organizations: e.g., Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council, tribal consortiums (e.g., Kawerak Inc.), local Indigenous governments and communities. Environmental NGOs and community-based monitoring programs. Scientific organizations and universities. Federal agencies supporting Arctic research and monitoring (e.g., IARPC) International Arctic agencies and projects: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF)
Creating methods, protocols, and best practices that bridge Indigenous Knowledge Systems with larger-scale scientific observations	Common space and infrastructure to bridge and improve understanding of ecosystem responses to multiple/ compounding disturbances such as permafrost thaw, fire, erosion, droughts, floods, infrastructure development, and tipping elements.	Local governments and Indigenous organizations: to support Indigenous knowledge holders in co-production approaches. Scientific organizations and universities: scientists should co-develop these protocols with Indigenous knowledge holders, Indigenous organizations and local organizations. Federal and International agencies supporting Arctic research: e.g., NSF, EU Horizon supporting planning/development, pilot projects, and evaluation to test and refine these methods, SAON. Federal and International funding agencies.

Priority 1 *continued*: Co-develop integrated monitoring and management frameworks with Arctic Indigenous Peoples.		
Implementation: Implementation actions:	**How to implement the actions:**	**Who to address the actions:**
Establishing training programs to build capacity for Indigenous researchers in scientific methods	Promote knowledge sharing that enhances the value of Indigenous Knowledge Systems within scientific contexts. These programs should include mentorship, hands-on fieldwork, and access to scientific tools and technologies in the community. Establish workforce development programs in communities to foster an increased number of entry level to advanced level positions.	Indigenous-led organizations: e.g., Inuit Tapiriit Kanatami, Arctic Indigenous Youth Council; to design and deliver these programs. Scientific organizations and universities: providing accreditation. Federal and International funding agencies: e.g., ArcticNet, Nordic Council of Ministers offering financial support.
Implementing long-term, inclusive monitoring networks that integrate multiple knowledge systems	Integrate knowledge systems and research techniques to provide real-time data on ecosystem resilience and tipping elements under climate change pressures, especially where ground-truthing models can be leveraged.	Indigenous communities: lead design and operation of these networks. Federal agencies and International agencies that support Arctic research, intergovernmental bodies: e.g., NOAA, Arctic Council Working Groups to provide technical expertise and governments ensuring long-term funding.
Meaningfully investing in Indigenous Peoples' capacity to fully participate in Arctic research	Indigenous-led observing, collaborating on reconstruction and prediction efforts, and setting research priorities.	Funding agencies: e.g., U.S. NSF, European Research Council should allocate dedicated funds for Indigenous-led research. Indigenous governments and organizations: e.g., Inuit Circumpolar Council, Sami Council overseeing the allocation and use of these resources.

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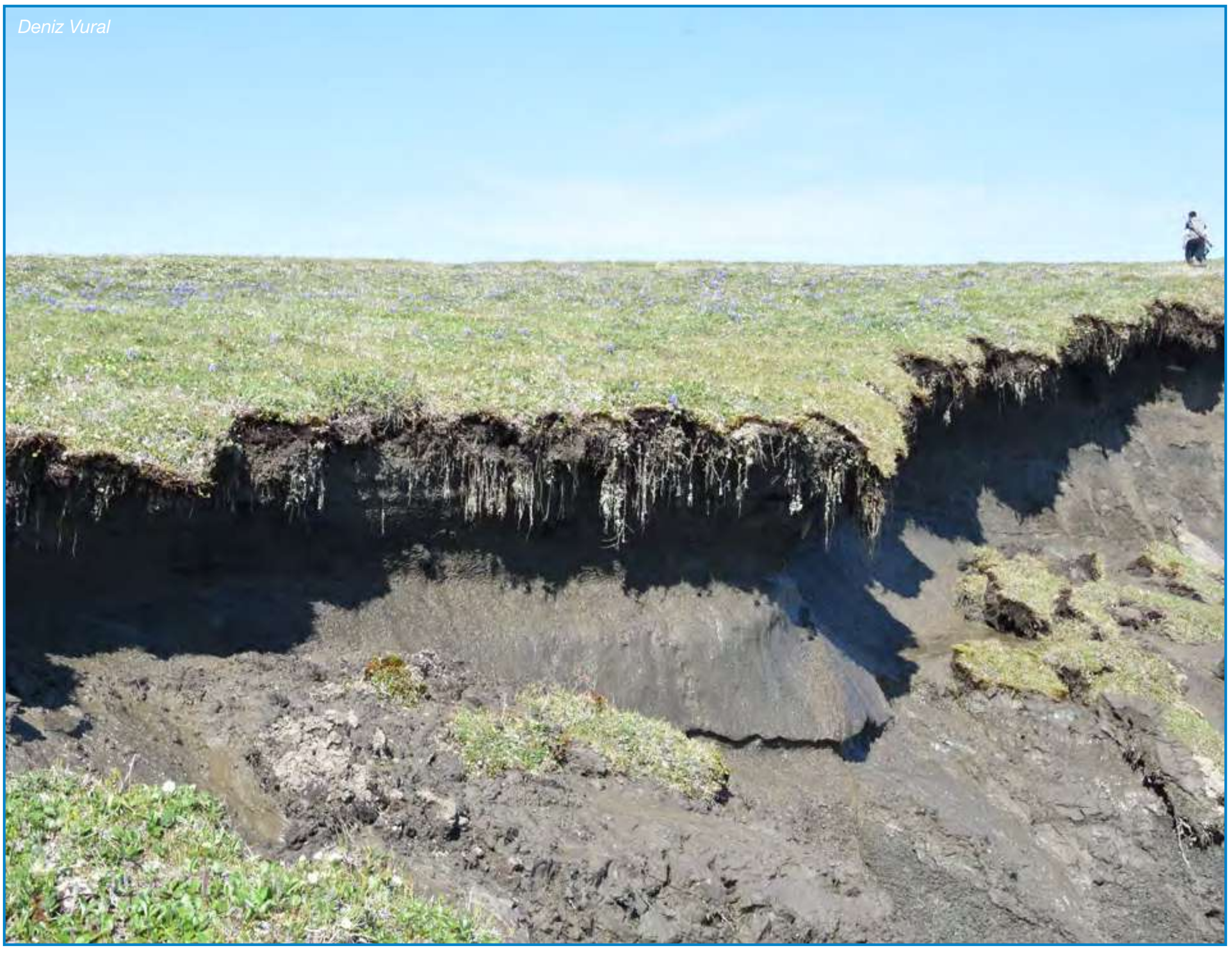
Priority 2: Enhance integrated cryosphere monitoring and modeling.		
Spatial scale:	Pan-Arctic, with global and regional implications	
Time scale:	Immediate relevance (next 5 years) for improving current climate models. Long-term relevance (next 10 years) for integrating findings into global climate assessments and policy development.	
Funding requirements and potential sources:	National and international research funding agencies (e.g., EU Horizon Europe, NSF Arctic Program, NASA Programs (including Cryosphere, Carbon Cycle Science), Research Council of Norway and other national research councils). Climate and polar research initiatives and projects (e.g. World Climate Research Programme (WCRP), Arctic Monitoring and Assessment Programme (AMAP). Private sector for direct funding and partnerships for satellite data acquisition and computational modeling and computing support.	
Infrastructure needs and requirements:	Research into feedback often requires significant computing capabilities for running models and storing and analysing outputs. The need for national infrastructure in this regard is increasingly common. For CMIP6 for instance, the data are stored on an international system that needs to be maintained and even expanded for the 7th generation of intercomparison.	
Data needs and requirements:	• Continuation of long-term observations and datasets, and strategic expansion to fill gaps in areas under-represented by the current monitoring networks. • Remote sensing data: Satellite observations of sea ice, ground ice, permafrost distribution and depth, glacier mass balance, and ocean-atmosphere interactions. • In situ measurements: Permafrost borehole/temperature, land subsidence and ground composition data, ice-core samples, long term mass balance, albedo measurements, and eddy covariance and tall tower data to track greenhouse gas fluxes. • Reconstructions: Reconstructions of past nonlinear responses for improved mechanistic understanding. • Climate model outputs: Data from CMIP6 and regional climate simulations, particularly those incorporating permafrost and ice-sheet dynamics. • Hazard mapping and assessment: Broad-scale hazard identification and assessment across the Arctic are needed to better inform stakeholder decision making and disaster preparation. • Indigenous Knowledge Systems and local knowledge: Observational records from Arctic communities on changing seasonal patterns and ecosystem shifts. • Machine learning, AI-driven analysis, and data assimilation: Advanced data assimilation techniques to improve mapping of changes in the cryosphere and modeling of climate feedbacks.	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Strengthening Arctic observation networks	Expand and enhance monitoring of key cryospheric feedback processes through existing networks (e.g., permafrost carbon release, ice sheet mass loss, changes in Arctic storm intensity).	International scientific organizations and projects: WCRP, AMAP, INTERACT, POLARIN, EU Horizon, SAON, International Permafrost Association (Global Terrestrial Network for Permafrost, Circumpolar Active Layer Monitoring Network). National, International, Federal agencies: NASA, NOAA, NSF, ESA, UNEP. Universities and research institutions. Indigenous organizations and community-based monitoring programs.
Improving model parameterization of cryosphere-climate feedbacks	Incorporate high-resolution cryospheric data into global and regional climate models to better capture feedbacks, thresholds and tipping elements.	Climate modeling centers: CMIP6, IPCC Working Groups, Arctic CORDEX. Scientific organizations and universities. Supercomputing facilities and AI research teams for improved data assimilation techniques.
Fostering interdisciplinary collaboration and knowledge co-production	Strengthen collaboration between climate scientists, Indigenous knowledge holders, and policymakers to integrate diverse knowledge systems.	International Arctic governance bodies: Arctic Council (AMAP, CAFF, PAME). Indigenous Organizations and Indigenous Knowledge networks: Inuit Circumpolar Council, Saami Council, and other regional entities. SIKU, ISN, and other knowledge networks. Scientific networks: APECS, IASC, Future Earth, Permafrost Carbon Network.
Developing targeted policy recommendations	Translate research findings into actionable policy strategies for Arctic and global climate adaptation and mitigation actions.	National and regional policymakers in Arctic nations. Climate advocacy organizations and NGOs. Intergovernmental bodies: UNFCCC, IPCC, Arctic Council.

Priority 3: Assess present and past Arctic Ocean circulation, characterizing Arctic land-shelf-basin and Arctic-Subarctic Ocean interactions, and their relations to marine biogeochemical cycles and ecosystem functioning.	
Spatial scale:	Pan-Arctic with local to global implications through the Atlantic Meridional Overturning Circulation (AMOC).
Time scale:	For the next 5 to 10 years and beyond.
Funding requirements and potential sources:	• Platforms that facilitate integrated expedition activities across individually funded projects. This secures possibility for activities that are quality checked through individual nations funding schemes. • Development of modular and scalable platforms for deployment in the various Arctic environments and collection of high resolution observations. • Integration of artificial intelligence (AI)-driven navigation systems in robotic platforms to improve data collection in remote areas (e.g. deep ocean and under-ice environments), to upscale the spatial and temporal coverage, and to reduce the risk for human operators in the field. • Improvement of machine learning systems for use in marine ecosystem monitoring and management. Potential sources may be: • National and international research funding agencies • Private sector for technological development, machine learning and computing support
Infrastructure needs and requirements:	• Research icebreaker (needs) for an international research platform (requirements). • Maintenance of the ARGO float programme. • Data systems and computational infrastructure
Data needs and requirements:	• Hydrographic data • Marine biogeochemical (including bio-essential (micro-nutrients) and potentially toxic (pollutants) trace metals) data • Biological datasets (including high taxonomic resolution inventories through morphological, DNA-based, and physiological rate approaches) • Sea ice reconstructions, in particular from past warm climate states • Pan-Arctic and Arctic-subarctic data syntheses from multiple projects

Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Coordinating and sustaining cross-basin (i.e., coast to deep ocean) multi-nation wide-area observations	Use internationally coordinated icebreakers and long-term in situ observation platforms (e.g., oceanographic moorings) to expand current spatial and temporal data collection coverage (e.g. guarantee data collection in key areas even during winter season). Maintain and collaborate across existing initiatives (e.g. Pan-Arctic Distributed Biological Observatory (DBO), Synoptic Arctic Survey (SAS)) that support long-term integrated measures of hydrographic, marine biogeochemical and biological data, resulting in data syntheses from multiple projects to shed light on the changes in ocean circulation and impacts on marine biogeochemical cycles and ecosystem function. Increased coordination to understand marine-terrestrial interface in coastal regions, in particular the underpinning ecosystem functions and biogeochemical cycles that form the basis of life in the Arctic. In addition, improved taxonomic resolution and biomass estimates of macrofauna (e.g., biodiversity, connectivity, abundance, productivity, and timing of blooms and reproduction), for a thorough understanding of the cascading effects of environmental changes on ecosystem functionality.	National and International governments, international bodies supporting Arctic research: Establish an international pool of collaborative infrastructure platforms (e.g. icebreakers), with equal opportunities for funded projects and activities. The goal is integrated, collaborative expeditions addressing the full Earth system at all sites, securing comparable data in time and space from key sites (e.g., Polar Observing Assets working group - POAwg, Pan-Arctic DBO, SAS).
Achieving Interdisciplinary coordinated actions in support of the co-development of modular and scalable platforms for data collection and high resolution observations	Bring together expertise from different fields and multiple knowledge systems to discuss critical weaknesses of the Arctic Ocean observing system and collaboratively create more effective technological solutions in support of automated collection of standardized data, and improved spatial and temporal coverage (e.g. data collection in the vicinity of glacier ice fronts or in the winter).	Federal and international research agencies. Scientific organizations and universities. Indigenous organizations and local governments.

Priority 4: Understand Arctic disturbances and ecosystem stability under climate change.		
Spatial scale:	Local, regional, pan-Arctic.	
Time scale:	Now to 5 years.	
Funding requirements and potential sources:	Long-term, sustained funding is required. Potential funding sources include national and international research funding agencies, Arctic research initiatives, and international scientific organizations, and private philanthropy.	
Infrastructure needs and requirements:	Maintenance of remote sensing platforms such as satellites, drones and ARGOS tracking infrastructure.	
Data needs and requirements:	• Long-term in situ data: vegetation inventory and monitoring, eddy covariance data from flux towers. • Paleoecological data: tree ring data, lake and peatland sediment records, ice cores. • Remotely sensed data: satellite imagery, active sensor data, airborne and UAV based imagery, animal movement data. • Genetic/ genomic data. • Indigenous Knowledge Systems and community-based monitoring	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Prioritize long-term monitoring of disturbances, undisturbed control sites, long-term field experiments, and ecosystem change.	Understanding Arctic vulnerability and stability to change requires sustained, uninterrupted, long-term monitoring combined with reconstructions of natural variability to change. 1. Utilize and expand existing monitoring capacity, e.g. enhancing coordination between established research stations or observation networks to improve efficiency and expand the scope of coverage, expand existing networks. 2. Efforts should be directed to establish new long-term observation networks, focusing on current gaps in Arctic data collection and, where appropriate, community based monitoring. In all cases, uninterrupted funding and operation are critical to success. 3. take advantage of existing long-term field experiments to understand the drivers and processes of change, and expand to new areas that are under-represented.	International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF), IPA. Existing networks, initiatives, and coordinated programs: Circumpolar Arctic Vegetation Science Initiative (CAVSI), Arctic Vegetation Archive (AVA), the international tundra experiment (ITEX), U.S. National Science Foundation's National Ecological Observatory Network (NEON), U.S. National Science Foundation's Long Term Ecological Research (LTER) Network, U.S. National Science Foundation's Arctic Observatory Network (AON), Circumpolar Active Layer Monitoring network (CALM). Scientific organizations and universities.
Prioritizing community-based monitoring	Co-develop community-based monitoring programs (See RPT2 Priority 1 Implementation Strategy for more details) that engage with rightsholders and stakeholders in tracking disturbances and species shifts. Develop/adopt standardized monitoring protocols with scientific guidance and local input. Facilitate regular training sessions and workshops to build local capacity for data collection, analysis and interpretation. Collaboration with existing observation networks would be helpful.	Local governments and Indigenous organizations: e.g. Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council, Kawerak Inc., local Indigenous governments and communities. Environmental NGOs and community-based monitoring programs. Scientific organizations and universities. Federal agencies supporting Arctic research and monitoring. International Arctic agencies, working groups, and projects: e.g/ WCRP, INTERACT, POLARIN, Arctic Council WGs (AMAP, CAFF).
Studying the socio-ecological impacts of disturbance/ change (e.g. fire, permafrost thaw, coastal erosion) on food security, water, and cultural practices	1. Engage with Indigenous Knowledgeholders and social scientists to assess socio-ecological impacts on Arctic communities; promote co-production of knowledge methodologies. 2. Prioritize Indigenous-led research that centers issues of greatest importance to communities. 3. Focus efforts on assessing and mapping the risk of disturbances and environmental changes across Arctic communities. 4. Use historical and paleodata to understand past permafrost dynamics, wildfire regimes, hydrologic patterns, and polynya dynamics. 5. Focus on understanding the linkages between the socio-economic system and the ecosystems to increase socio-ecological resilience.	International Arctic agencies, working groups, and projects: WCRP, INTERACT, POLARIN, Arctic Council WGs (AMAP, CAFF), International Permafrost Association. Local governments and Indigenous organizations: e.g. Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council, Kawerak Inc., Indigenous governments and communities. Scientific organizations and universities.

Priority 4 *continued*: Understand Arctic disturbances and ecosystem stability under climate change.		
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Identifying factors that determine ecosystem resilience or vulnerability in the face of rapid climate change	To understand Arctic ecosystem resilience, a multi-pronged approach is necessary. Research should aim to incorporate data from: controlled experiments, paleoecological approaches, long-term field studies, genetic and genomic analysis, Indigenous Knowledges, and remote sensing and satellite imagery. More specifically: 1. Controlled experiments can be used to assess species' adaptive capabilities. 2. Genetic data can be used to identify adaptive traits and assess species' evolutionary potential. 3. Paleoecological approaches can establish baseline conditions and provide context regarding past tipping points and ecosystems' responses to a changing Arctic. 4. Indigenous Knowledges can provide intimate, place-based information that contextualizes Arctic ecosystem resilience and change. 5. Long-term in situ data can be used to identify key factors contributing to multidimensional stability. 6. Remote sensing and satellite imagery can be used to track large-scale ecosystem changes, and understand spatial patterns of Arctic ecosystem resilience and vulnerability.	Scientific organizations and universities Initiatives supporting Arctic inventory and monitoring: Circumpolar Arctic Vegetation Science Initiative (CAVSI), Arctic Vegetation Archive (AVA), the international tundra experiment (ITEX), U.S. National Science Foundation's National Ecological Observatory Network (NEON), U.S. National Science Foundation's Long Term Ecological Research (LTER) Network, International Long Term Ecological Research (ILTER) Network, Critical Zone Observatories (CZO), U.S. National Science Foundation's Arctic Observatory Network (AON). Local governments and Indigenous organizations: e.g. Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council, Kawerak Inc., Indigenous governments and communities. Federal and international research agencies.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Priority 5: Identify and understand the underlying key interactive processes at the interface between spheres to enable prediction of larger-scale impacts and responses through the integration of reconstructions, observations and modeling approaches.	
Spatial scale:	All scales.
Time scale:	Relevant now and for the next 10 years into the future.
Funding requirements and potential sources:	Small project grants to large consortia. National and international funding.
Infrastructure needs and requirements:	• Long-term, co-located observatories at key boundaries—river mouths/estuaries, glacier–fjord termini, permafrost coasts, shelf breaks, marginal ice zone, glaciers-atmosphere and inland ecosystems linkages, crevass and meltwater development near the margins of Greenland Ice Sheet (which is closely related to glacier instability), and Arctic Ocean gateways (Fram, Bering Strait, Canadian Arctic Archipelago). • Ice breakers, Standardized moorings, flux towers, permafrost boreholes, tide gauges, wave buoys, ice-tethered profilers, remote sensing, community camera networks, sediment cores, bathymetric mapping. • Coordinated Arctic Ocean cross nation and disciplines field/ship campaigns. • Satellite backhaul (Iridium/Starlink). • Fund modular, interoperable measurement platforms (plug-and-play sensors, cold-rated power/telemetry), robotic/auto systems, autonomous vehicles, /(air, water, surface, under-ice), and coordinated satellite tasking. • A FAIR/CARE-compliant platform hosting data, code, protocols, and observation–model fusion dashboards with near-real-time streams.
Data needs and requirements:	• Data needed from all interfaces between the spheres that shape Arctic climate feedback mechanisms to increase understanding of Arctic ecosystems responses. A combination of field, satellite and modelling data are needed from all interfaces between these spheres. • Glacier–ocean-atmosphere (tidewater/ ice-shelf): Repeat multibeam bathymetry at fronts/sills; temperature/ salinity/ oxygen/ turbulence microstructure sections; ADCP currents; terminus position and subglacial discharge (radar/ dye/ electrical); fjord moorings; UAV/ photogrammetry; ICESat-2/ CryoSat-2/ SAR for frontal change for Submarine melt rates, plume entrainment/mixing, seasonal to winter dynamics, melt–calving partition, ice-atmosphere interactions, especially targeting surface crevasse and meltwater. • Land–river–estuary–shelf–basin continuum: Gauged year-round discharge; dissolved organic carbon, primary organic carbon, chromophoric dissolved organic matter optics, nutrients/alkalinity/pCO_2/pH/ O_2; suspended sediment and minerals; isotopic source tracing; moorings & gliders across salinity fronts; bathymetry & high frequency radar. • Establish comprehensive monitoring programs to understand the linkages between cryospheric dynamics (such as glaciers and permafrost), the atmosphere, and inland ecosystems. These programs should include monitoring of atmospheric deposition (e.g., dust, organic carbon, black carbon, major ions, isotopic tracers, and contaminants/ pollutants), inland water ecosystems (rivers and lakes), water chemistry (using automatic monitoring stations, or well established fieldstations), ice cover (via satellite imagery and local photo cameras), and permafrost dynamics (e.g., active layer depth and related parameters, including the mobilization of old carbon by measuring radiocarbon), and reconstructions of these representing Arctic environmental linkages under past warm climate states.

Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Integrating observational, modeling and reconstruction approaches	Coordination and establishment of communication and collaboration between researchers with expertise in different fields/methodologies to identify specific needs to bridge the gaps.	Scientific organizations and universities: e.g., Individual researchers and/or expert groups or communities of practice coming together. International agencies supporting Arctic research: SAON (CON, and ADC for data), IASC WGs. Knowledge, observing and coordinated networks: e.g., GTN-G, GTN-P/CALM, ArcticGRO, IABP, SIPN, DBO, CBMP, Arctic ROOS and uses AOS to align priorities and track delivery.
Forming interdisciplinary working groups on small and larger scales (e.g. individual projects and larger consortia)	• Establish closer communication between different scientific fields, organize interdisciplinary research schools and field work campaigns. • Initiate targeted interdisciplinary research projects.	Scientific organizations and universities: e.g., Individual researchers and/or expert groups or communities of practice coming together on cross-cutting approaches. National and international initiatives: e.g., SAS, GOOS, DBO, POLARIN, Polhavet 2050)
Advancing technologies and methodologies across scientific fields, specifically targeting interfaces between spheres	Co-develop new technologies and methodologies together across fields (e.g. modular measurement platforms, robotic systems, satellites).	Scientific organizations and universities: e.g., Individual researchers and/or expert groups or communities of practice coming together on cross-cutting approaches. National and international initiatives: IASC working groups (cross-cutting approaches), SAS, GOOS, DBO, POLARIN, International Polar Year, IPA.

Priority 5 *continued*: Identify and understand the underlying key interactive processes at the interface between spheres to enable prediction of larger-scale impacts and responses through the integration of reconstructions, observations and modeling approaches.		
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Identifying and studying feedback loops that can result in tipping points	Observational needs must be identified, ideally with the help of models and model users, the findings need to be shared in an interactive, open-source, and virtual Arctic knowledge space.	Individual researchers, IASC working groups (cross-cutting approaches), coordinate with national and international initiatives (e.g. Synoptic Arctic Survey SAS, Global Ocean observing system GOOS, Distributed biological observatory DBO, POLARIN, International Polar Year)
Increasing understanding of cascading effects and linkages across Arctic systems.	Increase multidisciplinary and interdisciplinary activities (workshops, meetings) to raise awareness and highlight the need for cross-cutting research. Move beyond our comfort zone of expertise and knowledge.	Scientific organizations and universities: e.g., Individual researchers and/or expert groups or communities of practice coming together on cross-cutting approaches. Scientific organizations and universities: e.g., Individual researchers and/or expert groups or communities of practice coming together on cross-cutting approaches, e.g., IASC working groups using cross-cutting approaches. National and international initiatives, working groups, and projects: e.g., SAS, GOOS, DBO, POLARIN, International Polar Year, Polhavet 2050. Knowledge, observing and coordinated networks: including Indigenous knowledge holders, experts, scholars, and networks

4.2. Implementation of the Cross-Cutting Priorities

Longer narratives including more details and context are in Appendix 2.

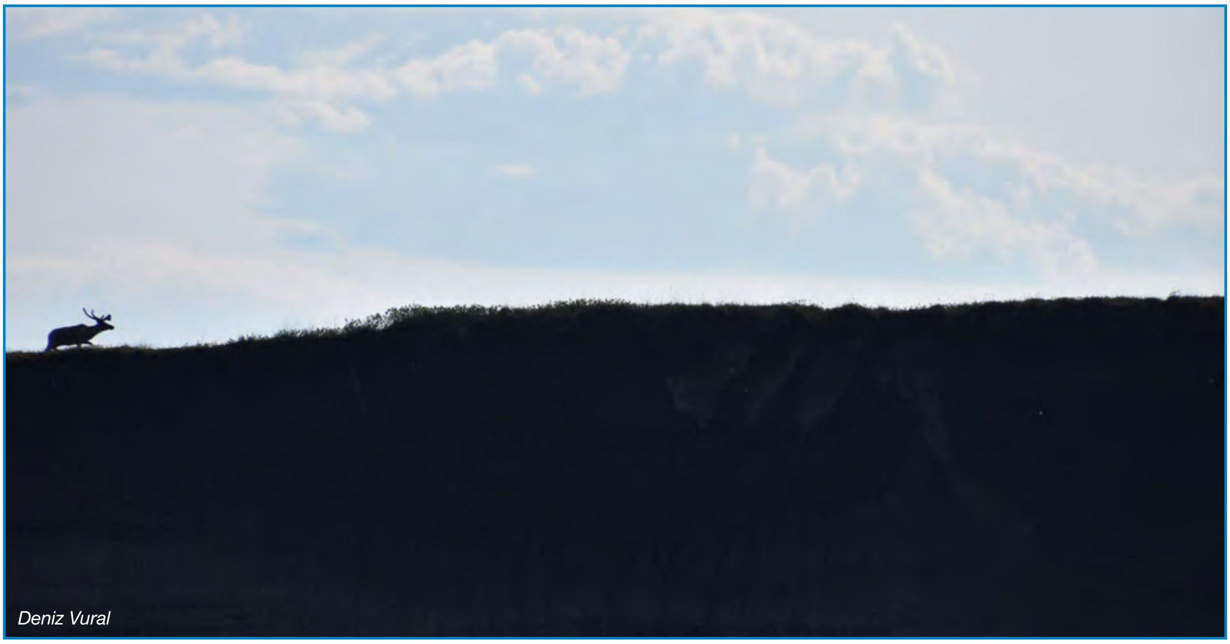
Priority 1: Strengthen Indigenous-led governance and decision-making in Arctic research.		
Spatial scale:	Local, regional, and pan-Arctic.	
Time scale:	Immediately relevant to strengthen Indigenous-led research; long-term relevance for next 10 years to shift decision-making frameworks and processes concerning Arctic research.	
Funding requirements and potential sources:	National and international funding agencies, as well as nonprofit organizations, should provide sustained funding for capacity-sharing to achieve Indigenous sovereignty.	
Infrastructure needs and requirements:	Training in Indigenous sovereignty and allyship for researchers, institutions, organizations that do Arctic research; Infrastructure in communities to house scientific equipment, researchers (local and non-local); transportation and IT infrastructure; administrative and governance support (e.g., to produce protocols, agreements, statements, permits, etc)	
Data needs and requirements:	Ensuring that all data is owned by the Indigenous community/organization; all data collection and use adhere to Indigenous data sovereignty principles defined at the appropriate level of the Indigenous partner(s), and that Indigenous communities have control over how their knowledge is gathered and used.	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Developing Indigenous-led research protocols and ethics.	Support Indigenous communities in developing their own research protocols, guidelines, and policies to ensure that both new and previously collected data align with their cultural values and governance.	Indigenous governance bodies should lead this process, with researchers and funding agencies providing technical (as requested) and financial support.
Changing access and permissions on existing data sets.	Changing access and permissions on existing data sets in consultation with relevant Indigenous groups to meet new data ethics standards, and ensuring that newly collected data sets adhere to these standards, as well.	Researchers, data managers, and Indigenous communities should work together to revise data access and permissions. Data managers (e.g., NOAA, Arctic Data Center) and Indigenous communities should collaborate to revise data access and permissions.
Building trust and improving research validity.	Ensuring that research practices respect Indigenous Knowledge Systems and build trust between researchers and Indigenous communities, thereby improving the validity and applicability of research outcomes.	Indigenous Knowledge holders, researchers, in conjunction, should prioritize trust-building and ethical research practices by ensuring that Indigenous communities have decision-making authority over research design, data collection, and dissemination processes.

Priority 2: Evaluate impacts of Arctic atmospheric circulation.		
Spatial scale:	Pan-Arctic	
Time scale:	Next 5 years (2025–2030).	
Funding requirements and potential sources:	$10–20M; UNEP, Arctic Council, National and international funding agencies, nonprofit and philanthropic organizations, dedicated Indigenous-led research funds.	
Infrastructure needs and requirements:	Physical infrastructure in communities (office, laboratory, vehicles, etc), IT support, connectivity.	
Data needs and requirements:	Community/ local level to regional observations, scientific datasets, data sovereignty and sharing agreements and frameworks.	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Co-designing research questions and programs	• Hold workshops, convenings, gatherings to align goals (Cochran et al., 2013), foster communication throughout the process • On-the-ground visits to foster face to face relationship building • Co-develop joint monitoring campaigns (see RPT2 Research Priority 1)	Indigenous Peoples Organizations (e.g., Inuit Circumpolar Council, Saami Council), Arctic Council working groups Scientific organizations and universities.
Developing long-term data-sharing platforms	Create interoperable repositories (multi-language, culturally appropriate) that integrate Indigenous Knowledges with scientific datasets, while also protecting data sovereignty, so that the user has control over who the data are shared with.	Arctic Data Centers
Unifying Indigenous observing and monitoring and research networks (into a "network of networks")	Support Guardians, Rangers, Sentinel and other Indigenous-led monitoring programs that are already functioning and can be expanded/ strengthened Convening a Community of Practice centering and focusing on networking these networks together around shared priorities and goals as relevant to pan-Arctic perspectives	Indigenous leads of individual networks and initiatives functioning to collect relevant data Initiatives supporting Arctic inventory and monitoring (e.g., CAFF, CBMP) U.S. National Science Foundation's Arctic Observatory Network (AON), SAON
Implementing wider participatory, mixed methods, and interdisciplinary/ multidisciplinary approaches	• Expand peer-reviewed published literature with studies successfully using these methods • Expanded trainings and workshops on these methodologies	Indigenous scholars and researchers with uplifting support from research institutions Experienced non-Indigenous academic researchers from research institutions
Spotlighting equitable Indigenous-Institutional partnerships throughout the ICARP and IPY processes	Create a committee of cross-cutting collaborators from RPT 1, 2, 3, 5, and 6 to guide communication IPY and ICARP-IV committees	Co-Leads of a cross-cutting committee formed from multiple RPTs. Initiatives engaging in these partnerships ICARP and IPY committees
Co-producing policy	Translate integrated science–Indigenous Knowledge findings into targeted policy briefs for Arctic Council and UNFCCC negotiations	Arctic Council working groups, Indigenous Peoples Organizations, climate advocacy NGOs

Priority 3: Fund long-term data collection programs and emphasize cross-boundary data sharing.	
Spatial scale:	Pan-Arctic.
Time scale:	For the next 10 years.
Funding requirements and potential sources:	Establish a common framework for use and maintenance of instrumentation, data collection, storage and processing. A FAIR/CARE-compliant platform hosting pan-Arctic data, code, protocols, and observation–model fusion dashboards with near-real-time streams. Regular fieldwork (on ground and water) where the establishment of a permanent infrastructure is not possible (see e.g. Tara Polar Station) New research stations in geographical areas with identified data gaps. Flagship programmes to kick off and help to establish new sites
Infrastructure needs and requirements:	• Establish a common framework for use and maintenance of instrumentation, data collection, storage and processing. A FAIR/CARE-compliant platform hosting pan-Arctic data, code, protocols, and observation–model fusion dashboards with near-real-time streams. • Regular fieldwork (on ground and water) where the establishment of a permanent infrastructure is not possible (see e.g. Tara Polar Station) • New research stations in geographical areas with identified data gaps. • Flagship programmes to kick off and help to establish new sites
Data needs and requirements:	• Data that fills existing gaps and connects the different spheres. • Data that is collected and archived using standardized protocols. • Data that adheres to equitable Arctic research principles. • Inventory of existing observation datasets. • Analysis to support implementation of new observation networks to fill gaps and benefit societal needs.

Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Coordinating IPY implementation	Prioritize communication between IPY and ICARP-IV committees to align efforts and combine resources.	IASC, SCAR and other IPY supporters: the World Meteorological Organization (WMO), International Science Council (ISC), University of the Arctic, International Arctic Social Sciences Association (IASSA), the Association of Polar Early Career Scientists (APECS), Sustaining Arctic Observing Networks (SAON)
Identifying and focusing efforts on filling geographic gaps in data collection	Metcalfe et al., 2018 provide a good framework for addressing sampling bias and filling in geographic gaps in Arctic data collection: 1. Conduct a comprehensive review of existing Arctic data in several languages to improve integration of literature from poorly cited areas, and non-English data sources. 2. Expand observations at existing research stations and establish new research stations in regions with identified data gaps. 3. Plan expeditions to underrepresented areas (e.g. Russian Arctic and Canadian Archipelago).	Data management centers: DataOne, Environmental Data Initiative (EDI), Arctic Data Center (ADC), Copernicus Arctic Hub, SAON Data Portal, Movebank, Indigenous data centers, GTN-P. Universities and research institutions, particularly those from underrepresented areas Indigenous organizations and community-driven monitoring programs Federal and international research agencies
Strengthening cooperation among international research organizations, government agencies, research institutions, Indigenous communities, and policymakers	Strong cooperation will be necessary to develop, fund and prioritize cross-boundary programs and organizations. For example: • Prioritize international sources of funding that facilitate cross-border cooperation. • Expand international research networks. • Develop joint research programs and projects. • Organize regular Arctic Science Summit Weeks and other international Arctic science conferences to facilitate face-to-face interactions and knowledge sharing. • Develop agreements and programs to facilitate cross-border research station access. • Develop formal agreements on enhancing international Arctic scientific cooperation. • Prioritize co-production of research with Indigenous People and communities. • Improve education on equitable Arctic research practices.	Arctic Council Funding agencies and governments Indigenous organizations: Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council

Priority 3 *continued*: Fund long-term data collection programs and emphasize cross-boundary data sharing.		
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Establishing and funding permanent observation networks	• Continue to fund existing long-term research stations and observation networks. Long-term, uninterrupted records are extremely valuable for detecting change, and long term research at field stations provide context for understanding ecological processes and predicting future ecosystem responses. Establish new long-term research stations and observation networks, focusing on filling existing gaps in Arctic data collection. A "hub and spoke collaboration" between field stations and community based observation networks might be helpful in some places. Selection of key sites for expansion of long monitoring data series through reconstructions.	International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF), IPA/GTN-P. Initiatives supporting Arctic inventory and monitoring: Circumpolar Arctic Vegetation Science Initiative (CAVSI), Arctic Vegetation Archive (AVA), the international tundra experiment (ITEX), U.S. National Science Foundation's National Ecological Observatory Network (NEON), U.S. National Science Foundation's Long Term Ecological Research (LTER) Network, International Long Term Ecological Research (ILTER) Network, Critical Zone Observatories (CZO), U.S. National Science Foundation's Arctic Observatory Network (AON), Permafrost Pathways (US Program), SAON, GTN-P, CALM.
Developing and publicizing standardized protocols for data collection and processing	Develop standardized protocols for data collection and processing in conjunction with efforts to coordinate and continue long-term monitoring programs. Protocols should encompass a wide range of field data collection types and be detailed, yet flexible enough to account for resource differences amongst researchers. Protocols related to community based monitoring and field data collection suitable for remotely sensed mapping should also be considered.	International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF), SAON, IPA (GTN-P, CALM) Initiatives supporting Arctic inventory and monitoring: CAVSI, AVA, ITEX, NEON, LTER, ILTER, CZO, AON, SAON.
Developing and supporting existing development a pan-Arctic, cross-discipline data portal	Support development of a pan-Arctic data portal. This would involve aggregating and synthesizing existing data, building off efforts of existing data portals. Ideally, the portal could host all types of data (e.g. field based, observational, experimental, remotely sensed) from all scientific disciplines. The portal needs to be easy to find, easy to use, and accessible to all. It should be available for free and should not require log-in information or a specific type of affiliation to use.	Data management centers: DataOne, EDI, ADC, Copernicus Arctic Hub, SAON Data Portal, Movebank, Permafrost Discovery Gateway Universities and research institutions with expertise in data management, web design, and Arctic science International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF), GCOS, ACTRIS, ICOS Initiatives supporting Arctic inventory and monitoring: CAVSI, AVA, ITEX, NEON, LTER, ILTER, CZO, AON, SAON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Priority 4: Improving modeling capabilities for Arctic terrestrial and marine ecosystems, to better incorporate cryospheric processes, transport, and feed-back to the atmosphere.		
Spatial scale:	All are relevant.	
Time scale:	Now into the next 10 years.	
Funding requirements and potential sources:	Multi-national funding is required for development and continuity of modeling efforts.	
Infrastructure needs and requirements:	• Maintenance and development of new national-scale computing and data storage infrastructure. • Establish a common framework for use and maintenance of data collection, storage and processing. A FAIR/CARE-compliant platform hosting pan-Arctic data, code, protocols, and observation–model fusion dashboards with near-real-time streams.	
Data needs and requirements:	• Inventory of existing modeling groups/efforts. • Data required to constrain key model parameters.	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Funding long-term modeling efforts	A multi-national effort is needed to fund model development and coordinate developments among modeling groups. Funding at the multi-national level will allow researchers and institutions to prioritize model development, and will allow model development to continue, uninterrupted, beyond typical national funding periods of 1-5 years.	National and international research funding agencies Funding foundations International scientific organizations: ECMWF, Copernicus. WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF) Initiatives supporting Arctic modeling: NGEE Arctic, Permafrost Pathways, Q-Arctic, ESA Permafrost CCI
Improving coordination between process-based ecosystem modeling groups	Increased communication and cooperation between modeling groups will limit duplicated effort, allow groups to pool resources, and speed progress. Establishing clear mechanisms and protocols for collaboration amongst groups will be critical. Advancements in technology have led to several new mechanisms for code modularity, sharing, and interoperability that should be utilized to harmonize efforts. With a unified modeling community, significant progress can be made filling known gaps in modeling efforts, including acquiring data needed to constrain model parameters.	Modeling organizations: International Land Modelling Forum, Coupled Model Intercomparison Project (CMIP), Paleoclimate Modelling Intercomparison Project Universities and research institutions Initiatives supporting Arctic modeling: NGEE Arctic, Permafrost Pathways, Q-Arctic
Increasing communication between modeling and empirical research communities, as well as local and Indigenous communities	Organize opportunities for face-to-face interactions and knowledge sharing between these communities. Identify priority areas for dataset development and modeling that are co-developed with empirical researchers and Indigenous communities.	International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF), IPA Indigenous organizations: Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council, Kawerak Inc.
Hindcasting	Hindcasting models under previous paleoclimates is not frequently done, but can be beneficial for understanding paleo environments, establishing baseline conditions (especially with regard to disturbance), and validating model response under different climates.	Modeling organizations: Paleoclimate Modelling Intercomparison Project, Coupled Model Intercomparison Project (CMIP) Universities and research institutions

Priority 5: Funding system transformation.		
Spatial scale:	All scales are relevant.	
Time scale:	Relevant now and for the next five years should be highly prioritized.	
Funding requirements and potential sources:	Funding should prioritize long-term academic and non-academic careers in polar sciences. To achieve this, we must provide equal opportunities to all polar career pathways, support transition periods in all career stages, and eliminate unpaid labor (e.g., support in the field by local population) in the polar science enterprise. By investing in the full range of polar careers, we will reduce undue burdens on individuals and foster an environment that values all.	
Infrastructure needs and requirements:	• Facilitate international collaboration and access to polar research stations and infrastructure. • Leverage university alliances to construct infrastructure that promotes data-steward-led education and skill development to foster an open science culture. • Improve infrastructure for researcher-community communication of priorities.	
Data needs and requirements:	While supporting open science, data accessibility needs to be balanced with ethical considerations. Data are ideally standardized, readily accessible, and interoperable, and simultaneously uphold Indigenous data sovereignty. Global standards for data sharing should ensure that open science practices do not perpetuate extractive research relationships. Accessibility must extend beyond data to include participation in all stages of research processes and decision-making. Promote open science by leveraging transparent and ethical practices at every stage of the research lifecycle and ensuring equitable access, management, and interoperability of data and code. This includes reducing or eliminating journal paywalls, securing sustainable funding, and establishing early and abundant training mechanisms to build technical capacity. Encourage the use of FAIR (Findable, Accessible, Reproducible, Reusable) and CARE (Collective benefit, Authority to control, Responsibility, Ethics) principles to guide data management, with Indigenous data sovereignty at the center. Move towards global standards, inter-institutional collaboration, and international governance, resilient to sociopolitical disruption to ensure long-term accessibility of data. Recognize and fund open science, code, and data as a full lifecycle process, including maintenance of code and data Post-publication. Emerging technologies such as artificial intelligence and machine learning should be leveraged responsibly, with consideration for special ethical concerns.	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Support collaborative, relationship-based research	Develop funding models that prioritize long-term partnerships and relationship building between researchers, Indigenous communities, local experts, and non-academic organizations. Require relational accountability (co-developed goals, reciprocal benefits) as part of funding criteria. Include Indigenous and local knowledge holders as co-leads and co-PIs on proposals.	National funding agencies (e.g., Research Councils, EU Horizon, NSF) Universities and Arctic research institutes Community organizations and Indigenous governance bodies (for co-design and review of proposals)
Justly distribute funding across diverse communities and groups	Eliminate unpaid labor. Institutions should pay the following individuals at equitable rates for all the work in which they are engaged: Indigenous partners, community coordinators/managers, early career representatives, etc. Institutions engaged in Arctic research need to reflect on existing funding mechanism systems and evaluate the ways in which they need to be improved to pay underrepresented and non-academic individuals efficiently and effectively for their work. Integrate cost-of-living adjustments and equitable pay structures for field support staff and community partners. Create funding mechanisms specifically designed for underrepresented and non-academic groups in polar research (e.g., community researchers, early-career Indigenous scholars, data stewards).	National funding agencies (e.g., Research Councils, EU Horizon, NSF) University consortia National and regional governments (for policy-level equity frameworks)
Better distribute long-term funding that encourages collaborative resource sharing	Reduce barriers to international collaboration. E.g., Incentivize inter-institutional resource sharing (e.g., equipment, data platforms, training programs). Establish multi-year core funding streams for Arctic research infrastructure, community engagement, and data stewardship. Support long-term career pathways by integrating positions for research data managers, community liaisons, and technicians into institutional budgets.	National funding agencies (to design sustained programs rather than project-based ones) University alliances and Arctic research networks (to develop shared infrastructure) National research councils and ministries (to adjust funding cycles and career structures)

Priority 5 *continued*: Funding system transformation.		
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Reduce institutional gatekeeping	Enable direct to community funding mechanisms to prioritize research led by Indigenous Knowledge holders and local communities. Simplify application and reporting processes to lower administrative barriers for non-academic and community partners. Require open review panels that include non-academic experts (e.g., Indigenous representatives, NGOs). Increase transparency in funding allocation and selection criteria.	Funding agencies and foundations University administration and research offices Arctic governance and advisory councils
Build and fund infrastructure that supports open, ethical, and collaborative science	Leverage existing university alliances to build interoperable data and code repositories aligned with FAIR and CARE principles. Invest in training programs for data stewardship and ethical data management. Provide sustained support for code and dataset maintenance post-publication.	Universities and inter-university alliances (for infrastructure development) International data consortia Funding bodies (to recognize and fund data/code maintenance as research output)
Establish governance and standards for ethical AI and data use	Develop Arctic-specific ethical frameworks for AI/ML applications in research. Require AI-related proposals to address bias, data sovereignty, and transparency. Foster cross-disciplinary oversight boards including Indigenous and data ethics experts.	International Arctic Council working groups Research ethics boards and data centers National funding agencies (to embed ethics requirements in grant calls)


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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?
Strengthen Arctic observation networks	Assign DOIs to datasets; conduct mid-term review at ASSW in 2030; require annual progress reporting.	AMAP, WCRP, INTERACT, POLARIN, SAON, national agencies, specific assigned working groups	Use networks as baseline datasets for IPY 2032–33 synthesis projects
Improve model parameterization	Track inclusion of new cryosphere modules in CMIP/CORDEX outputs; ensure all outputs cite “Produced under ICARP IV process.”	Climate modeling centers (CMIP6, CORDEX, ECMWF, Copernicus), IPCC WG I	Require model intercomparison projects at IPY to reference ICARP IV outcomes
Foster interdisciplinary collaboration and co-production	Monitor number of co-designed workshops, joint publications, and community agreements produced under ICARP IV.	IASC, Arctic Council, Indigenous Knowledge networks	Make co-production a core evaluation criterion for IPY projects
Develop targeted policy recommendations	Track references to ICARP IV outputs in Arctic Council statements, IPCC reports, and UNFCCC submissions.	National Arctic policy offices, NGOs, IPCC liaison groups	Ensure IPY policy briefs explicitly reference ICARP IV contributions

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Appendix 1: About RPT 2

1.1. Approaches / Methods used to complete the RPT 2 tasks

RPT 2 first met online on 28th February 2024, and then in person at the Arctic Science Summit Week in Edinburgh in Scotland (21st - 29th March). The meeting included the construction of a model for stakeholders in the ICARP process. Subgroups were set up to develop priorities and identify research gaps based on a literature review and consideration of submissions to the ICARP process via the central online form. The volume of literature was so large that artificial intelligence was used to produce summaries of part of it (see https://docs.google.com/spreadsheets/d/13WWl3q-ofNXEV718zzm0WpLuGWRqC5k_n6k9ngrqd7c/edit?gid=1034942738#gid=1034942738), although we note that these recommendations are distinct from that summary and our report has not been written using artificial intelligence. Individual sub-groups met independently over the summer of 2024 to produce a preliminary set of sub-group specific priorities. The cochairs met in Akureyri, Iceland, in October with these preliminary priorities, and coordinated with other RPTs. These priorities were then refined over the following five months in the lead up to the ICARP summit in Boulder, Colorado, USA, in March 2025, where the priorities were again presented and discussed at a community townhall meeting. This document was then produced based on discussions and fine-tuning at the summit.

1.2. Overlaps and Synergies with other RPTs

RTP 2 had significant overlap with RPT 1 ("The Arctic in the global system"). This was identified but not fully resolved at the cochairs meeting in Akureyri. Because of differences in the work timelines of the two groups, it was difficult to coordinate the efforts of the two groups which was challenging.

RPT2 should have more overlap with RPT 7 ("Technology, Infrastructure, Logistics and Services"), as RPT7 should take into account the needs identified by RPT2 for their planning.

RPT 2 also had significant overlap with RPT 5 ("Co-Production and Indigenous-led Arctic Research"). This was largely synergistic, particularly due to the differences in the team sizes (with RPT 2 being much larger than RPT 5).

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1.3. RPT 2 Membership

Author	Institution	Country
Co-Chairs		
Syndonia Bret-Harte	Institute of Arctic Biology/ Department of Biology & Wildlife, University of Alaska Fairbanks	United States
Wilson (Wai Yin) Cheung	Queen's University, Ice Climate and Environment Lab (ICElab), Department of Geography and Planning	Canada
Robbie Mallett	Earth Observation Group, UiT The Arctic University of Norway	Norway
Margaret Rudolf	International Arctic Research Center, University of Alaska Fairbanks	United States
Members		
Hélène Angot	CNRS, Institute of Environmental Geosciences	France
Manuel Bensi	National Institute of Oceanography and Applied Geophysics, OGS, Trieste	Italy
João Canário	Instituto Superior Técnico - University of Lisbon	Portugal
Lauren M. Divine	Aleut International Association	United States
Eugenie S. Euskirchen	University of Alaska Fairbanks, Institute of Arctic Biology	United States
Kaitlyn J. Fleming	Trent University, Trent School of the Environment	Canada
Lisa W. von Friesen	Linnaeus University	Sweden
Laura Ghigliotti	National Research Council of Italy, Institute for the study of Anthropic impacts and Sustainability in the marine environment	Italy
Ramona J. Heim	University of Münster, Institute of Landscape Ecology	Germany
Astrid Lampert	TU Braunschweig, Institute of Flight Guidance	Germany
Jan Rene Larsen	Secretariats of Arctic Monitoring and Assessment Programme (AMAP) and Sustaining Arctic Observing Networks (SAON)	Denmark
Maarten Loonen	University of Groningen, Arctic Centre	The Netherlands
Rob Middag	Royal Netherlands Institute for Sea Research	The Netherlands
Sue Natali	Woodwell Climate Research Center	United States
Shigeto Nishino	Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Japan
Anna H. Olafsdottir	Marine and Freshwater Research Institute, Iceland	Iceland
Kathleen Orndahl	Northern Arizona University	United States
Sergi Pla-Rabes	Universitat Autonoma de Barcelona & CREAF	Spain
Bjørg Risebrobakken	NORCE Research, Climate & Environment, and Bjerknes Centre for Climate Research	Norway
Brendan M Rogers	Woodwell Climate Research Center	United States
Alcide di Sarra	ENEA, Sustainability Department	Italy
Nozomu Takeuchi	Graduate School of Science, Chiba University	Japan
Vito Vitale	Consiglio Nazionale Ricerche (CNR) Institute of Polar Sciences (ISP)	Italy
Deniz Vural	Alfred Wegener Institute, University of Potsdam	Germany
Patrik Winiger	Laboratory for Atmospheric Chemistry, PSI Center for Energy and Environmental Sciences, Paul Scherrer Institute	Switzerland
Gabriel J. Wolken	International Arctic Research Center, University of Alaska Fairbanks	United States
Xiaofan Yang	Beijing Normal University, Faculty of Geographical Science	China

Appendix 2: Detailed Narratives of Research Needs / Gaps / Priorities

This appendix contains the longer, more detailed narratives for the Research Needs / Gaps and the Priorities that have been condensed into chapter 3. This information is provided for the sake of completeness, and to provide more detail to those who wish to see it.

2.1. Detailed Narratives for Research Needs / Gaps

RPT2 Research Need / Gap 1 Narrative: Data gaps in the Central Arctic Ocean and knowledge gaps along the Arctic land-shelf-basin continuum and between Arctic-Subarctic ocean linkages regarding ongoing climate change

How will ecosystem functioning and biogeochemical cycles in the Arctic Ocean change with new scenarios of global warming, sea ice reduction and state-shifts along the Arctic land-shelf-basin continuum and between Arctic and subarctic oceans? For example, increased fluvial input, permafrost thawing, and coastal erosion will cause changes in (micro-)nutrient input, ecosystem functioning and biogeochemical cycles, and their changes will propagate along the Arctic land-shelf-basin continuum through ocean circulation and dense water production. Enhanced influences from the Atlantic and Pacific to the Arctic Ocean will also impact the ecosystem functioning and biogeochemical cycles not only in the Atlantic and Pacific gateways but also in the Central Arctic Ocean where the data is definitely deficient.

On the other hand, the Arctic Ocean changes could cause state-shifts of subarctic oceans. For example, changes in outflow of freshwater, carbon and (micro-) nutrients, and dissolved organic matter from the Arctic Ocean may impact the Atlantic Meridional Overturning Circulation (AMOC). This would affect sequestration of carbon and other material into the deep water.

Long-term sustained observations and reconstructions from the Arctic Ocean are overwhelmingly lacking whereas climate change is both profound and fast in the Arctic region (polar amplification). The polar amplification is accelerating environmental (hydrographical and biogeochemical) and ecosystem changes along the Arctic land-shelf-basin continuum and its linked subarctic oceans with feedback on, e.g., the global climate, carbon cycles, biological productivity, and human activities such as shipping and fisheries. The changes in nearshore marine environments and ecosystems are critical for Arctic Indigenous communities.

RPT2 Research Need / Gap 2 Narrative: Understanding of environmental disturbances and ecosystem stability under climate warming

We lack comprehensive long-term data on the impacts of increased disturbances, such as more frequent wildfires and abrupt permafrost thaw. This limitation extends to our understanding of biotic interactions, species thresholds and potential ecological tipping points that could trigger irreversible ecosystem transformations.

Another critical area of uncertainty lies in the complex interactions among multiple climate and global change-related stressors, which can be both abiotic and biotic, as they relate to ecosystems, communities, populations and individuals. The combined effects of warming temperatures, fire, pollutants, and consumers on ecosystem dynamics, for instance, are poorly understood. Furthermore, our knowledge of species-specific responses and adaptations to changing Arctic conditions is insufficient.

Significant gaps also persist in our understanding of Arctic carbon cycle feedbacks, biogeochemical cycling, and biodiversity dynamics. Climate-induced disturbances, including weather-related events like permafrost thaw, rain-on-snow, droughts and floods, may alter carbon and nutrient storage and release patterns.

Climate change is rapidly transforming Arctic ecosystems, yet our understanding of these shifts remains incomplete. Both disturbance and more gradual changes have the potential to create feedback loops that could either accelerate or mitigate the effects of climate change. Furthermore, Arctic environmental change will have serious socio-ecological impacts e.g. on food security, water availability, and cultural practices.

RPT2 Research Need / Gap 3 Narrative: Knowledge gaps in the interactions at the interfaces between different spheres shape Arctic climate feedback mechanisms and Arctic ecosystems responses.
Natural and anthropogenic stressors are forcing large changes in the whole Arctic system. The different spheres (atmosphere, hydrosphere, cryosphere, lithosphere, biosphere, pedosphere, and anthroposphere) are often thematically assessed in individual silos, and the interaction of processes between them remains a key knowledge gap. Understanding interactive processes is crucial to predicting the effects of climate change, large scale feedback loops, and the triggering of tipping points.

The need to understand interactions between climate dynamics and ecosystem responses lies in their interactive nature. Understanding interaction between the atmosphere, cryosphere, land, inland waters and ocean systems under different global change scenarios, includes their effects on the socio-ecological systems and large-scale feedback loops, cascading effects, and tipping points. Interactive processes (e.g., atmospheric interconnection, carbon fluxes, change in fauna migrations and populations, contaminant distribution and impacts, human exploitation, invasive species, tipping points, ocean productivity) are often overlooked but can have substantial impact, and it is here put forward as an important knowledge gap covering local to global and Pan-Arctic scales.

RPT2 Research Need / Gap 4 Narrative: Observe and understand the impact of changes in the Arctic atmosphere's energy budget and precipitation patterns, as well as transport of moisture, contaminants, aerosols, and trace gases, on ecosystems and populations.
Global climate models suggest that the Arctic atmosphere will respond strongly to increasing concentrations of greenhouse gases. Independent from its driver, changes occurring in atmospheric circulation and precipitation patterns over different spatial scales, have a very large impact on Arctic environment and ecosystems. The impact can occur by altering local temperature, surface radiation, and precipitation, but also by a different contribution of heat, moisture, and aerosols and trace gases from the mid-latitudes. And finally, by altering the timing of seasonal events. Ecosystem changes can include habitat loss for species, disruptions to food webs, shifts in migration patterns, and increased stress on ecosystems from permafrost thaw, carbon release, remobilization of contaminants, wildfires and extreme weather events. Despite Arctic Amplification being a fundamental feature of past, present, and modelled future climate, the causes of this "amplification" within Earth's climate system are not fully understood. There is a need to better understand the relevance of local within-Arctic processes vs. external forces, as well as to deepen representation in climate regional models of their complex interconnection. Continuous and improved observations are important mainly to better identify relevance of different change drivers and provide input on local and regional scales, useful for ecosystem models as well as for decision-making actions to mitigate negative impact of a rapidly changing Arctic.

RPT2 Research Need/Gap 5 Narrative. Coupling models and observations of atmospheric circulation patterns over different spatial scales, from historical trends, current patterns to future predictions to better understand current state of knowledge and gaps.
The Atmosphere largely determines the input of mass, momentum and heat to all other spheres, connecting all of them. The impact of a changing Atmosphere needs to be assessed as well as possible considering its influence on life of ecosystems and humans. Society urgently needs regionally relevant predictions of how changes in atmospheric dynamics and connected processes impact their everyday lives, in order to be prepared for day to day activities as well as potential extreme events.

The Atmosphere is what connects all other ecosystems with each other and its climate forced changes need to be understood today, and historically to provide the basis for realistic predictions of an amplified Arctic change. Atmospheric changes affect extreme weather, sea ice behavior, and biosphere interactions, which urgently need to be understood to mitigate the adverse impacts of these changes. For the Arctic, a specific aspect is that changing circulation patterns may impact sources, pathways, and fate of some Contaminants of Emerging Arctic Concern (CEACs) to and in the Arctic. Regional forecasts are crucial for preparedness and adaptation strategies for Arctic communities. These predictions will influence everything from weather awareness to extreme events preparedness. Society urgently needs regionally relevant predictions of how changes in atmospheric dynamics impact their everyday lives, in order to be prepared for day to day activities as well as potential extreme events.

2.2. Detailed Narratives for Priorities for Arctic Research

RPT2 Research Priority 1 Narrative: Co-developing integrated monitoring and management frameworks with Arctic Indigenous Peoples

Co-developing integrated monitoring and management frameworks with Arctic Indigenous Peoples ensures that Indigenous Knowledge Systems are equally valued alongside scientific methods, leading to more holistic and effective solutions to environmental challenges. This approach supports Indigenous rights, sovereignty, and self-determination, while addressing urgent climate change impacts such as permafrost thaw, coastal erosion, and food security. By prioritizing co-development, ICARP IV can foster equitable partnerships, build trust, and deliver actionable research that benefits Arctic communities directly.

RPT2 Research Priority 2 Narrative: Enhance integrated cryosphere monitoring and modeling

The rapid pace of cryospheric change—sea ice retreat, permafrost thaw, and glacier melt—outstrips current modeling capabilities, leading to uncertainties in predicting climate dynamics and cryosphere and ecosystem responses (Smithsonian Magazine, 2022; van den Broeke et al., 2017; Schaedel et al,. 2024). Enhanced monitoring, using advanced remote sensing and in-situ stations, is critical to capture nonlinear feedbacks, such as permafrost greenhouse gas emissions and albedo changes (Schuur et al., 2015; Serreze & Barry, 2011) and identify hazards and evaluate potential landscape change for adaptation and mitigation planning (Wolken et al., 2021). Integrating Indigenous Knowledges further refines these models by adding socio-ecological insights, such as habitat shifts and water quality impacts, often overlooked by the academic scientific community (Pulitzer Center, 2023; Vogel et al., 2020). This priority addresses the urgent need to improve predictive accuracy for sea-level rise (up to 30 inches from Greenland alone if trends continue; Shepherd et al., 2020) and regional climate shifts (Cohen et al., 2014). It's actionable within the 2025–2035 timeframe through existing technologies and Arctic Council frameworks, making it a feasible ICARP IV focus. The scale of impact—global climate stabilization and local community resilience—justifies its inclusion.

RPT2 Research Priority 3 Narrative: Assess current and past Arctic Ocean circulation, characterizing Arctic land-shelf-basin and Arctic-Subarctic Ocean interactions, and their relations with marine biogeochemical cycles and ecosystem function

The Arctic Ocean circulation, including dense water production, is expected to change further in association with reductions in sea ice, with consequences for global ocean circulation, export of both (fresh) water and carbon/nutrients from the Arctic, and species distribution. Therefore, elucidating the impact of the change in the Arctic Ocean circulation on marine biogeochemical cycles and ecosystems in the Arctic and other ocean basins is an urgent issue.

Results from the Synoptic Arctic Survey (2020-2022) show that the ocean circulation in the Central Arctic is changing. As a result, low oxygen and acidified water that may impact the marine ecosystem, previously observed only in coastal areas, has been discovered in the central Arctic Ocean; and changes in nutrient and phytoplankton distributions could have occurred there. Moreover, currently we do not know what (micro-)nutrient will be limiting summer primary productivity in the future ice-free Arctic Ocean, leading to large uncertainties about future productivity and biological carbon uptake in addition to uncertainty about other carbon uptake pathways. Hence, we need to investigate the capacity of the Arctic Ocean to sequester atmospheric carbon under new scenarios of global warming, sea ice reduction, and changes in circulation and dense water production.

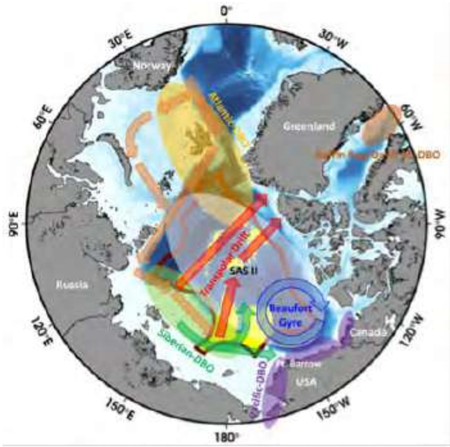
Information from past warm climates can inform on expected future changes. But, reconstruction from the central Arctic Ocean (and circum Arctic terrestrial locations) is almost non-existing.

It is important to sustain and implement long-term observations (with shared international initiatives) in the key areas of the Arctic Ocean, to monitor the change of and to guarantee the reconstruction of the Arctic Ocean circulation and its interaction with marine biogeochemical cycles and ecosystems. To detect changes in biodiversity and ecosystem functionality, as well as an improved knowledge of ecological patterns and processes are key to supporting environmental management and conservation.

Priority 3: Assess current and past Arctic Ocean circulation, characterizing Arctic land-shelf-basin and Arctic-Subarctic Ocean interactions, and their relations to marine biogeochemical cycles and ecosystem function.		
Geographical scale:	Pan-Arctic with local to global implications through the Atlantic Meridional Overturning Circulation (AMOC).	
Time scale:	For the next 5 to 10 years and beyond.	
Funding requirements and potential sources:	Funding is required in support of: • Platforms that facilitate integrated expedition activities across individually funded projects. This secures possibility for activities that are quality checked through individual nations funding schemes. • Development of modular and scalable platforms for deployment in the various Arctic environments and collection of high resolution observations. • Integration of artificial intelligence (AI)-driven navigation systems in robotic platforms to improve data collection in remote areas (e.g. deep ocean and under-ice environments), to upscale the spatial and temporal coverage, and to reduce the risk for human operators in the field. • Improvement of machine learning systems for use in marine ecosystem monitoring and management. Potential sources may be: • National and international research funding agencies • Private sector for technological development, machine learning and computing support	
Infrastructure needs and requirements:	• Research icebreaker (needs) for an international research platform (requirements). • Maintenance of the ARGO float programme. • Data systems and computer	
Data needs and requirements:	• Hydrographic data • Marine biogeochemical (including bio-essential (micro-nutrients) and potentially toxic (pollutants) trace metals) data • Biological datasets (including high taxonomic resolution inventories through morphological, DNA-based, and physiological rate approaches) • Sea ice reconstructions, in particular from past warm climate states • Pan-Arctic data synthesis from multiple projects	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Coordinated and sustained cross basin (coast to deep ocean) multi-nation wide-area observations	Use icebreakers and long-term in situ observation platforms (e.g., oceanographic moorings) as international shared research infrastructures to expand current spatial and temporal data collection coverage (e.g. guarantee data collection in key areas even during winter season). There are existing initiatives and programs that support long-term integrated measures; however, it is necessary to ensure that they are maintained. The Pan-Arctic Distributed Biological Observatory (DBO), which is an integrated project across the Pacific, Atlantic, Siberian, and Baffin Bay/Davis Strait DBOs, conducts observations (monitoring) in the waters surrounding the central Arctic Ocean every year or every few years. The changes in the marine environment and ecosystem observed by the Pan-Arctic DBO are expected to spread and accumulate in the central Arctic Ocean.	Establishment of an international pool of collaborative infrastructure platforms financed by national governments (e.g. icebreakers), with equal opportunities for funded projects/activities. This could promote a transfer from single project expeditions to integrated, collaborative expeditions addressing the full Earth System at any sites, securing comparable data in time and space from key sites.

Priority 3 *continued*:
Assess current and past Arctic Ocean circulation, characterizing Arctic land-shelf-basin and Arctic-Subarctic Ocean interactions, and their relations to marine biogeochemical cycles and ecosystem function.

Implementation:

Implementation actions:	**How to implement the actions:**	**Who to address the actions:**
	 Nishino et al. (2025) https://doi.org/10.1016/j.polar.2025.101210 A second project of the Synoptic Arctic Survey (SAS II) is planning to conduct observations (mapping) in the central Arctic Ocean around 2030. The SAS II could help understand the changes in the environment and ecosystem of the central Arctic Ocean, which is a limited data area, on a time scale of about 10 years. Changes in the marine environment and ecosystem are thought to spread to the central Arctic Ocean through ocean circulation, so it is important to observe the Beaufort Gyre off Alaska and the Transpolar Drift off Siberia. These currents are located along the Chukchi Plateau and Lomonosov/Mendeleev Ridges, which have relatively shallow seafloors and are thought to be fishable areas, so they could also provide useful information for the Central Arctic Ocean Fisheries Agreement (CAOFA). It is further important to understand the marine-terrestrial interaction in coastal regions. Changes in coastal regions will have a profound influence for local communities, but also affect the open ocean where notably the productivity of marine ecosystems is primarily dependent on microbes and the supply of essential macro- and micro-nutrients (e.g. nitrate or iron). Hence, focus should be put on the underpinning ecosystem functions and biogeochemical cycles that form the basis of life in the Arctic. Improved taxonomic resolution and biomass estimation is also required for the macro-fauna of commercial but also non commercial or stake-holder interest: to expand current knowledge of seasonal and spatial patterns of pan-Arctic community structures, including species composition, biodiversity, connectivity, abundance, productivity, and timing of blooms and reproduction, is key to a throughout understanding of the cascading effects of environmental changes on the ecosystem functionality.	
Interdisciplinary coordinated actions in support of the co-development of modular and scalable platforms for data collection and high resolution observations	Bring together expertise from different fields to discuss critical weaknesses of the Arctic Ocean observing system and collaboratively create more effective technological solutions in support of automated collection of standardized data, and improved spatial and temporal coverage (e.g. data collection in the vicinity of glacier ice fronts or in the winter).	Ideally, the technological innovation co-production process should involve: • Federal and international research agencies • Scientific organizations and universities • Indigenous and Arctic residents organizations

RPT2 Research Priority 4 Narrative. Understanding Arctic disturbances and ecosystem stability under climate change

Research priorities for Arctic ecosystems should focus on comprehensive, long-term monitoring of disturbances. Identifying potential ecological tipping points is crucial for predicting and potentially mitigating irreversible ecosystem transformations. Experimental, observational and paleoecological studies should investigate the collective influence of factors such as warming temperatures, altered precipitation patterns, increased fire frequency, and changing wildlife populations on Arctic ecosystem dynamics.

Furthermore, research efforts should examine how individual Arctic species respond and potentially adapt to changing environmental conditions, including phenological shifts, range expansions or contractions, and physiological adaptations. Studies should also explore how climate change and disturbances affect carbon and nutrient storage and release patterns. Lastly, research should prioritize identifying factors that contribute to ecosystem resilience and stability in the face of rapid climate change.

Priority 4: Understanding Arctic disturbances and ecosystem stability under climate change.		
Geographical scale:	Local, regional, pan-Arctic	
Funding requirements and potential sources:	• Long-term, sustained funding is required • Potential funding sources include national and international research funding agencies, Arctic research initiatives, and international scientific organizations. Specific examples can be drawn from the “who should address these actions?” section of each Implementation Action	
Infrastructure needs and requirements:	Maintenance of remote sensing platforms such as satellites, drones and ARGOS tracking infrastructure.	
Data needs and requirements:	• Long-term in situ data: vegetation inventory and monitoring, eddy covariance data from flux towers • Paleoecological data: tree ring data, lake and peatlands sediment records, ice cores • Remotely sensed data: satellite imagery, active sensor data, airborne and UAV based imagery, animal movement data • Genetic/genomic data • Indigenous knowledge and community base monitoring	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Prioritize long-term monitoring of disturbances, undisturbed control sites, and ecosystem change. To understand ecosystem resilience, we need to assess places that are not changing, as well as places that are changing, as the climate warms.	Understanding Arctic vulnerability and stability to change requires sustained, uninterrupted, long-term monitoring combined with reconstructions of natural variability to change. This can be accomplished by first utilizing and expanding existing monitoring capacity. For example, enhancing coordination between established research stations or observation networks to improve efficiency and expand the scope of coverage. Existing networks could also be expanded to cover larger spatial areas or to include additional measurements. Second, efforts should be directed to establish new long-term observation networks, focusing on current gaps in Arctic data collection and, where appropriate, community based monitoring. Third, paleoecological data can extend the study timeframe to centuries or even millennia, offering valuable insights into the long-term stability and resilience of Arctic ecosystems across the study area under varying climate and environmental conditions. In all cases, uninterrupted funding and operation are critical to success.	International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF), International Permafrost Association Existing initiatives/programs: Circumpolar Arctic Vegetation Science Initiative (CAVSI), Arctic Vegetation Archive (AVA), the international tundra experiment (ITEX), U.S. National Science Foundation’s National Ecological Observatory Network (NEON), U.S. National Science Foundation’s Long Term Ecological Research (LTER) Network, U.S. National Science Foundation’s Arctic Observatory Network (AON), GTN-P, CALM Scientific organizations and universities

Priority 4 *continued*:
Understanding Arctic disturbances and ecosystem stability under climate change.

Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Prioritize community-based monitoring	Establish community-based monitoring programs that engage with rightsholders and stakeholders in tracking disturbances and species shifts. Develop/ adopt standardized monitoring protocols with scientific guidance and local input. Facilitate regular training sessions and workshops to build local capacity for data collection, analysis and interpretation. Collaboration with existing observation networks would be helpful.	Local governments and Indigenous organizations: e.g. Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council, Kawerak Inc., local Indigenous governments and communities Environmental NGOs and community-based monitoring programs Scientific organizations and universities Federal agencies supporting Arctic research and monitoring International Arctic agencies: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF), SAON
Study the socio-ecological impacts of disturbance / change (e.g. fire, permafrost thaw, coastal erosion) on food security, water, and cultural practices	Facilitate coordination between natural and social scientists to better understand issues at the socio-ecological intersection. Prioritize Indigenous led research that centers issues of greatest importance to communities. Focus efforts on assessing and mapping the risk of disturbances and environmental changes across Arctic communities. Utilise historical and paleodata to comprehend past permafrost dynamics, wildfire regimes, hydrological patterns, polynya, biogeochemical, and biodiversity dynamics.	International Arctic agencies: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF) Local governments and Indigenous organizations: e.g. Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council, Kawerak Inc., local Indigenous governments and communities Scientific organizations and universities
Identify factors that determine ecosystem resilience or vulnerability in the face of rapid climate change	To understand Arctic ecosystem resilience, a multi-pronged approach is necessary. Research should aim to incorporate data from: controlled experiments, paleoecological approaches, long-term field studies, genetic and genomic analysis, Indigenous knowledge, and remote sensing and satellite imagery. More specifically: • Controlled experiments can be used to assess species' adaptive capabilities. • Genetic data can be used to identify adaptive traits and assess species' evolutionary potential. • Paleoecological approaches can establish baseline conditions and provide context regarding past tipping points and ecosystem stability under different climate and environmental scenarios across the Arctic region • Indigenous knowledge can provide intimate, place-based information that contextualizes Arctic ecosystem resilience and change. • Long-term in situ data can be used to identify key factors contributing to multidimensional stability. • Remote sensing and satellite imagery can be used to track large-scale ecosystem changes, and understand spatial patterns of Arctic ecosystem resilience and vulnerability	Scientific organizations and universities Initiatives supporting Arctic inventory and monitoring: Circumpolar Arctic Vegetation Science Initiative (CAVSI), Arctic Vegetation Archive (AVA), the international tundra experiment (ITEX), U.S. National Science Foundation's National Ecological Observatory Network (NEON), U.S. National Science Foundation's Long Term Ecological Research (LTER) Network, International Long Term Ecological Research (ILTER) Network, Critical Zone Observatories (CZO), U.S. National Science Foundation's Arctic Observatory Network (AON) Local governments and Indigenous organizations: e.g. Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council, Kawerak Inc., local Indigenous governments and communities Federal and international research agencies

RPT2 Research Priority 5 Narrative: Identifying and understanding the underlying key interactive processes at the interface between spheres to enable prediction of larger-scale impacts and responses through the integration of reconstructions, observations, and modeling approaches.

With a changing climate, the coupling between spheres of the Arctic system are changing. To cover interactive processes at the interfaces between spheres, it is a priority to integrate observational, modeling and reconstruction approaches. Particular emphasis should be placed on feedback loops that can result in tipping points (e.g. transition of the Arctic from a white to a blue system with sea ice disappearance or terrestrial Arctic greening). Further, attention should be paid to cascading effects and linkages across Arctic systems such as changes in marine, terrestrial and freshwater biological productivity resulting from warming effects on precipitation patterns, cryosphere dynamics, and atmospheric pollution; that alter glacier dust deposition, runoff, weathering rates , permafrost dynamics, cloud properties and surface energy budget.

Priority 5: Identifying and understanding the underlying key interactive processes at the interface between spheres to enable prediction of larger-scale impacts and responses through the integration of reconstructions, observations and modeling approaches		
Geographical scale:	All scales	
Time scale:	Relevant now and for the next 10 years into the future.	
Funding requirements and potential sources:	Small project grants to large consortia	
Data needs and requirements:	It remains unknown how the interactions at the interfaces between different spheres shape Arctic climate feedback mechanisms and Arctic ecosystems responses. Data is needed from all interfaces between these spheres.	
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Integrate observational, modeling and reconstruction approaches	Coordination and establishment of communication and collaboration between researchers with expertise in different fields/ methodologies to identify specific needs to bridge the gaps.	Individual researchers and/or expert groups coming together
Form interdisciplinary working groups on small and larger scales (e.g. individual projects and larger consortia)	Establish closer communication between different institutions and scientific fields, organize interdisciplinary research schools and field work campaigns. Initiate targeted research projects and share resources.	Individual researchers, IASC working groups (cross-cutting approaches), coordinate with national and international initiatives (e.g. Synoptic Arctic Survey SAS, Global Ocean observing system GOOS, Distributed biological observatory DBO, POLARIN, Polhavet 2050)
Technological and methodological advancement across scientific fields, specifically targeting interfaces between spheres	Develop new technology and methodology together across fields (e.g. modular measurement platforms, robotic systems, satellites)	Individual researchers, IASC working groups (cross-cutting approaches), coordinate with national and international initiatives (e.g. Synoptic Arctic Survey SAS, Global Ocean observing system GOOS, Distributed biological observatory DBO, POLARIN, International Polar Year)
Identify and study feedback loops (e.g. albedo changes due to increasing ocean warming, interactions between permafrost changes, atmospheric emissions, perturbation to the energy budget and surface mass balance; linkages between dust, wildfires, atmospheric composition, surface albedo, etc.) that can result in tipping points (e.g. transition of the Arctic from a white to a blue system with sea ice disappearance or terrestrial arctic greening)	Observational needs must be identified, ideally with the help of models and model users, the findings need to be shared on an interactive, open-source, virtual Arctic knowledge space	Individual researchers, IASC working groups (cross-cutting approaches), coordinate with national and international initiatives (e.g. Synoptic Arctic Survey SAS, Global Ocean observing system GOOS, Distributed biological observatory DBO, POLARIN, International Polar Year)
Attention should be paid to cascading effects and linkages across Arctic systems such as changes in marine, terrestrial and freshwater biological productivity resulting from warming effects on precipitation patterns, cryosphere dynamics, atmospheric pollution and clouds; that alter glacier dust deposition, runoff, weathering rates, permafrost dynamics, cloud properties and surface energy budget.	Observational needs need to be identified, ideally with the help of models and model users, the findings need to be shared on an interactive, open-source, virtual Arctic knowledge space	Individual researchers, IASC working groups (cross-cutting approaches), coordinate with national and international initiatives (e.g. Synoptic Arctic Survey SAS, Global Ocean observing system GOOS, Distributed biological observatory DBO, POLARIN, International Polar Year, Polhavet 2050)

Additional implementation steps:

Priority: Coupling models and observations of atmospheric circulation patterns over different spatial scales, from historical trends, current patterns to future predictions to better understand current state of knowledge and gaps.	
Geographical scale:	All scales
Time scale:	Relevant now, but as time progresses increasingly more relevant due to expected changes in the system
Funding requirements and potential sources:	Small project grants to large consortia
Infrastructure needs and requirements:	Harmonization of observations (NEED); Promote / encourage networks at regional and pan-Arctic Scale (RECOMMENDATION); Better connect to Global observing networks (RECOMMENDATION).
Data needs and requirements:	Observations combining methods, (enhanced ground-based network and dedicated airborne campaigns, advanced remote sensing techniques, ship-based campaigns), closely coupled to modeling activities of different complexity (reanalyses, paleo reconstructions) using advanced analysis tools (artificial intelligence)

Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Promote International collaborative effort	Funding calls should be identified/created and distributed to reach Arctic stakeholders and rights holders	Ideally a high-level interest groups or organisation
Enhanced ground-based network, i.e. carry out additional projects, enhancing the already existing facilities	Relevant ground-based stations need to be identified and scouted for the possibility of implementing enhanced campaigns with multiple participants	Scientists, Station owners
Airborne campaigns	Platforms need to be identified, made available and accessible	Scientists, Platform owners
Remote sensing techniques	Identify relevant satellites and make use of their data	Scientists
Ship-based campaigns	Platforms need to be identified, made available and accessible	Scientists, Ship owners
Observations coupled to modeling activities	Observational needs need to be identified, ideally with the help of models and model users, the findings need to be shared on an interactive, open-source, virtual Arctic knowledge space	Scientists, stakeholders, rights holders

Cross-Cutting Research Need 1 Narrative: Sufficient Indigenous participation in Arctic research

1) How Arctic research, including Arctic observations, reconstructing, and predicting, are actionable for Indigenous self-determination and supporting Indigenous rights and sovereignty, and 2) Consideration of ethics and actions for Arctic research, including past environmental data collection, without free, prior, and informed consent, and lack of support for Indigenous data sovereignty.

Regional research recommendations from Arctic Indigenous groups have common themes of research relevant to Arctic Indigenous communities, increased participation of Arctic Indigenous Peoples, scientific and Indigenous knowledge being utilized by policy decision-makers, and co-production of knowledge and decolonial methodologies. These groups, including but not limited to Inuit Circumpolar Council, Inuit Tapiriit Kanatami, Naalakkersuitsut, and Sami Council, have put forth guidelines on how they and their communities want to interact with scientists/researchers and funding agencies.

Cross-Cutting Research Need 2 Narrative: The status of data collection across the Arctic: geographic, temporal, and subject matter coverage

Arctic science has a decades long history of data collection and sharing. However, most data collection has historically been performed in an ad hoc manner resulting in data that is collected for specific projects, often over short time periods, and regularly in an opportunistic manner resulting in data “hotspots” around field stations, roads, and other infrastructure with geographic gaps elsewhere. Additionally, although community-wide data repositories do exist, data are not always publicly archived or shared between nations, research organizations, government agencies, academic institutions and/or disciplines.

Due to the current lack of knowledge on the status of data collection across the Arctic, the Arctic science community risks duplicating efforts collecting data that might already exist.

Cross-Cutting Research Need 3 Narrative: Modeling capabilities for hindcasting and future projections of terrestrial ecosystem responses

The current generation of process-based models, from site-level, to global-scale land surface models contained within Earth system models, contain longstanding and well-documented limitations for terrestrial ecosystems. These limitations are particularly acute with regards to: interactions between the terrestrial environment and permafrost thaw, including dynamic thermokarst processes; nutrient cycling; herbivory; changing vegetation composition and ranges; interactions with disturbances; and snow and soil moisture dynamics. Hindcasting models under previous paleoclimates is not frequently done, but can be beneficial for understanding paleo environments, establishing baseline conditions (especially with regard to disturbance), and validating model response under different climates.

Process-based models remain the best, and often only, way of projecting future Arctic terrestrial ecosystem responses and feedbacks to climate change.

Cross-Cutting Research Need 4 Narrative: Integration of diverse knowledge systems and research techniques for understanding terrestrial and inland water ecosystems and cryosphere research in the Arctic

There is a critical knowledge gap in the effective integration of Indigenous Knowledge with contemporary scientific methods for understanding and managing terrestrial and inland water ecosystems in the Arctic. While Indigenous communities possess extensive, long-term observations of environmental changes, including ecosystem dynamics, seasonal variations, and species behaviour, these insights are often undervalued or disconnected from scientific research that predominantly relies on field data, remote sensing technologies, and manipulative experiments.

This gap is further compounded by challenges in reconciling different temporal and spatial scales—Indigenous Knowledge often provides highly localized, long-term, and context-specific observations, while scientific techniques like remote sensing and manipulative experiments tend to emphasize broader regional patterns or controlled, short-term studies.

Filling this gap requires developing frameworks that prioritize equitable collaboration with Indigenous communities, encourage co-production of knowledge, and combine diverse research methodologies to yield more holistic insights into the functioning and sustainability of Arctic terrestrial and freshwater ecosystems.

There's a gap in systematically incorporating Indigenous and local knowledge into cryosphere monitoring and climate modeling, despite its proven value in understanding socio-ecological impacts, such as permafrost thaw effects on wildlife, water quality, hazards, and various aspects of the ecosystem.

The lack of integration of diverse knowledge systems (i.e. Indigenous knowledge and contemporary scientific methods) means that critical insights into the resilience and tipping points of ecosystems, particularly under the pressures of climate change, may be missed or underutilized.

This need enhances research relevance and accuracy across RPTs (e.g., ecosystems, human dimensions) by adding local perspectives to scientific data (Cochran et al., 2013; Pearce et al., 2015). It's feasible via existing community networks and has high impact for policy and adaptation, justifying its urgency for 2025–2035.

Cross-Cutting Priority 1 Narrative: Strengthening Indigenous-led governance and decision-making in Arctic research

Strengthening Indigenous-led governance in Arctic research is critical for ensuring that research practices are equitable, inclusive, and aligned with the needs and rights of Indigenous communities. This priority addresses historical inequities, supports self-determination, and fosters long-term partnerships that enhance the relevance and impact of Arctic research. By prioritizing Indigenous-led governance, ICARP IV can set a global standard for ethical and impactful research that benefits both Indigenous communities and the broader scientific community.

Cross-Cutting Priority 2 Narrative: Foster partnerships between scientists and Indigenous communities

Integrating Indigenous knowledge into cryosphere and biosphere research addresses gaps in understanding socio-ecological impacts (e.g., habitat loss, water quality) that complement physical science (Pulitzer Center, 2023). This priority is urgent as cryospheric changes disrupt Indigenous livelihoods, requiring adaptive strategies informed by both science and traditional ecological knowledge (CAFF/PAME, 2022; Krupnik & Jolly, 2002). It's feasible through Arctic Council programs and builds resilience across RPT topics like ecosystems and societies. The global relevance of accurate climate predictions justifies its inclusion.

Cross-Cutting Priority 3 Narrative: Fund long-term data collection programs and emphasize cross-boundary data sharing

Although data has been collected across the Arctic for decades, these data are not always publicly available, oftentimes not standardized, and not necessarily suitable for establishing the long-term records of change needed to assess climate change impacts across the region. A concerted effort is needed to assess the status of data collection across the Arctic, aggregate data from disparate sources, and, where possible, make existing data publicly available. This will allow researchers to truly assess where data gaps exist, both geographically, temporally and across disciplines. Strengthening cooperation among international research organizations, government agencies, research institutions, Indigenous communities, and policymakers will be crucial to this process. Looking forward there is a need for long-term, funded, monitoring programs to collect baseline data for various ecosystems and track environmental change. Continuous monitoring of vegetation, permafrost, biodiversity, terrestrial carbon flux, inland waters and ecosystem dynamics is crucial to building a complete understanding of Arctic terrestrial ecosystems and how they are likely to change as the climate warms. This should include the establishment of permanent networks, standardized protocols, and regular assessments to track changes over time. This should also include enhancing observation systems, utilizing advancing technologies like remote sensing, incorporating Indigenous Knowledge, and integrating paleoecological approaches to increase the geographical and temporal scope of data collection across the region through international and cross-discipline cooperation. These needs are particularly acute for terrestrial ecosystems where field stations are often operated at the national level and international collaboration can be challenging. Existing efforts such as the international tundra experiment (ITEX), INTERACT research stations, and the U.S. National Science Foundation's National Ecological Observatory Network (NEON) are models that can either be expanded or used as examples for future networks.

Priority : Fund long-term data collection programs and emphasize cross-boundary data sharing.	
Geographical scale:	Pan-Arctic
Time scale:	For the next 10 years
Funding requirements and potential sources:	Sustained funding for existing long term observation and research programs, which can be addressed by national funding agencies and international funding agencies (e.g. the European Union); data sharing can be enhanced by international agreements at a political level, and by convergence on metadata standards that allow data to be easily found. Multi-national funding is required for development and continuity of data management, archival, and availability
Infrastructure needs and requirements:	Establish new research stations in geographical areas with identified data gaps Development of a pan-Arctic data portal
Data needs and requirements:	This priority addresses data across all disciplines and outlines desirable characteristics of data collection and storage over the next 10 years. This includes: • Data that fills existing gaps and connects the different spheres • Data that is collected and archived using standardized protocols • Data that adheres to equitable Arctic research principles • Inventory of existing observation datasets • Analysis to support implementation of new observation networks to fill gaps and benefit societal needs

Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Coordinate with IPY-5	Prioritize communication between IPY-5 and ICARP IV committees to align efforts and combine resources.	IASC, SCAR and other IPY supporters: the World Meteorological Organization (WMO), International Science Council (ISC), University of the Arctic, International Arctic Social Sciences Association (IASSA), the Association of Polar Early Career Scientists (APECS)
Identify and focus efforts on filling geographic gaps in data collection	Metcalfe et al., 2018 provide a good framework for addressing sampling bias and filling in geographic gaps in Arctic data collection: • Conduct a comprehensive review of existing Arctic data in several languages to improve integration of literature from poorly cited areas, and non-English data sources. • Expand observations at existing research stations and establish new research stations in regions with identified data gaps. • Plan expeditions to underrepresented areas, like the Russian Arctic & Canadian Arctic. Metcalfe, D.B., Hermans, T.D., Ahlstrand, J., Becker, M., Berggren, M., Björk, R.G., Björkman, M.P., Blok, D., Chaudhary, N., Chisholm, C. and Classen, A.T., 2018. Patchy field sampling biases understanding of climate change impacts across the Arctic. Nature ecology & evolution, 2(9), pp.1443-1448.	Data management centers: DataOne, Environmental Data Initiative (EDI), Arctic Data Center (ADC), Copernicus Arctic Hub, SAON Data Portal, Movebank, Indigenous data centers Universities and research institutions, particularly those from underrepresented areas Indigenous organizations and community-driven monitoring programs Federal and international research agencies
Strengthening cooperation among international research organizations, government agencies, research institutions, Indigenous communities, and policymakers	Strong cooperation will require a concerted effort to develop, fund and prioritize cross-boundary programs and organizations. For example: • Prioritize international sources of funding that facilitate cross-border cooperation. • Expand international research networks. • Develop joint research programs and projects. • Organize regular Arctic Science Summit Weeks and other international Arctic science conferences to facilitate face-to-face interactions and knowledge sharing. • Develop agreements and programs to facilitate cross-border research station access. • Develop formal agreements on enhancing international Arctic scientific cooperation. • Prioritize co-production of research with Indigenous People and communities. • Improve education on equitable Arctic research practices.	Arctic Council Funding agencies and governments Indigenous organizations: Inuit Circumpolar Council, Aleut International Association, Arctic Athabaskan Council, Gwich'in Council International, Russian Association of Indigenous Peoples of the North, Saami Council

Priority *continued*: Fund long-term data collection programs and emphasize cross-boundary data sharing.		
Implementation: **Implementation actions:**	**How to implement the actions:**	**Who to address the actions:**
Establish and fund permanent observation networks	Continue to fund existing long-term research stations and observation networks, because long term, uninterrupted records are extremely valuable for detecting change, and long term research at field stations provide context for understanding ecological processes and predicting future ecosystem responses. Establish new long-term research stations and observation networks, focusing on filling existing gaps in Arctic data collection. A "hub and spoke collaboration" between field stations and community based observation networks might be helpful in some places. Selection of key sites for expansion of long monitoring data series through reconstructions.	International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF) Initiatives supporting Arctic inventory and monitoring: Circumpolar Arctic Vegetation Science Initiative (CAVSI), Arctic Vegetation Archive (AVA), the international tundra experiment (ITEX), U.S. National Science Foundation's National Ecological Observatory Network (NEON), U.S. National Science Foundation's Long Term Ecological Research (LTER) Network, International Long Term Ecological Research (ILTER) Network, Critical Zone Observatories (CZO), U.S. National Science Foundation's Arctic Observatory Network (AON), Permafrost Pathways (US Program).
Develop and publicise standardized protocols for data collection and processing	Develop standardized protocols for data collection and processing in conjunction with efforts to coordinate and continue long-term monitoring programs. Protocols should encompass a wide range of field data collection types and be detailed, yet flexible enough to account for resource differences amongst researchers. Protocols related to community based monitoring, and field data collection suitable for remotely sensed mapping should also be considered.	International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF) Initiatives supporting Arctic inventory and monitoring: Circumpolar Arctic Vegetation Science Initiative (CAVSI), Arctic Vegetation Archive (AVA), the international tundra experiment (ITEX), U.S. National Science Foundation's National Ecological Observatory Network (NEON), U.S. National Science Foundation's Long Term Ecological Research (LTER) Network, International Long Term Ecological Research (ILTER) Network, Critical Zone Observatories (CZO), U.S. National Science Foundation's Arctic Observatory Network (AON), SAON, GTN-P, CALM.
Develop or support existing development of a pan-Arctic, cross-discipline data portal	Support development of a pan-Arctic data portal. This would involve aggregating and synthesizing existing data, building off efforts of existing data portals. Ideally, the portal could host all types of data (e.g. field based, observational, experimental, remotely sensed) from all scientific disciplines. The portal needs to be easy to find, easy to use, and accessible to all. It should be available for free and should not require log-in information or a specific type of affiliation to use.	Data management centers: DataOne, Environmental Data Initiative (EDI), Arctic Data Center (ADC), Copernicus Arctic Hub, SAON Data Portal, Movebank, Permafrost Discovery Gateway Universities and research institutions with expertise in data management, web design, and Arctic science International scientific organizations: WCRP, INTERACT, EU Horizon, Arctic Council WGs (AMAP, CAFF) Initiatives supporting Arctic inventory and monitoring: Circumpolar Arctic Vegetation Science Initiative (CAVSI), Arctic Vegetation Archive (AVA), the international tundra experiment (ITEX), U.S. National Science Foundation's National Ecological Observatory Network (NEON), U.S. National Science Foundation's Long Term Ecological Research (LTER) Network, International Long Term Ecological Research (ILTER) Network, Critical Zone Observatories (CZO); U.S. National Science Foundation's Arctic Observatory Network (AON), SAON, GTN-P, CALM

Cross-Cutting Priority 4 Narrative: Improving modeling capabilities for Arctic terrestrial ecosystems, inland water ecosystems, marine ecosystems, and for the atmosphere, to better represent cryospheric and transport processes

Addressing this gap will require a concerted effort among modelers, data providers, and funders. Modeling gaps have been identified; what's needed now is a multi-national effort to fund model development and coordinate developments among modeling groups. Typical funding structures, especially from government agencies, do not prioritize model development, and therefore progress in addressing modeling gaps has been relatively slow. Additionally, process-based terrestrial ecosystem modeling groups have historically not coordinated developments. A closer coordination could speed progress, especially with new mechanisms for code modularity, sharing, and interoperability. Increased communication between modeling and empirical research communities, as well as local communities, would help prioritize and address dataset development needed for modeling.

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ICARP IV Research Priority Team (RPT) 2. Final Report: Observing, Reconstructing, and Predicting Future Climate Dynamics and Ecosystem Responses

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