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Roadmap for optimisation of monitoring and modelling programmes

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Executive Summary

The document reviews a series of recent documents for their recommendations on Polar monitoring/observing and modelling. The majority (34) of the 41 documents had an Arctic focus, three had an Antarctic focus and four covered both areas. The recommendations are in general about the need for long-term, sustained observing, resulting in longer time-series of data. There is a need for a better spatial coverage and the inclusion of more variables in current monitoring/observing activities.

The document recommends a *Roadmap for Optimisation of Monitoring and Modelling Programmes for the Polar Regions* (ROMP). It should proceed under the following principles and assumptions:

- ROMP should complement and integrate, without duplication, the current planning approaches used by existing networks (national, regional or global), activities and projects.
- ROMP should support step-wise development through a flexible, federated and evolving structure that allows “bottom-up” identification of themes and foci. It recommends the definition of Essential Variables for the Polar Regions.
- Indigenous participation is critical to ROMP from its inception through its implementation.

1. Introduction. Scope and limitations

In recent decades, sustained observations of Polar environmental and socio-economic systems have revealed a pace, magnitude, and extent of change that is unprecedented by many measures. These changes include rapid depletion of the cryosphere in the Arctic (AMAP, 2017) and shifts in ecological communities (CAFF, 2013) that threaten biodiversity and resilience across northern communities. In addition to climatic and environmental changes, industrial development (including resource extraction and fisheries) and demography put pressure on indigenous livelihoods and social and cultural wellbeing of Arctic indigenous peoples.

These changes are not confined to the Polar Regions. Melting Polar land ice affects sea level globally, while regional alterations to the atmosphere and ocean influence the timing and severity of weather in mid-latitudes and global ocean circulation. Sustained observations of the regions along with model projections provide critical insights, yet Polar observations are currently too limited and insufficiently coordinated to adequately inform adaptive responses. As the Polar Regions are vast and span many national boundaries, international sharing of observation data and cooperation between observation systems is critical.

The aim of this deliverable D2.6 is to provide “a scheme for optimisation of infrastructure use”. In consultation with EU-PolarNet Consortium members it was decided early in the process to separate the "Roadmap for optimisation of monitoring and modelling programmes" from the infrastructures required for delivering them (data infrastructures as well as physical infrastructures), as these issues are dealt with more thoroughly in Work Package 3 ("Infrastructures, Facilities, and Data").

Inputs to this deliverable D2.6 are deliverables D2.3 ('Release of the inventory of existing monitoring and modelling programmes') and D2.5 ('Strategic analysis of monitoring and modelling programmes'). As described in D2.3 and D2.5, the inventories and the gap analysis based on them had shortcomings. In consultation with EU-PolarNet Consortium members, it was decided to supplement the gap analysis with a review of recommendations from recent documents that offer recommendations on polar monitoring/observing programmes and modelling. This supplementary process is described in section 2 ('Methodology').

Following the analysis, the document describes a roadmap or framework for the development of polar monitoring/observing and modelling. The document does not attempt to design or re-design polar observing, as this is the task for the participants in the described processes. The document offers overall recommendations for establishing requirements for a polar observing system, the essential variables to be measured, and how their data and products will be managed and made widely available.

The current deliverable is a contribution to EU-PolarNet Task 2.3 ("Optimisation of existing monitoring and modelling programmes") of Work Package 2 ("Polar research for Science and Society").

2. Methodology

2.1 Strategic analysis of monitoring and modelling programmes

The gap analysis provided in D2.5 had focus on gaps in polar monitoring/observation themes and in spatial coverage. The themes were the *European Polar Research Priorities* as identified in D2.1, and these were matched against the inventory of monitoring and modelling programmes as identified in D2.3 (See Appendix A). The spatial analysis of the monitoring/observing programmes was based on geographical mapping of the programmes' station/sampling locations. The analysis was complemented with additional input from key players and selected sources. The document pointed out that the analysis was limited by the contents and scope of the inventories and points out that information may have been missing.

2.2 Document recommendations review

In order to supplement the analysis provided in D2.5, it was decided to review a series of documents for their recommendations on polar monitoring/observing and modelling. The documents reviewed were Arctic Council Working Group documents (mostly assessment reports), EU-PolarNet deliverables, deliverables from the H2020 INTAROS programme[1] and a number of other sources. Input was solicited from EU-PolarNet WP2 and WP3 Participants and Contributors, and the SAON Committee on Observations and Networks (CON). The list of contributors is found in Appendix B and the full list of documents reviewed is found in Appendix C.

Documents were primarily reviewed in order to identify recommendations that were related to the development and expansion of monitoring/observing and modelling. In some cases, the recommendations contained statements on parallel activities that should be developed in order to make monitoring/observing and modelling efficient and relevant. These recommendations were categorised according to:

- Developing or refining monitoring/observing systems, including detection, sampling or analytical methods and technology. Develop and implement relevant protocols, including design of sampling location and quality assurance and control (QA/QC) processes. Education and training related to this
- Basic research, including process studies. These may be relying on observations/monitoring or modelling
- Data (access, analysis, organising, products, management)
- Emission studies (like studies on future emission scenarios and their possible impacts)
- Coordination/Funding/Governance
- Use of indigenous, local or traditional knowledge. Community-Based Monitoring. Capacity building. Ethical conduct of research
- Legislation/Regulation

The recommendations were also categorised according to *sphere*:

- Atmosphere
- Cryosphere (snow, ice, permafrost)
- Fresh water, including sediments
- Humans and social aspects, including human health and well-being. Food security
- Marine/Ocean, including sediments
- Land/Terrestrial

and according to *theme*:

- Biology (including microbiology), biodiversity (abundance, composition or distribution), ecology and ecosystems. Including processes like photosynthesis, productivity and respiration. Genetic/genomic. Fisheries

[1] https://intaros.nersc.no

- Contaminants and their effects. Includes radioactivity, litter and microplastics
- Diseases (broadly, including mental health and zoonosis)
- Social or socio-economic
- Geology
- Paleoceanography
- Climate and meteorology, including hydrology
- Other chemical and physical observations, including acidification and biogeochemistry
- Greenhouse gases and short-lived climate forcers

The recommendations were finally categorised according to *European Polar Research Priorities* (EU-PolarNet D2.1, Appendix A).

3. Analysis

3.1 Analysis of existing monitoring/observation and modelling programmes

The EU-PolarNet D2.5 ('Strategic analysis of monitoring and modelling programmes') concluded that that there is a dominance of natural sciences (cryosphere, atmosphere, ocean, and land) and to a lesser extent biological sciences in the analysed monitoring/observational and modelling programme inventories. This is as expected since (i) these disciplines link to global climate change and its consequences and these topics have been the target for past funding, and (ii) the understanding of the need to better connect physical and social systems is relatively new. In contrast to this, topics like space sciences, health, and human and social sciences are poorly covered in current monitoring/observing and modelling programmes.

Geographically, Arctic programmes dominate over Antarctic programmes in number and scope by an average ratio of 3:1 on average. Specific regional gaps concern large parts of the Russian Arctic, West Antarctica, and East Antarctica south of the Indian Ocean.

3.2 Document recommendations on monitoring/observing and modelling and their distribution on *spheres*, *themes*, and *European Polar Research Priorities*

A total of 41 documents, mainly from the period 2013-2018 were reviewed, but a few (6) were older (2004-2012) (Appendix C). 34 documents had an Arctic focus, three had an Antarctic focus and four covered both areas (Table 1). In the documents, a total of 317 recommendations were identified.

	Number	%
Arctic	34	83
Antarctic	3	7
Both	4	10
Total	41	

Table 1: Number of recommendation documents and their regional distribution.

Marine and ocean is the dominant *sphere* (25%) in terms of recommendations, followed by *cryosphere* (17.3%) and *atmosphere* (13.8%). *Humans and social/societal aspects* is the sphere with the lowest coverage (7.4%) (Table 2).

	Number	%
Atmosphere	63	13.8
Cryosphere	79	17.3
Fresh water	61	13.4
Humans and social/societal aspects. Including human health and well-being. Food security	34	7.4
Marine and ocean	114	25
Terrestrial	55	12
All/undefined	51	11.2
Total	457	

Table 2: Document recommendations and their distribution on *spheres*. Each of the 317 recommendations could refer to more than one *sphere*.

Biology, Contaminants and *Climate and Meteorology* are the dominant *themes*, accounting for 62.7% of the recommendations. The themes *Diseases, Social or socio-economic, Geology* and *Paleoceanography* are each represented in only 2% of the recommendations or less (Table 3).

	Number	%
Biology (including microbiology), biodiversity (abundance, composition or distribution), ecology and ecosystems. Including processes like photosynthesis, productivity and respiration. Genetic/genomic. Fisheries	71	19.9
Contaminants and their effects. Includes radioactivity, litter and microplastics	89	24.9
Diseases, including mental health and zoonosis	5	1.4
Social or socio-economic	7	2
Geology	2	0.6
Paleoceanography	1	0.3
Climate and meteorology, including hydrology	64	17.9
Other chemical and physical observations, including acidification and biogeochemistry	23	6.4
Greenhouse gases and short-lived climate forcers	49	13.7
All/undefined	27	12.9
Total	357	

Table 3: Document recommendation and their distribution on *themes*. Each of the 317 recommendations could refer to more than one *theme*.

With regards to the recommendations on monitoring/observing for the *European Polar Research Priorities* then 1) *Polar Climate Systems*, 2) *Cryosphere*, 4) *Polar Biology, Ecology and Biodiversity* and 5) *Human impacts* are dominating with a total of 80.9% of the recommendations. The remaining priorities are only represented with a few percent or absent (like *Astronomy, Astrophysics and Space*) (Table 4).

	Number	%
1. Polar Climate Systems	56	14.1
2. Cryosphere	67	16.8
3. Paleoclimate and Paleoenvironment	1	0.3
4. Polar Biology, Ecology and Biodiversity	91	22.9
5. Human impacts	108	27.1
6. Solid earth and its interactions	3	0.8
7. Sustainable management of resources	2	0.5
8. People, Societies and Cultures	19	4.8
9. Human health and Wellbeing	24	6
10. Astronomy, Astrophysics and Space	0	0
All/undefined	27	6.8
Total	228	

Table 4: Document recommendations on monitoring/observing and their distribution on *European Polar Research Priorities*.

Concerning the recommendations on modelling for the *European Polar Research Priorities*, then 2) *Cryosphere*, and 5) *Human impacts* each make up approximately 30% of the recommendations. The priorities *1) Polar Climate Systems and 4) Polar Biology, Ecology, and Biodiversity* make up 7.8% and 14.3%, respectively. The remaining priorities are only represented with low percentages or absent. The priorities *Paleoclimate and Paleoenvironment*, *Solid earth and its interactions*, and *Astronomy, Astrophysics and Space* are absent; the reason could be that these topics are less suited as targets for modelling, except perhaps for modelling of paleoclimate (Table 5).

	Number	%
1. Polar Climate Systems	10	7.8
2. Cryosphere	22	28.6
3. Paleoclimate and Paleoenvironment	0	0
4. Polar Biology, Ecology and Biodiversity	11	14.3
5. Human impacts	21	27.3
6. Solid earth and its interactions	0	0
7. Sustainable management of resources	1	1.3
8. People, Societies and Cultures	3	3.9
9. Human health and Wellbeing	3	3.9
10. Astronomy, Astrophysics and Space	0	0
All/undefined	6	7.8
Total	77	

Table 5: Document recommendations on *modelling* and their distribution on *European Polar Research Priorities.*

3.3. Summarising document recommendations

The recommendations reviewed originate from documents that are diverse in nature, ranging from scientific journals to high-level politically oriented documents. They consequently have very different level of details, making a weighted comparison and synthesis difficult. The summary of the recommendations in this section should consequently be seen as based on statistics (occurrence) rather than on the significance or weight of the recommendations.

The summary is meant to support the roadmap deliberations in Chapter 4, but should not be seen as comprehensive and defining future priorities. For EU-PolarNet, these priorities are defined in the *European Polar Research Priorities*, in the white papers[2] and the themes for the coming European Polar Research Programme (EPRP).

3.3.1 Monitoring/observation recommendations

There are a total of 201 recommendations on monitoring/observing (Table 6, *O* in column *Activity* in Appendix C). In addition, 25 recommendations are about the development or refining of monitoring/observing systems and their components, including sampling or analytical methods (*A* in column *Activity* in Appendix C); these recommendations can be seen as necessary prerequisites for implementing and strengthening monitoring/observing. Similarly, 76 recommendations are about basic research, especially process studies (*B* in column *Activity* in Appendix C); these may also be seen as necessary prerequisites for strengthening monitoring/observing.

	Number
Monitoring/observing	201
Modelling	56
Additional categories:	
Developing or refining monitoring/observing systems, including detection, sampling or analytical methods and technology. Develop and implement relevant protocols, including design of sampling location and QA/QC processes. Education and training in this.	25
Basic research, including process studies. These may be relying on observations/monitoring or modelling	76
Data (access, analysis, organising, products, management)	25
Emission studies (like studies on future emission scenarios and their possible impacts)	6
Coordination/Funding/Governance	10
Use of indigenous, local or traditional knowledge. Community Based Monitoring. Capacity building. Ethical conduct of research	19
Legislation/Regulation	3

Table 6: Document recommendations and their distribution on *Activity*.

The recommendations are in general about the need for long-term, sustained observing, obtaining observations that results in longer time-series of data. There is a need for a better

[2] EU PolarNet (2019): Set of white papers addressing priority questions in polar research and targeting funding agencies and policy makers (Deliverable 2.8): https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP2/D2.8_Set_of_white_papers_addressing_priority_questions_in_polar_research_and_targeting_funding_agencies_and_policy_makers.pdf

spatial coverage and the inclusion of more variables in current monitoring/observing activities.

For the cryosphere, more accurate snow observations are needed, and these should have a better spatial coverage. Observations on sea-ice extent, concentration, thickness and motion should also be strengthened. Many permafrost observational sites are not maintained for long-term monitoring and there are significant spatial gaps. For glaciers, mass balance measurements over long periods are available for only a small subset of Arctic glaciers. For the Greenland Ice Sheet, *in situ* observations are limited. For glaciers, observations are needed for the processes (ice dynamics, subglacial meltwater, ocean interaction) that accelerate melting. The hydrological cycle in the Polar Regions should be better understood and observed. Albedo observing (particularly for snow) should be strengthened. There is a general need for harmonizing observing of the cryosphere.

There is a lack of all types of atmospheric observations in the Polar region. This is in particular the case when it comes to observations of the vertical structure of the atmosphere.

For monitoring/observing of contaminants, it is recommended that the spatial coverage is expanded. More observations on the effects of contaminants are also needed. There is finally a need for more observations in order to better understand contaminant transport and behaviour. A series of upcoming contaminants (including microplastics) should have focus.

For the monitoring of the short-lived climate forcers *black carbon* and *tropospheric ozone*, there is a need for developing and standardising measurement methods. The spatial coverage should be improved. For *methane* monitoring of natural sources and atmospheric monitoring should be increased (better time resolution and more sampling sites). The amount of carbon available in permafrost areas and its relationship to the global carbon cycle should be observed. The amount and condition of permafrost-associated gas hydrates is still largely unknown.

For ecosystem and biodiversity studies, capability for species observing and for drivers of change (including relevant physical parameters and contaminants) is missing. For many species and ecosystem processes baseline of knowledge does not exist. Observations that improve the understanding of snow-land type-hydrologic changes and the impacts on terrestrial ecosystems are needed. There is need for harmonising sampling methods and taxonomic nomenclature as well as an intercalibration of methods. New approaches for long-term ecological research and monitoring should be implemented, including DNA-barcoding and environmental DNA (eDNA). Community-based monitoring should be promoted and should utilise Indigenous Knowledge (IK) as well as traditional and local knowledge (TLK).

Within the marine area, more observations on stressors are needed. Basic physical variables, including their vertical variation should be observed (temperature, salinity, currents, heat and salt fluxes, sea ice). Observations on the carbon dioxide system are needed; this should be integrated with measurements of other key variables (such as oxygen and nutrients). Observing for the combined effects of ocean warming and acidification should be strengthened. Observing of primary and secondary production and the cycling of bioactive compounds is needed. Analysis of species composition and fish stocks in the marine areas currently accessible should be given priority.

From a human perspective, a basic set of Arctic Social Indicators should be observed. From a human health perspective, human biomonitoring of contaminants and diet studies should be combined in order to produce better exposure estimates and better dietary advice. Mental health and vector-borne infections should be given priority.

The recommendations formulated on monitoring/observing and summarised in this section are in general well aligned with the analysis in document D2.5. It should be noted that the recommendations reviewed in this document and the inventories analysed in document D2.5 both reflect past priorities. It should also be noted that there probably is a tendency/bias in the recommendations reviewed in this document. As the most prominent example, Arctic Council Working Group documents make up almost 40% (16/41) of the documents reviewed. As a part of their mandate, the Arctic Council Working Groups will formulate (often detailed) recommendations to the political level. This also means that recommendations have a bias towards the scope of especially AMAP (contaminants, climate change and the effects of these) and CAFF (biodiversity). It should finally be noted that the overwhelming majority of recommendations are found in documents with an Arctic or both-polar scope (93% or 38/41).

Even though this is the scope for WP3, it should be noted that 25 recommendations have to do with organising and providing access to data and data products.

3.3.2 Modelling recommendations

There is a total of 56 recommendations on modelling (Table 6, *M* in column *Activity* in Appendix C).

In general, the performance of many models is poor in the Polar Regions, also over the Arctic Ocean. Many recommendations have to do with refining and developing Arctic climate models. This includes representing additional systems, like

- chemistry-climate models
- climate response to methane and ozone
- economics
- ecosystem processes
- feedback processes
- ice sheets and glaciers (the absence limits their use for projecting sea-level rise)
- ocean mixing and linkages to sea ice

- permafrost
- permafrost-soil-vegetation interactions
- snow-vegetation interactions
- extreme events
- Arctic Ocean as a methane source.

For contaminants, it is recommended that improved modelling studies are undertaken in order to investigate the impact of changes in meteorology, atmospheric chemical composition, land use and climate on their fate in the Polar regions. Models should be strengthened with regards to source attribution and temporal trends in contaminants. Transport models for contaminants need to be developed for Arctic conditions.

Improving projections of the consequences of climate change on society will depend in part on the advances in climate modelling. It would be useful for local decision-makers, if model projections of regional changes in climate could be improved.

Improvements in numerical weather, sea-ice, and ocean prediction models is essential to ensure safety in navigation and in all the human activities carried out by local community and Arctic infrastructure operators.

Many models need observational data in order to secure parameterisations and validation. Remote sensing data are needed to initialize and validate certain models. Sensitivity analysis is the study of how the uncertainty in the output to a model can be divided and allocated to different sources of uncertainty in its inputs (data, parameters); there is a need for this for some models.

4. Roadmap for optimisation of monitoring and modelling programmes for the Polar Regions (ROMP)

4.1. The proposed ROMP process

A Roadmap for optimisation of monitoring and modelling programmes for the Polar regions should be a planning tool to be used in science and technology development processes to set the conceptual direction for where polar monitoring/observing and modelling programmes need to go and how the various partners and players are going to collectively work towards getting there. Central to defining will be a consensus view of observational priorities, the requirements for their acquisition and a strategy for their timely dissemination across a broad base of users. Developing such consensus views will require the inclusion of a diversity of subject matter experts.

The proposed ROMP development is envisioned as a bi-directional process. Leadership and guidance from existing polar monitoring/observing networks and initiatives will be critical to achieving a successful ROMP process, as will Indigenous experts, regional and global networks, national initiatives and emerging activities. For the ROMP process to be effective in advancing sustained Polar monitoring/observing, it will also need to be relevant to national funding and operational agencies. As such, the process outlined is targeted towards policy-makers at all levels, Arctic Indigenous Peoples organizations, Arctic and non-Arctic states, academia, civil society and the private sector, as well as engagement from other multilateral/international groups.

4.2. Guiding principles

The ROMP process should include these guiding principles[3]:

- The process values both research and operational needs for Polar observations;
- The design and operation of the observing programmes will be guided by a balance between bottom-up and top-down needs and priorities;
- For the Arctic, the process will work in partnership with Arctic Indigenous Peoples, and utilise Indigenous Knowledge (IK) and traditional and local knowledge (TLK), guided by ethical use and honouring the proprietary rights of data contributors;
- The process will work with counterparts in the global, regional and national observation communities, where appropriate.

In recognition of the complex dimensions of Polar observing systems, and the equally complex organizational patchwork of observing partners, the concept for ROMP is of an interrelated system of systems, a significant portion of which are independently initiated from “the bottom up” by the academic research community through revolving funds.

4.3. Guidance for design. Assessment framework

EU-PolarNet has outlined 10 *European Polar Research Priorities* (D2.1) and this document has reviewed and summarized document recommendations for the strengthening of polar monitoring/observing and modelling programmes. In 2017, following the first Arctic Science Ministerial[4], SAON members, networks and representatives of its intended user base collaborated with the US Science and Technology Policy Institute (STPI) to develop a tool to support the assessment of observational requirements: The International Arctic Observing Assessment Framework (IAOAF) (IDA and SAON, 2017). The IAOAF identified 12 Arctic-specific Societal Benefit Areas (SBAs) including *Disaster Preparedness*, *Human Health*, *Fundamental Understanding of Arctic Systems* and *Food Security*. In a follow-up process, the IMOBAR project documented the economic benefits of Arctic observing (IMOBAR (2018).

Employing the IAOAF as an assessment tool in the ROMP process, along with the EU-PolarNet *European Polar Research Priorities*, the United Nations *Sustainable Development*

[3] The list is inspired by the *Guiding Principles* of the *Sustaining Arctic Observing Networks (SAON) Strategy 2018-2018* (https://www.arcticobserving.org/strategy)
[4] https://www.whitehouse.gov/the-press-office/2016/09/28/joint-statement-ministers

Goals (SDGs)[5], the *Sendai Framework for Disaster Risk Reduction*[6] and the *Paris Accord*[7] will assure that ROMP requirements result in an optimized network that broadly serves societal needs in the Polar regions and globally.

4.4. Essential Polar Variables (EPVs)

The Roadmap Task Force of the Sustaining Arctic Observing Networks (SAON) (see box) has reviewed planning approaches employed by a variety of global and regional observing networks[8]. The essential variable (EV) strategy emerged as a best practice for supporting network development. The *Framework for Ocean Observing* (UNESCO, 2012) applied systems engineering approaches to provide a common language and consistent handling of requirements, observing technologies, and information flow among different, largely autonomous observing elements linked in a collaborative framework. The approach described is conceptually holistic, yet can proceed step-wise as elements achieve readiness.

The Sustaining Arctic Observing Networks (SAON) is a joint initiative of the Arctic Council and the International Arctic Science Committee that aims to strengthen multinational engagement in pan-Arctic observing. SAON's vision is a connected, collaborative, and comprehensive long-term pan-Arctic Observing System (AOS) that serves societal needs. To achieve this vision, SAON facilitates and advocates for coordinated international pan-Arctic observations and mobilizes the support needed to sustain them.
In agreement with its *Guiding Principles*, SAON aims to mobilize the support needed to implement and sustain observations on time scales of decades and beyond. In its recent strategic plan (SAON (2018)), SAON has identified the need for a Roadmap to support this mobilization and ensure optimized benefits to users from an Arctic Observing System, including free and ethically open access to all Arctic observational data. SAON's Roadmap goal was supported by the Second Arctic Science Ministerial.
In order to initiate the AOS process, a task force (Roadmap Task Force, RMTF) was established in early 2019 to set forth definitions and guidelines for the SAON community to follow. The ROMP recommendations outlined in this chapter are in agreement with *Community Guidelines for contributing to the SAON Roadmap for Arctic Observing and Data Systems (ROADS)* (SAON RMTF, 2019, *in prep.*)

Box: SAON and the *Roadmap Task Force (RMTF)*

[5] https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[6] https://www.unisdr.org/we/coordinate/sendai-framework
[7] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[8] Including the GOOS Framework for Ocean Observing; Circumpolar Biodiversity Monitoring Program (and GEOBON); Arctic Monitoring Assessment Program (and GCOS); GEO Global Water Sustainability (GEOGLOWS).

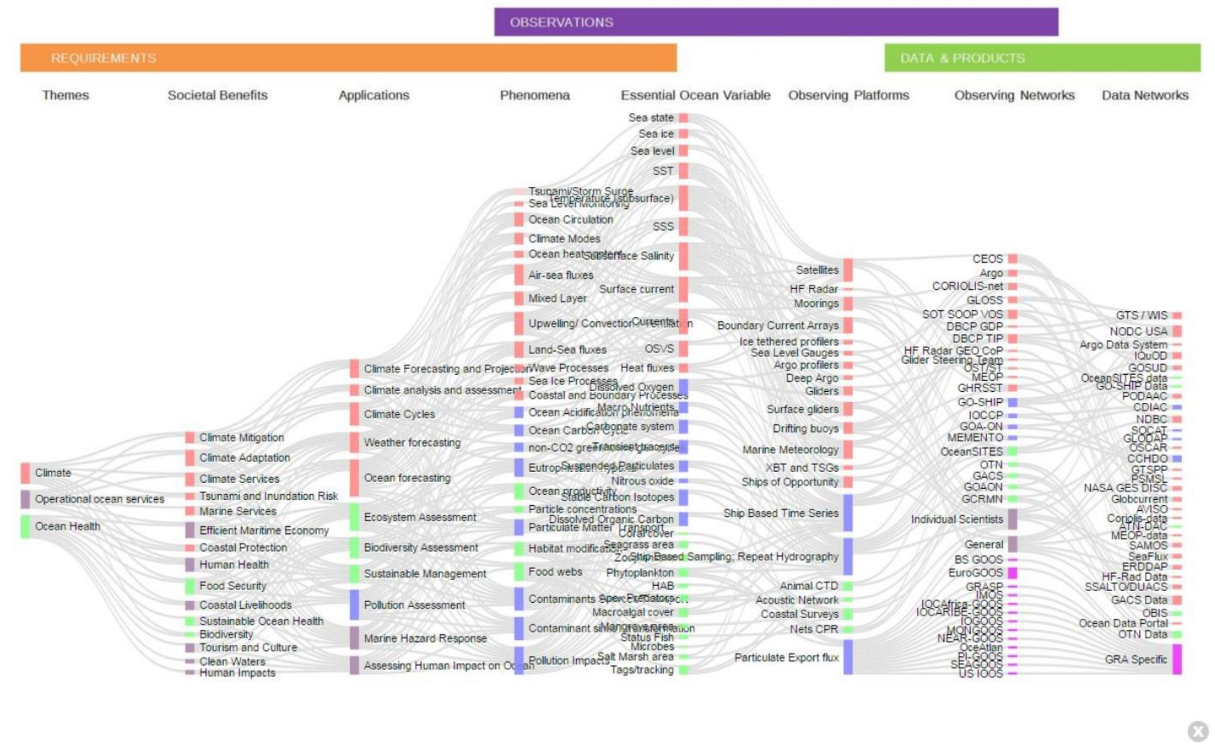

Figure: This visualization of an observing system (in this case, the Global Ocean Observing System (GOOS)) shows the links of Essential Variables to observing networks and applications and how they contribute to societal benefits.

The Figure illustrates how societal benefits, applications, EVs and observing networks can be linked together. The ROMP process should be organized around Essential Polar Variables (EPVs). These are conceptually broad observing categories (e.g. "sea ice") identified for their criticality to achieving societal benefits. EPVs are defined by their observing system requirements, which are technology-neutral and should transcend specific observing strategies, programs or regions. They are implemented through specific recommendations based on best available technology and practices. A holistic and collaborative observing system of EPVs is achieved through employing consistent, consensus strategies in identifying, linking and developing requirements for observing. The EPV approach allows for progress on implementation, under an expectation of continuous innovation in the underlying technologies. Importantly, EPVs provide a structured interface for coordination and collaboration in support of societal benefit.

The Figure also illustrates how the development of polar modelling should be coordinated. Under the ROMP process, models will consume data observed as EVs and will on the other hand inform *Applications* (forecasting's and assessments).

In keeping with the ROMP principle of complementing current efforts in a non-duplicative approach, a rational starting point for identifying most EPVs will be from existing essential variables associated with global networks. It is recognised that new EPVs (unique to the Polar Regions) will also be identified through relevant topical expert groups, following practices of knowledge co-production. The ROMP process should refine the definition of their requirements based on regionally specific user needs and recommend implementation strategies that account for Polar conditions (e.g. polar night) and opportunities (e.g. community observers). The ROMP process for each EPV should fully specify the observing and data systems requirements from acquisition through high impact information dissemination.

Many global networks have defined templates[9] and principles for essential variable development. The ROMP process should work closely through a series of pilot efforts to develop an EPV template that is consistent with the mentioned guiding principles, while complementary to other efforts.

4.5. Governance Structure

Given the complexity of the ROMP process, a well-defined governance structure is necessary. The ROMP process could proceed under a structure with Advisory Panels and Expert Panels.

A. Advisory Panels

The ROMP Advisory Panels will provide a neutral standing body to assure that each EPV is identified, defined and implemented according to ROMP principles. Further, the Advisory Panels will have the ability to foster integration with other panels; facilitate inclusion of broadest expertise, including Indigenous experts; mobilize international participation and collaboration with global networks; identify potential overlap with other Expert Panels (see below) and work to cultivate consensus approaches across overlapping interests. The ROMP Advisory Panels can also work with relevant funding agencies to advance support for expert panel efforts. The panels convene as required to review and approve proposals from the Expert Panels to initiate all phases of work and to organize peer review of their recommendations.

For some EPVs there may be reasons to create separate Arctic and Antarctic Advisory Panels. SAON, through its broad constituency of board and committee members, as well as its rigorous mandate from the Arctic Council, IASC and the Arctic Science Ministers, could make an appropriate governing body for the Arctic. Here, it should be emphasized that Arctic Indigenous Peoples need to be recognized as rights holders in the Arctic, and research in their homeland needs to be conducted in partnership with them. A prerequisite for this is capacity building for Arctic Indigenous Peoples and their organisations. A similar body should be established for the Antarctic, probably through SCAR. The Arctic and Antarctic Advisory

[9] For example, specifications for: *Essential Climate Variables* (Global Climate Observing System - GCOS); *Essential Ocean Variables* (Global Ocean Observing System – GOOS) and Essential Biodiversity Variables (The Group on Earth Observations Biodiversity Observation Network – GEOBON)

Panels will convene jointly to review cross-regional recommendations from the Expert Panels.

B. Expert Panels

Expert Panels convene around subject and/or region of interest. Ideally, the scope should be broad enough to cover at least one EPV, preferably a set of related EPVs. Subject matter experts will be recruited from academia, Indigenous organizations, northern communities, operational agencies, industry, etc. SAON and SCAR do not have the capacity to initiate EPV development. Self- organization of the community will be the most effective and quality-driven means to proceed.

The work within the Expert Panels will be organized in these phases:

- Initiation: Write a brief proposal to the ROMP Advisory Panels, outlining a proposed scope of activities and participants.
- Phase I: Convene a community-wide process to identify relevant EPVs for the scope. For the Arctic, relevance should be systematically assessed using the IAOAF. Support of the EU-PolarNet *European Polar Research Priorities*, the United Nations *Sustainable Development Goals* (SDGs), the *Sendai Framework for Disaster Risk Reduction* and the *Paris Accord* are also encouraged.
- Phase II: Convene a community-wide process to specify the requirements for each relevant EPV. Requirements should be comprehensive of data collection, management, analysis, system management, and dissemination.
- Phase III - Convene a community-wide process, in collaboration with relevant funding agencies, to outline strategies for implementation and engage commitments for sustainability. This process should describe which infrastructures are essential for current implementation. These include satellite earth observation programs, terrestrial stations, vessels, aircraft and various autonomous platforms providing observing systems. Implementation should also describe how these infrastructures would be integrated into value-added services and products and the strategy for their dissemination. This phase of work should also identify technology development needs in order to improve readiness of future generations of the observing system.

Given the complexity and progressive nature of the proposed ROMP process, it will be critical to evaluate both the process and its elements on a revolving basis. It is recommended that the ROMP process is evaluated after 3 years and each EPV be evaluated after 5 years.

The outlined ROMP process is a holistic concept and one that can proceed step-wise so that the most imperative polar observing elements can be rapidly deployed. For each Essential Polar Variable identified, the ROMP process will result in well-specified requirements for observing and a strategy for their implementation and timely dissemination. Funding agencies will recognize the merits of an integrated and systematic community-wide process with coordinated international engagement. In addition, global networks will recognize the value of regional facilitation through EPV's that extend the definitions and utility of their own essential variables.

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EU-PolarNet (2018). Strategic analysis of monitoring and modelling programmes (Deliverable 2.5) (https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/D2.5_Strategic_analysis_of_monitoring_and_modelling_programmes_final.pdf)

Impact assessment study on societal benefits of Arctic observing systems (IMOBAR, 2018) (https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/impact-assessment-study-societal-benefits-arctic-observing-systems)

SAON Road Map Task Force (2019): Community Guidelines for contributing to the SAON Roadmap for Arctic Observing and Data Systems (ROADS) (*in prep*) (https://www.arcticobserving.org/news/378-guidelines-for-contributing-to-saon-s-roadmap-for-arctic-observing-and-data-systems-roads)

SAON Strategy 2018-2028 (2018) (https://www.arcticobserving.org/images/pdf/Strategy_and_Implementation/SAON_Strategy_2018-2028_version_16MAY2018.pdf)

The International Arctic Observations Assessment Framework (IAOAF) (IDA and SAON (2017)) (https://www.arcticobserving.org/news/268-international-arctic-observations-assessment-framework-released)

Appendix A: European Polar Research Priorities

(As defined in *Report on prioritised objectives in polar research* (D2.1, EU-PolarNet (2016)).

1. Polar Climate Systems
2. Cryosphere
3. Palaeoclimate and Palaeoenvironment
4. Polar Biology, Ecology and Biodiversity
5. Human impacts
6. Solid earth and its interactions
7. Sustainable management of resources
8. People, Societies and Cultures
9. Human health and Wellbeing
10. Astronomy, Astrophysics and Space

Appendix B: List of contributors

These contributors provided proposal for documents to review for recommendations on polar monitoring/observing and modelling

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Appendix C. Document recommendations

Documents reviewed for recommendations on Polar monitoring/observing and modelling

Table	Year	Title	Web source
		Arctic Council Working Group reports	
1	2004	ACIA, Impacts of a Warming Arctic: Arctic Climate Impact Assessment (AMAP, CAFF, IASC)	https://www.amap.no/documents/doc/impacts-of-a-warming-arctic-2004/786
2	2011	Mercury in the Arctic (AMAP)	https://www.amap.no/documents/download/989/inline
3	2011	Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere (AMAP)	https://www.amap.no/documents/download/1448/inline
4	2011	The Impact of Black Carbon on Arctic Climate (AMAP)	https://www.amap.no/documents/download/977/inline
5	2013	Arctic Biodiversity Assessment (CAFF/CBMP)	https://www.caff.is/assessment-series/233-arctic-biodiversity-assessment-2013/download
6	2013	Arctic Ocean Acidification (AMAP)	https://www.amap.no/documents/doc/amap-assessment-2013-arctic-ocean-acidification/881
7	2015	Human Health in the Arctic (AMAP)	https://www.amap.no/documents/download/2594/inline
8	2015	Methane as an Arctic climate forcer (AMAP)	https://www.amap.no/documents/download/2499/inline
9	2015	Radioactivity in the Arctic (AMAP)	https://www.amap.no/documents/download/2772/inline
10	2016	Chemicals of Emerging Arctic Concern (AMAP)	https://www.amap.no/documents/download/3003/inline
11	2017	Snow, Water, Ice and Permafrost in the Arctic (SWIPA) (AMAP)	https://www.amap.no/documents/download/2987/inline
12	2017	State of the Arctic Marine Biodiversity Report (CAFF/CBMP)	https://caff.is/monitoring-series/431-state-of-the-arctic-marine-biodiversity-report-full-report/download
13	2018	Arctic Ocean Acidification (AMAP)	https://www.amap.no/documents/download/3055/inline
14	2018	Biological Effects of Contaminants on Arctic Wildlife and Fish (AMAP)	https://www.amap.no/documents/download/3080/inline

15	2018	State of Arctic Freshwater Biodiversity Report (CAFF/CBMP)	https://www.caff.is/monitoring-series/488-state-of-the-arctic-freshwater-biodiversity-report-full-report/download
16	2019	Desktop Study on Marine Litter including Microplastics in the Arctic (PAME)	https://pame.is/index.php/document-library/pame-reports-new/pame-ministerial-deliverables/2019-11th-arctic-council-ministerial-meeting-rovaniemi-finland/423-desktop-study-on-marine-litter-including-microplastics-in-the-arctic/file
		EU-PolarNet Deliverables	
17	2016	Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Arctic Health and Wellnes (D1.8)	https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP1/D1-8_Minutes_of_International_Stakeholder_Workshop_at_ASSW.pdf
18	2016	Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Research Needs on Arctic Ecosystems and Ecosystem Services (D1.12)	https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP1/D1.12__Minutes_of_workshop_with_international_partners_and_stakeholders_at_a_relevant_Arctic_Conference.pdf
19	2017	Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Research Needs on Climate-related Effects on the Arctic Cryosphere and Adaptation Options (D1.15)	https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP1/D1_15_Minutes_of_workshop_with_international_partners_.pdf
20	2019	Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Research Needs on Arctic Biology and Terrestrial Ecosystems (D1.19)	https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP1/D1_19_Minutes_of_Stakeholder_Workshop_at_Arctic_Conference.pdf
21	2019	Set of white papers addressing priority questions in polar research and targeting funding agencies and policy makers (Deliverable 2.8)	https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP2/D2.8_Set_of_white_papers_addressing_priority_questions_in_polar_research_and_targeting_funding_agencies_and_policy_makers.pdf
		INTAROS deliverables	
22	2017	Initial Requirement Report (D1.1)	https://intaros.nersc.no/content/initial-requirement-report
23	2018	Report on present observing capacities and gaps: Ocean and sea ice observing system (D2.1)	https://intaros.nersc.no/content/report-present-observing-capacities-and-gaps-ocean-and-sea-ice-observing-system
24	2018	Report on present observing capacities and gaps: Atmosphere (D2.4)	https://intaros.nersc.no/content/report-present-observing-capacities-and-gaps-atmosphere
25	2018	Report on present observing capacities and gaps: Land and cryosphere (D2.7)	https://intaros.nersc.no/content/report-present-observing-capacities-and-gaps-land-and-cryosphere

26	2018	Observational gaps revealed by model sensitivity to observation (D2.12)	https://intaros.nersc.no/content/observational-gaps-revealed-model-sensitivity-obser-vations
27	2018	Community based monitoring programmes in the Arctic: Capabilities, good practice and challenges (D4.1)	https://intaros.nersc.no/sites/intaros.nersc.no/files/D4_1_updated_1.pdf
		Other documents	
28	2010	Arctic Social Indicators- a follow-up to the Arctic Human Development Report	http://library.arcticportal.org/712/1/Arctic_Social_Indicators_NCoM.pdf
29	2012	SIOS Infrastructure Optimisation Report	https://www.sios-svalbard.org/sites/sios.metsis.met.no/files/common/D3.4_SIOSInfrastructureOptimisationreport.pdf
30	2013	Evaluating the Antarctic Observational Network with the Antarctic Mesoscale Prediction System (AMPS); Karin A. Bumbaco; Joint Institute for the Study of Atmosphere and Ocean, University of Washington, Seattle, Washington	https://journals.ametsoc.org/doi/full/10.1175/MWR-D-13-00401.1
31	2014	EU Seventh Framework Programme: ARCRISK: Arctic Health Risks: Impacts on health in the Arctic and Europe owing to climate-induced changes in contaminant cycling	https://www.amap.no/documents/download/1901/inline
32	2015	3rd International Conference on Artic Research Planning (ICARP III)	https://icarp.iasc.info/images/articles/downloads/ICARPIII_Final_Report.pdf
33	2015	ICC Alaska Food Security Report	https://iccalaska.org/wp-icc/wp-content/uploads/2016/03/Food-Security-Summary-and-Recommendations-Report.pdf
34	2015	International Quiet Ocean Experiment. Science Plan	https://www.researchgate.net/profile/Edward_Urban2/publication/281110764_Science_Plan_for_International_Quiet_Ocean_Experiment/links/55d618e508aed6a199a4c0a3/Science-Plan-for-International-Quiet-Ocean-Experiment.pdf
35	2016	Antarctic Near-shore and Terrestrial Observation System	https://www.scar.org/scar-library/search/science-4/physical-sciences/antos/3446-2015-antos-workshop-report/file/
36	2016	CliC/AMAP/IASC, 2016. The Arctic Freshwater System in a Changing Climate	https://www.amap.no/documents/doc/the-arctic-freshwater-system-in-a-changing-climate/1375

37	2016	Polaris. User needs and High-Level Requirements for Next Generation Observing Systems for the Polar Region (Polar View Earth Observation Limited). Summary Report	https://www.arcticobserving.org/images/pdf/RMTF/20190603/Polaris_Summary_Report.pdf
38	2018	Southern Ocean Modelling: Status and observational data requirements	http://soos.aq/resources/reports?view=product&pid=57
39	2018	A review of the scientific knowledge seascape off Dronning Maud Land, Antarctica	https://www.researchgate.net/profile/Andrew_Lowther/publication/327051373_A_review_of_the_scientific_knowledge_seascape_off_Dronning_Maud_Land_Antarctica/links/5b75241292851ca65063d7b2/A-review-of-the-scientific-knowledge-seascape-off-Dronning-Maud-Land-Antarctica.pdf?origin=publication_detail
40	2018	Canadian National Inuit Strategy on Research	https://www.itk.ca/wp-content/uploads/2018/03/National-Inuit-Strategy-on-Research.pdf
41	2018	User Requirements for a Copernicus Polar Mission	http://publications.jrc.ec.europa.eu/repository/bitstream/JRC111068/2018.1802_src_polar_expert_group_-_phase_2_-_final_report_20180726final2.pdf

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- AntarcticGlaciers.org (http://www.antarcticglaciers.org/)
- ANTOS - The Scientific Committee on Antarctic Research (https://www.scar.org/science/antos/antos/)
- ConnectingGEO (http://www.connectingeo.net/)
- Exchange for Local Observations and Knowledge of the Arctic (ELOKA) (https://eloka-arctic.org/)
- ExtremeEarth (http://extremeearth.eu)
- INTERACT – International Network for Terrestrial Research and Monitoring in the Arctic: https://eu-interact.org/
- Local Observations and Knowledge: Data Management Issues and Practices (ELOKA) (https://eloka-arctic.org/about/manual/index.html)
- MOSAiC – International Arctic Drift Expedition (https://www.mosaic-expedition.org)
- SEARCH: Study of Environmental Arctic Change: Products (https://www.searcharcticscience.org/products)
- Southern Ocean Observing System (SOOS): http://www.soos.aq/

Key to table columns

Sphere
A: Atmosphere
C: Cryosphere (snow, ice, permafrost)
F: Fresh water, including sediments
H: Humans and social aspects, including human health and well-being. Food security
M: Marine/Ocean, including sediments
T: Land/Terrestrial

Theme
B: Biology (including microbiology), biodiversity (abundance, composition or distribution), ecology and ecosystems. Including processes like photosynthesis, productivity and respiration. Genetic/genomic. Fisheries
C: Contaminants and their effects. Includes radioactivity, litter and microplastics
D: Diseases (broadly, including mental health and zoonosis)
E: Social or socio-economic
G: Geology
H: Paleoceanography
K: Climate and meteorology, including hydrology
P: Other chemical and physical observations, including acidification and biogeochemistry
S: Greenhouse gases and short-lived climate forcers

Activity
A: Developing or refining observational systems, including detection, sampling or analytical methods and technology. Develop and implement relevant protocols, including design of sampling location and QA/QC processes. Education and training in this.
B: Basic research, including process studies. These may be relying on observations/monitoring or modelling
D: Data (access, analysis, organising, products, management)
E: Emission studies (like studies on future emission scenarios and their possible impacts)
G: Coordination/Funding/Governance
I: Use of indigenous, local or traditional knowledge. Community-Based Monitoring. Capacity building. Ethical conduct of research
L: Legislation/Regulation
M: Modelling
O: Monitoring/observing

Table 1. ACIA, Impacts of a Warming Arctic: Arctic Climate Impact Assessment (AMAP, CAFF, IASC)

Web source: https://www.amap.no/documents/doc/impacts-of-a-warming-arctic-2004/786

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Long-Term Monitoring: Long-term time series of climate and climate-related parameters are available from only a few locations in the Arctic. Continuation of long-term records is crucial, along with upgrading and expanding the observing systems that monitor snow and ice features, runoff from major rivers, ocean parameters, and changes in vegetation, biodiversity, and ecosystem processes.	C, F, M, T	B, K, P	O	1, 2, 4
Process Studies: Many Arctic processes require further study, both through scientific investigations and through more detailed and systematic documentation of indigenous knowledge. Priorities include collection and interpretation of data related to climate and the physical environment, and studies of the rates and ranges of change for plants, animals, and ecosystem function. Such studies often involve linking climate models with models of ecosystem processes and other elements of the arctic system.	-	B, K	B, I, M	1, 2, 4
Modelling: Improvements in modelling arctic climate and its impacts are needed, including in the representation of ocean mixing and linkages to sea ice, permafrost-soil-vegetation interactions, important feedback processes, and extreme events. Model refinement and validation is required for models within scientific disciplines, and there is also a need to link and integrated models across disciplines. Developing, verifying, and applying very high-resolution coupled regional models to improve projections of regional changes in climate would also help provide more useful information to local decision-makers.	C, M	B, K	M	1, 2, 4
Analysis of Impacts on Society: Improving projections of the consequences of climate change on society will depend in part on the advances in climate modelling mentioned above as well as on generating improved scenarios of population and economic development in the Arctic, developing and applying impact scenarios, forging improved links between scientific and indigenous knowledge, and more thoroughly identifying and evaluating potential measures to mitigate and adapt to climate change.	H	E	I, M	1, 8

Table 2. Mercury in the Arctic (AMAP)

Web source: https://www.amap.no/documents/download/989/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Where Does Mercury in the Arctic Environment Come From, and How Does it Get There?				
For assessment of global transport and impacts of Hg and for the development of strategies for reducing the impacts, it is necessary to reduce the uncertainty of emission inventories. Information on Hg contents in fuels and raw materials as well as information on the current technical status of industrial sectors is lacking. Emission estimates from some sectors notably intentional use and waste handling are associated with large uncertainties and need to be better characterized.	A	C	E	5
Estimates of natural emissions and re-emissions are often based on a very limited number of measurements and models using a mass balance approach. Further research into the transfer of Hg from different environmental compartments to air is a high priority.	A	C	B, E	5
Model estimates of the source attribution and temporal trends of Hg in the Arctic depend highly on the reliability of anthropogenic emissions data and on the speciation of Hg emissions. Therefore, further improvements of global Hg emission inventories are needed.	A	C	E, M	5
Studies are required for quantitative and mechanistic understanding of natural and revolatilized Hg emissions from various surfaces (soils, water, snow, vegetation) for constraining the models uncertainties.	A	C	B	5
Improved understanding of Hg chemical mechanisms, reaction rates and products in gas, aqueous and heterogeneous phases in global and Arctic environment is needed through laboratory and field measurement studies. Better understanding of bromine reaction rate constants in air and Hg reduction chemistry in snow are of particularly importance for the Arctic.	A	C	B	5
The models are generally consistent with each other for quantities that are better measured such as GEM, however the differences are large for quantities lacking observations such as wet and dry deposition in the Arctic. Measurements over the Arctic basin are largely missing which severely restricts the evaluation of the models over the Arctic Ocean. There is a need for a comprehensive network of measurements in the Arctic that includes concentrations of speciated Hg and chemical reactants in air, as well as wet and dry deposition.	A	C	M, O	5

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Modelers need to explore the use of surface measurements such as Hg concentrations in snowpacks, streams and sediments to constrain the models.	A, C, F	C	M	5
Comprehensive parameterizations for Hg exchange between air and cryosphere need to be developed to limit the uncertainty in net deposition estimates to the Arctic.	A, C	C	B	5
Although, the atmospheric reservoir of mercury is comparatively much smaller, the atmosphere serves as an efficient mechanism for exchanging Hg between the two large reservoirs of Hg in the terrestrial and oceanic systems. Biogeochemical models linking atmosphere, ocean and terrestrial systems are needed to take into account the entire cycling of Hg in the environment for an adequate assessment of Hg inputs to the Arctic. It is particularly relevant for the evaluation of long-term trends, future scenarios and the impact of climate change on Hg pollution in the Arctic.	A, M, T	C	M	5
Modeling studies are needed to investigate the impact of changes in meteorology, atmospheric chemical composition, landuse and climate on Hg budgets in the Arctic.	A	C	M	5
It is possible that precipitation type as well as amount may be an issue in relation to the model calculations. The relative scavenging effect of snow vs rain on the flux of atmospheric Hg is a research area needing attention.	A	C	B, M	5
Sampling both dry and wet deposition under Arctic conditions is an important area requiring further research and development; sampling snowfall is a particular challenge in this respect. These measurements are important for improved parameterization of models.	A,C	C	O, M	5
Depositional and flux measurement techniques and campaigns are needed as wet deposition may be similar at different times and locations yet re-volatilization may be quite different.	A	C	O	5
It is of the utmost importance that better techniques be developed for measuring the geographical and temporal dynamics of Hg deposition and the concomitant re-emission of atmospheric Hg to the Arctic and the rest of the World. Because of the global cycling of Hg it is not possible to develop an accurate model of the Arctic portion of the global cycle in regional isolation. Therefore, technological development of measurement techniques is needed so that the concentrations of Hg species in the atmosphere can be measured rather than only the fractionation of Hg. Furthermore, there is only one published study of the fluxes of RGM and a few studies of the fluxes of GEM in the Arctic.	A	C	A, M	5
Further studies to investigate the possible over-estimation of atmospheric wet deposition fluxes by lake sediments and atmospheric models, and the reasons for any over-estimation are needed. These studies must be corroborated with studies of Hg in annually deposited snow and ice where possible, using uniformly agreed sampling and analysis methods.	A	C	A	5

Topic	Sphere	Theme	Activity	European Polar Research Priorities
One of the gaps in knowledge for future studies is the need to develop and accept common sampling and dating routines, as best practice, to allow better intercomparison of the data sets.	A	C	A, D	5
AMAP should recommend the creation of an expert working group to address the question of exactly what studies and data are needed ensure that the models are properly parameterized to predict the future deposition and likely re-emission of Hg and its ultimate fate in future Arctic ecosystems.	A, C, F, M, T	C	M	5
There is a need for standardized best practices for sampling and later biogeochemical analysis in environmental archives, as such protocols do not exist in the literature except for peat (see Givelet et al., 2004a). Studies presenting Hg as stand alone data generally therefore do not advance overall understanding.	A, C, F, M, T	C	A	5
What is the Fate of Mercury Entering the Arctic Environment?				
The rates of Hg entry into the alternative pathways in aquatic and terrestrial ecosystems are poorly constrained, and require further elucidation. As the marine environment is the penultimate source of most of the risk of Hg exposure to wildlife and people in northern communities, a particular focus on the fate of Hg entering marine systems would be appropriate. The role of microbial communities in Hg fate in the Arctic has been largely overlooked but could be crucial to our understanding.	A, C, F, M, T	C	B	5
It is unknown whether MeHg enters Arctic food webs mainly through the microbial populations responsible for its formation, or primarily as dissolved MeHg assimilated by phytoplankton and algae. Rates of inorganic and MeHg uptake by Arctic microbial and algal communities have not been adequately determined.	F, M	C	B	5
The aquatic MeHg cycle in the Arctic is very poorly understood, and requires further research as a matter of priority. In particular, little is known about the Arctic marine MeHg cycle, which is key to understanding the human risk developed from Hg exposure via traditional animal foods.	F, M	C	B	5
The bioavailable fraction of AMDE-related Hg, and its rate of accumulation by biota, is a priority for further investigation as it is a potentially important process contributing to Hg exposure in aquatic food webs.	F, M	C	B	5
Although it is unknown whether MeHg formation also takes place in Arctic seawaters, the Arctic Ocean does exhibit nutrient maxima which may be suggestive of this effect. Confirmation and measurement of this process in the Arctic Ocean would be a significant advance in understanding of the Arctic Hg cycle.	M	C	B	5
How Does Climate Change Influence Arctic Mercury?				

Topic	Sphere	Theme	Activity	European Polar Research Priorities
The uncertainty about the net effect of temperature increases on AMDE chemistry and Hg deposition, coupled with the unknown relative contributions of frost flowers and first-year sea ice to atmospheric Br chemistry, make it impossible to even qualitatively predict how rising average temperatures will impact on Br levels, and atmospheric Hg chemistry, in the future. Given the important role AMDEs may play in THg inputs to the Arctic, additional laboratory and field investigations of temperature effects are warranted.	A	C	B	5
Additional research is warranted on this processes, as well as other processes which could be important: release of Hg, nutrients and labile carbon into lakes and the ocean as a result of thawing of permafrost soils and peatlands; the 'greening' of the Arctic tundra with grasses and woody plants which may add more carbon to aquatic systems; and altered hydrological regimes which will probably see reduced lake water levels, lower snowpacks and so reduced spring freshets.	C, F, M, T	C	B	5
Most of the insights into possible climate – Hg methylation linkages are gleaned from temperate locations and extrapolated to the Arctic. Bacterial demethylation and its relationship to climate variables is poorly understood. As net methylation rate is the key rate-limiting step link between the inorganic Hg forms which dominate the environment and toxic MeHg which biomagnifies in food webs, research into this area should be a priority.	C, F, M, T	C	B	5
Experimental evidence is largely lacking for interactions between climate warming and Hg bioaccumulation in Arctic freshwater food webs, which limits predictive ability.	F	C	B	5
The number and scope of studies examining marine biotic Hg–climate relationships needs to be expanded in terms of numbers of species and time span; sea-ice obligate marine mammals and fish may be most affected by climate change.	C, M	C	B	5
Owing to its probably growing importance as a major source of inorganic Hg and carbon to aquatic environments, the role of permafrost in the Arctic Hg cycle should become a priority research issue.	C	C	B	5
Mass balance budgets for MeHg in Arctic marine systems may be as revealing as they were for lakes, but first require significantly greater efforts aimed at measuring MeHg masses and transformation rates in different environmental compartments.	M	C	B, O	5
Are Mercury Levels in Arctic Biota Increasing or Decreasing, and Why?				
In terms of long-term trends, available information is limited to fewer than ten wildlife species in the Canadian and Greenlandic regions of the Arctic; coverage of low trophic level species and invertebrates is particularly limited. Historical	C, F, M, T	C	O	5

Topic	Sphere	Theme	Activity	European Polar Research Priorities
time series from the Alaskan and Russian Arctic would be a valuable addition to knowledge of anthropogenic impacts on modern Hg levels.				
For recent biotic time series, there is a regional imbalance in data availability. Few or no tissue monitoring data which met the specified data requirements were available from the Alaskan, Russian or Finnish areas of the Arctic. Continued support for ongoing time series, and initiation of biotic Hg monitoring in regions presently lacking coverage, will further add to the accuracy of the picture of recent trends in biotic Hg concentrations.	C, F, M, T	C	O	5
Uncertainties concerning the net deposition rate of Hg from AMDEs and other wet and dry atmospheric deposition processes in the Arctic (see Chapter 3) limit the ability to evaluate competing theories about the important drivers of recent trends in biotic Hg levels. Little is known about how changes in the Arctic cryosphere (snow, lake and sea ice, brine, permafrost) are affecting Hg bioaccumulation in Arctic ecosystems. Also lacking is systematic information on habitat and feeding behavior for many Arctic species, which can affect Hg concentrations in biota through alterations in MeHg assimilation and biomagnification.	C, F, M, T	C	B, O	5
What are the Toxicological Effects of Mercury in Arctic Biota?				
Investigations that explore combined effects under a multiple stressor framework should be initiated to improve understanding of how chemical and non-chemical stressors interact to affect the health of Arctic biota and the broader Arctic ecosystem.	C, F, M, T	C	B	5
The possible interspecies differences in the effectiveness of demethylation, selenium biochemistry, and sensitivity to MeHg exposure would be highly relevant to future studies on Arctic species. The antioxidant role of Se directly and indirectly (e.g., as cofactor for glutathione peroxidase) should also be investigated. Future studies should also consider sequestration of Se by Hg, which may result in Se deficiency.	C, F, M, T	C	B	5
Owing to the importance of brain neurochemistry in multiple aspects of animal health, the ecological and physiological significance of prolonged disruption to brain neurochemistry needs to be addressed. Future studies should also evaluate Hg exposure and effects in other high trophic level Arctic wildlife and in other brain regions that may accumulate more Hg than the brain stem. Other toothed whales, such as pilot whales and narwhal, should be investigated to see if Hg concentrations as high as those in beluga can be detected.	C, F, M, T	C	B	5

Topic	Sphere	Theme	Activity	European Polar Research Priorities
The populations having tissue concentrations of concern should be investigated for Hg-induced health effects. Future histopathological work should include other physiologically important tissues such as the brain, reproductive organs, and the developing organism.	H	C	B, O	5
Continued sampling of blood should include measures of Se and Se-associated enzymes to better assess the Hg-Se interaction in the blood and to assess Se as a nutrient (not just in countering Hg toxicity), along with measures of carbon-, nitrogen- and sulfur-stable isotopes and fatty acids to better assess pathways of exposure (diet).	H	C	B, O	5
Effect studies that correlate Hg exposure with biological responses should be carried out on polar bears in northern Canada and northwestern Greenland (as well as reference areas) showing upward Hg trends and hair and (other tissue) concentrations of concern.	M	C	B, O	5
A MeHg egg-injection study was recently conducted on thickbilled murres to develop toxicity thresholds, and this should be extended to include other relevant Arctic species.	M	C	B, O	5
Additional studies should be undertaken to determine Hg levels and possible effects in a wider range of marine species, especially including top predatory species such as sharks.	M	C	O	5
Additional studies to determine levels and possible effects in species at risk should be conducted, especially studies on top predators from areas with the highest contaminant loads.	M	C	O	5
What is the Impact of Mercury Contamination on Human Health in the Arctic?				
Monitoring is urgently needed to ensure early detection of climate-induced human health threats related to contaminants. Essential monitoring elements include contaminant levels in humans and wildlife food species, zoonotic diseases in wildlife, and observations of environmental parameters such as water quality, ice, permafrost, and weather.	H	C, P	O	5
Improved predictive models of contaminant transport and behavior in the Arctic are needed to understand the likely impacts of climate change with respect to contaminants. The models require improved comprehensive circumpolar monitoring of environmental matrices integrated with weather and climate data.	A, C, F, H, M, T	-	M, O	5
A global agreement to control Hg emissions should be pursued to complement national and regional efforts to reduce environmental Hg concentrations and to lower human exposure to Hg in the Arctic.	H	C	L	5
More research about determinants of food choices and availability is needed to provide better dietary advice relevant to local conditions and preferences. This research should focus on differences by age and gender.	H	C	L	5

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Because consumption of imported food is likely to continue increasing in most of the Arctic, health authorities should work vigorously with local and national food agencies to promote the availability and consumption of imported food items with high nutritional value.	H	C	L	5
Studies should combine human biomonitoring of contaminants with total diet studies in the Arctic in order to produce better exposure estimates and better dietary advice.	H	C	B, O	5
Continued monitoring of legacy POPs, Hg, and lead in humans and traditional/local foods is needed to obtain valid exposure trends and to track the effectiveness of national, regional, and international action to reduce releases.	H	C	O	5
Because the exposure level to MeHg continues to be high in some Arctic populations, continued monitoring of temporal trends is warranted.	H	C	O	5
Further research is needed on the relationship between Hg and cardiovascular disease in Arctic populations. Contaminant-nutrient interactions should be further investigated in prospective Arctic cohort studies.	H	C	B, O	5
Further general recommendations from the 2009 AMAP human health assessment (AMAP, 2009b)				
Considering the importance of general health and the influence of changing diets and contaminants on disease outcomes, more effort needs to be made to systematically collect, analyze, and report on the health status of Arctic populations and especially indigenous peoples.	H	C, D	O	5
It is very important to maintain and expand current human population cohorts in the Arctic as identified in this assessment, such as those in Canada, Greenland, and the Faroe Islands. Only long-term prospective studies will provide the information needed to track adverse health outcomes associated with contaminants and changing conditions related to climate change, socio-cultural conditions, and diet.	H	C, D	O	5, 9
Uniform reporting of key health status indicators should occur every three to five years, should include trend information, should be broken down by age and gender, and should be provided by all circumpolar jurisdictions at appropriate regional levels.	H	C, D	D	5
Because genotype may influence responses to contaminants, more knowledge about genetic variability and susceptibility among Arctic peoples is needed. Including genetics in studies that examine lifestyle and contaminant interactions will provide better insight into individual and population vulnerability to contaminants.	H	C	O	5

Abbreviations: AMDE = Atmospheric mercury depletion event; GEM = Gaseous elemental mercury; MeHg = MethylMercury; RGM = Reactive gaseous mercury; THg = Total mercury

Table 3. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere (AMAP)
Web source: https://www.amap.no/documents/download/1448/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Observational needs and knowledge gaps for the cryosphere				
Snow: There is no pan-Arctic dataset of *in situ* snow measurements. There are few measurements of snow depth on sea ice. Space-based capabilities for snow extent are robust, but methods of estimating snow water equivalent and snow depth are limited. Precipitation gauge networks are the most important source of information on high latitude snowfall but have large errors. Satellite methods are challenging but promising. Further work is needed to improve models of snow-vegetation interactions. There are dramatic differences in snow model response if vegetation is included.	C	K	M, O	2
Sea ice: While satellites have provided reliable observations of sea ice extent, concentration, and motion for over 30 years, methods for estimating ice thickness from space are only now being developed. *In situ* measurements of ice thickness are sparse. Sea-ice observations are not well suited for model assimilation because their error structures are not well known at the grid cell or pixel level.	M, C	K	M, O	2
Permafrost: There are numerous boreholes that provide temperatures for permafrost studies but many of the records are discontinuous and short. There is a wealth of historical data extending back 50 to 100 or more years; data rescue efforts are needed. Many of the observational sites are not maintained for long-term monitoring. There are significant thematic and regional gaps in the present networks, especially in eastern and central Canada, most ice-free areas in Greenland, and north-central and northeastern Russia. There are considerable uncertainties in modeling future permafrost distribution and dynamics. These include an under-representation of the ice content and the organic layer and its importance in insulating permafrost during climatic warming. Permafrost models also fail to adequately represent the disequilibrium that has arisen because some current permafrost is related to past climates.	C	K	M, O	2

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<tr><th>Topic</th><th>Sphere</th><th>Theme</th><th>Activity</th><th>European Polar Research Priorities</th></tr>
<tr><td>Glaciers: Glacier inventories have basic data for less than half of the world’s glaciers. Satellite-based inventories are discontinuous. Mass balance measurements over long periods are available for only a small subset of Arctic glaciers.
Models that link meteorology to glacier mass balance and dynamic response need to be improved. Downscaling techniques need to be developed for feeding such models with GCM data. Remote sensing data are needed to initialize and validate these models.</td><td>C</td><td>K</td><td>M, O</td><td>2</td></tr>
<tr><td>Greenland Ice Sheet: The climate on the Greenland Ice Sheet has been studied intensively in an effort to quantify the surface mass balance and to estimate its contribution to global sea level. However, in situ observations are limited due to the large area and remoteness of the ice sheet.
Climate models generally do not include ice sheets and glaciers, which limits their use for projecting sea-level rise. Particular challenges in modeling sea-level rise are the coupling of ice sheet and ice bed and of ice sheet, ice shelf, and ocean. Key uncertainties in predicting Greenland’s contribution to sea-level rise are ice dynamics and surface mass balance.</td><td>C</td><td>K</td><td>M, O</td><td>2</td></tr>
<tr><td>Modeling chryospheric processes: There are considerable uncertainties in modeling cryospheric processes. Permafrost models under-represent ice content and the insulating effect of the organic layer; climate models do not resolve the steep topography of the Greenland Ice Sheet margins; models of snow-vegetation interactions need to be improved; and models that link meteorology to glacier mass balance need to incorporate downscaling techniques and satellite data.</td><td>C</td><td>K</td><td>M</td><td>2</td></tr>
<tr><td><table>
<tr><td colspan="2">Observational readiness: Major gaps in observations. Ocean</td></tr>
<tr><td>Ice extent</td><td>In situ coverage is sparse and Incomplete</td></tr>
<tr><td>Ice concentration</td><td>Potentially large uncertainties in satellite retrievals in summer</td></tr>
<tr><td>Ice thickness</td><td>Satellite methods are still developing; snow depth on ice is an unknown</td></tr>
<tr><td>Ice motion</td><td>Important small-scale motions not captured by satellites; in situ measurements sparse</td></tr>
<tr><td>Snow depth on ice</td><td>Satellite method is limited to first-year ice with potentially large uncertainties; in situ data are sparse</td></tr>
<tr><td>Sea level</td><td></td></tr>
<tr><td>Surface temperature</td><td>Uncertainty in satellite estimates due to cloud cover</td></tr>
<tr><td>Albedo</td><td>Sparse in situ coverage; significant uncertainty</td></tr>
</table></td><td>C, M</td><td>K</td><td>O</td><td>1, 2</td></tr>
</table>

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<tr><th>Topic</th><th>Sphere</th><th>Theme</th><th>Activity</th><th>European Polar Research Priorities</th></tr>
<tr><td>
<table>
<tr><td colspan="2">Observational readiness: Major gaps in observations. Terrestrial</td></tr>
<tr><td>Snow cover</td><td>In situ network is declining</td></tr>
<tr><td>Snow depth</td><td>Satellite method is limited to tall-grass prairie</td></tr>
<tr><td>Snow water equivalent</td><td>In situ coverage is sparse</td></tr>
<tr><td>Freshwater ice</td><td>Declining observation network</td></tr>
<tr><td>Glacier, ice cap, ice sheet thickness</td><td>Sporadic coverage</td></tr>
<tr><td>Glacier, ice cap, ice sheet motion</td><td>Sporadic coverage</td></tr>
<tr><td>Permafrost: ground temperature</td><td>Large portions of the Arctic not covered</td></tr>
<tr><td>Permafrost active layer thickness</td><td>Large portions of the Arctic not covered</td></tr>
<tr><td>Surface temperature</td><td>Satellite method is clear sky only</td></tr>
<tr><td>Albedo</td><td>Sporadic in situ coverage;</td></tr>
</table>
</td><td>C, F, T</td><td>K</td><td>O</td><td>1, 2</td></tr>
</table>

Table 4. The Impact of Black Carbon on Arctic Climate (AMAP)

Web source: https://www.amap.no/documents/download/977/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Recommendations for improved characterization of spatial and vertical distribution of BC and OC in the Arctic environment and deposition processes				
Improve the accuracy of measurements of BC and OC and further understanding of the effects of the measurement method on the retrieved concentration values.	A	S	B, O	5
Continue efforts to resolve and/or standardize monitoring methods and protocols for BC and OC to ensure data comparability among national programs, field campaigns, and emission studies.	A	S	D, E, O	5
Improve tracer based characterization of bio-mass burning and fossil fuel combustion sources to Arctic BC and OC at the surface and aloft to improve source identification of Arctic BC.	A	S	B	5
Add long-term surface monitoring sites in regions that are currently under represented and/or anticipated to experience increased emissions to establish baselines and assess future impacts.	A	S	E, O	5
Implement measurements of BC and/or aerosol light absorption at long-term surface monitoring sites that currently have no such measurements (Tiksi, Valdardai, Amderma, and the White Sea in Russia; Behchoko in Canada; Denali (IM-PROVE), Poker Flats, and Homer in Alaska; Summit in Greenland) for spatial characterization of Arctic BC.	A	S	O	5
Implement measurements of OC, ^{14}C (for differentiation of biomass and fossil fuel combustion sources), and additional tracer species at all long-term monitoring sites for source identification of measured BC.	A	S	O	5
Undertake systematic, vertically resolved (surface to aloft) observations of BC and OC for vertical characterization of Arctic BC.	A	S	O	5
Implement routine measurements of BC and tracer species in snow in close proximity to long-term atmospheric monitoring sites to characterize BC deposition processes and sources of deposited BC.	C	S	O	5
Undertake process studies for characterizing aerosol removal during atmospheric transport and dry and wet deposition or for development of seasonally and spatially resolved deposition rates.	A	S	B	5
Perform detailed case studies and statistical analyses of pan-Arctic BC, OC, and tracer data to determine dominant source types and regions using methods independent of complex chemistry transport and climate models.	A	S	D	5
Make intensive field campaign and long-term monitoring data sets publically available.	A	S	D	5

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Initiate a data recovery project to put all relevant observations available into a single accessible format.	A	S	D	5
Recommendations for emissions information				
Satellite and monitoring data should be utilized to validate and refine spatial and temporal distribution of emissions in the inventories.	A	S	D, E, O	5
Recommendations for model development, evaluation and application				
Apply existing chemical transport models and climate models to evaluate the impact of within-Arctic and global SLCF and LLCF (long-lived climate forcer) emissions on Arctic climate with the objective of clarifying: • relative contributions of extra-Arctic and Arctic forcing and the resulting climate response; • relative contributions of atmospheric direct forcing and snow/ice forcing for current and future climate;. • relative importance of SLCF forcing and LLCF forcing over the next 100 years; and • source region and source type resolved Arctic forcing.	A	S	M	5
Evaluate model output with appropriate observational data sets including surface, aircraft, and satellite-based observations.	A	S	M	5
Incorporate state of the art aerosol – cloud processes, carbon cycle chemistry, and cloud processes into chemical transport models and climate models to provide an integrated assessment of BC and co-emitted species, CH4, and O3 forcing on Arctic climate and climate response.	A	S	M	5
Test the sensitivity of model results to model resolution and reduce possible numerical problems at and around the North Pole.	A	S	M	5
Perform sensitivity calculations with revised wet deposition schemes to further evaluate the influence of this process on model results (including radiative forcing and identification of source regions). Test alternative schemes and compare with observational data to improve deposition schemes in general and to select the best available scheme.	A	S	M	5

Abbreviations: BC = Black Carbon; OC = Organic Carbon; SLCF = Short-lived Climate Forcers

Table 5. Arctic Biodiversity Assessment (CAFF/CBMP)

Web source: https://www.caff.is/assessment-series/233-arctic-biodiversity-assessment-2013/download

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Harvest of mammals, birds and fish				
Ongoing improvements in data gathering and analytical techniques for estimating sustained yield are needed. Ideally, such information would include an ability to differentiate populations and stocks, repeated estimations of stock or population abundance, and accurate and complete harvest or catch data including individuals not retrieved. The same applies to by-catch of mammals and birds – and non-targeted fish species – in fishing gear.	C, F, M, T	B	B, O	4
Continued and increased international cooperation on the gathering and assessment of data on population structure, harvest monitoring and harvest methods and regulations is needed, so as to improve the planning and management of harvests. Existing examples include the International Agreement on the Conservation of Polar Bears and cooperation through the North Atlantic Marine Mammal Commission. Many other species and inter-jurisdictional issues require such attention	C, F, M, T	B	B, O	4
Improved means of accessing and exchanging information between hunters, fishermen, scientists and management authorities is of paramount importance. This can involve implementing community monitoring programs, public education, information campaigns on sustainability, involvement in public debates, and more.	M	B	O	4
Stressors originating from outside the Arctic				
Enhanced integrated, multi-disciplinary research and monitoring could be established to improve our understanding of the fate, distribution and effects of contaminants on biota and on ecosystem structure and function, including achieving an improved mechanistic understanding of interactions with other relevant environmental stressors (e.g. climate variability/change) and cumulative effects.	C, F, M, T	C, B	B, O	4, 5
Cost-effective early detection monitoring networks for invasive alien species linked to a common repository would facilitate immediate and thereby effective response.	C, F, M, T	B	D, O	4
The large goose numbers established during the last half century need to be carefully monitored. Where not already existing, management plans could be developed, implemented and followed up in cooperation between range states of the populations involved.	T	B	O	4

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Knowledge gaps				
The lack of monitoring and modeling capability for many aspects of Arctic biodiversity and their drivers of change makes it difficult to assess change, its cause and implications, and what could be rational conservation actions. Change cannot be measured without a baseline. For many species and ecosystem processes, that baseline of knowledge does not exist. Similarly, modeling efforts have focused on the physical environment and a few key species or ecosystem parameters. A coordinated ecosystem-level oriented monitoring and modeling effort is needed to support biodiversity conservation efforts in a time of rapid change.	C, F, M, T	B	M, O	4
A great deal of research has been done on various aspects of Arctic biodiversity, but overall databases and knowledge bases do not exist for most topics.	C, F, M, T	B	D	4
Suggested Conservation and Research Priorities				
Improved monitoring and research is needed to survey, map, monitor and understand Arctic biodiversity including integrated, repeated data collection following recommended standardized protocols and priorities, and involving Arctic citizens in the survey and monitoring, if we are to move ahead with science informed decisions in the Arctic. Support for national and international coordinated efforts such as the CBMP and the BAR Code of Life is important to fill critical data gaps on population abundances and trends for many Arctic terrestrial and marine species as well as on changes in the functioning and services of Arctic ecosystems.	C, F, M, T	B	D, O	4

Table 6. Arctic Ocean Acidification (AMAP)

Web source: https://www.amap.no/documents/doc/amap-assessment-2013-arctic-ocean-acidification/881

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Monitoring of the seawater carbon dioxide system should be: Integrated within a framework that also monitors changes in other key variables (such as oxygen and nutrients).	M	P, S	O	1
Monitoring of the seawater carbon dioxide system should be: Closely coordinated with physical and biological observations.	M	B, P, S	O	1, 4
Monitoring of the seawater carbon dioxide system should be: Conducted from ships and in situ platforms (stationary and mobile).	M	P, S	O	1
New instrumentation will need to be developed for the extreme Arctic conditions.	M	P	A, O	1
Management of platform design, observational logistics, and data handling should be internationally coordinated	M	-	G	1

Table 7. Human Health in the Arctic (AMAP)

Web source: https://www.amap.no/documents/download/2594/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Further monitoring of contaminants is needed in all Arctic regions to determine whether the declining trends of some POPs continue, and monitoring of 'emerging' chemicals is also needed. Additional studies are needed to better understand recently observed health effects and risks associated with current levels of exposure in the Arctic.	H	C	O	5, 9
Conclusions drawn in the literature about the effects of contaminant exposure on health outcomes are based on a variety of methods, study designs and techniques for analysis, which has made it very difficult to combine and compare original studies. Studies should focus more on reporting descriptive statistics about the distributions of response variables and explanatory variables which are needed when summarizing and meta-analyzing the magnitude of effects.	H	C	D	5, 9
During the past five years there have been several EU-funded research projects on the health risks of environmental contaminants which have included Arctic population data sets. Study protocols should be harmonized wherever practical to improve opportunities for comparing contaminant levels and effects data between different regions of the world.	H	C	A	5, 9
Biomonitoring research that is linked to environmental change is required to understand how climate change may influence contaminant levels in wildlife and humans as well as the availability/access of Arctic populations to traditional foods including wildlife food species.	H	C	O	5, 9
As environmental contaminants are not the only threat to Arctic populations, adaptive strategies need to be developed at the community level that address contaminants, climate change and emerging zoonotic diseases, as well as interactions between these factors. Development of comparable international and circumpolar monitoring protocols for pathogens and contaminants would simplify the development of generalized human and wildlife public health adaptation strategies. As the effects are not uniform across the Arctic, region-specific adaptation strategies will be required and could be built in part upon the general strategies.	H	C, D, K	O	5, 9
Continued participation of analytical laboratories in an external QA/QC program is critical to ensuring high quality and comparability of human biomonitoring data on POPs and metals across the Arctic. Small errors can have large impacts on interpretations of data, and therefore it is recommended that laboratory participation in an external QA/QC program is	H	C	A	5, 9

Topic	Sphere	Theme	Activity	European Polar Research Priorities
mandatory, in order for AMAP to demonstrate convincingly that spatial and temporal trends in exposure levels are real and not a result of analytical artifacts.				

Table 8. Methane as an Arctic climate forcer (AMAP)

Web source: https://www.amap.no/documents/download/2499/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Natural terrestrial methane sources in the Arctic				
Increased ground-based monitoring of natural methane sources. The current capability for methane flux monitoring in the Arctic is very limited and needs increased areal coverage.	C, F, M, T	S	O	2
Cross-disciplinary approaches to document source to sink emissions and transport issues that include terrestrial, freshwater and near-coastal environments.	C, F, M, T	S	B, O	2
Airborne observations are needed to enhance spatial coverage, and space-based monitoring should be developed to an operational standard for monitoring ground-based source variations.	T	S	O	2
Natural marine methane sources in the Arctic				
Continued monitoring of Arctic marine methane sources remains of high importance, due to the large uncertainties involved. Although gas hydrates located in deep waters appear to be at low risk to release large amounts of methane into the atmosphere, there is still low confidence surrounding estimates of the size of the gas hydrate reservoir, which vary by orders of magnitude. Gas hydrates, therefore, remain an important area of interest, and a better assessment of how much is present, and their vulnerability, would help greatly to constrain emission estimates. Furthermore, the potential for emissions and the role of gas hydrates within the climate system would be more easily identified with an improved knowledge of past methane emissions through the evaluation of high-resolution records (e.g. from ice cores, marine sediment cores, or carbonate crusts).	M	S	O	2

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Moreover, the amount and condition of permafrost-associated gas hydrates is still largely unknown, and deserves more thorough understanding. This includes an improved mapping of the thermal state of subsea permafrost as well as more and improved measurements of the emission to the atmosphere from this region. Such measurements could benefit from the development and implementation of new techniques to determine the sea-to-air flux of methane. To understand this flux, an enhanced understanding is also needed on the production of methane within the surface mixed layer, where the various contributions to the observed methane supersaturation require improved comprehension.	C	S	A, O	2
In addition to improved characterization and quantification of methane sources, expanding knowledge of the processes that control consumption of methane within the sediment and the water column would help to improve flux estimates. The latter, for example, involves many unknowns, as knowledge of the microorganisms involved, and the processes controlling their activity, is oen lacking. While bubble plumes from the deep seabed are unlikely to reach the atmosphere, considerable uncertainty remains on how much of the methane dissolved in the water column bypasses oxidation and reaches the atmosphere, and what happens to larger outbursts of methane, such as from submarine landslides. Additionally, the impact of sea-ice decline on the oceanic methane budget is still poorly understood, as are the physical and biological processes in sea ice itself. How this affects methane emissions needs to be investigated further.	F, M	S	B, O	2
Because most of the processes mentioned here are currently poorly represented within models, any newly obtained knowledge following from these recommendations will need to be incorporated into models and validated, to expand capability to predict the future development of the Arctic Ocean as a methane source. Although current knowledge may seem to indicate that large changes within the oceanic methane budget are not expected to occur in the near future, the huge uncertainties and unknowns, combined with the large quantities of methane stored and generated within the seabed, warrants ongoing study and regular monitoring of emissions and processes to better assess the present and future impact of marine sources on the Arctic methane budget.	M	S	M	2
Anthropogenic methane sources, emissions and future projections				
Increase the number and type of systematic on-site measurements and make results publically available to help reduce the large uncertainty in global methane emission estimates. This would be particularly important for the potentially substantial fugitive methane emissions from oil and gas systems for which very few direct measurements exist that are source attributed and representative for different types of hydrocarbons in different world regions.	C, F, M, T	S	O	2

Long-term monitoring of atmospheric methane				
The data presented in this chapter have the potential to identify and locate major sources of Arctic methane by type and seasonality. However, continuity in long-term data records for both weekly and hourly measurements is essential to support this work. Integration of the long-term observational data (including isotopic measurements) with short-term airborne measurements and data from ground-based remote sensing platforms would provide a more accurate representation of the true spatial and temporal gaps in the observing system. is analysis should be completed as a next step. Subsequently, and as modelling capabilities continue to evolve, a detailed assessment of the adequacy of the observational network to detect future atmospheric change and to support the characterization of sources may be warranted. Ensuring the timely availability of both short- and long-term observational data to support future analyses is critical to ensuring a full understanding of the limitations of the current observing system. Common data archiving and quality control/assurance practices would also improve data inter-comparability.	A	S	D, M, O	2
Finally, maintaining the existing long-term data records, as well as continuing to evaluate the spatial and temporal coverage of Arctic atmospheric methane measurements is an essential component in improving the ability to assess the overall impact of regional and global methane sources, as well as to assess the response of the Arctic to climate change.	A	S	D	2
Modeling of atmospheric methane using inverse (and forward) approaches				
Increasing spatial coverage of surface observations, deployment of regular aircraft campaigns to characterize specific regions and seasons, and atmospheric column observations for vertical characterization of concentrations.	A	S	O	2
Further development and evaluation of ecosystem process-based models for estimating wetland sources.	F, T	S	M	2
Continuing improvements to atmospheric transport simulations to better represent convection and planetary boundary mixing processes at smaller spatial scales.	A	S	M	2
Modeling the climate response to methane				
Although progress is being made, most current-generation ESMs do not yet include processes that are necessary to model feedbacks specific to methane and the Arctic region. A representation of wetlands, permafrost, the soil sink of methane, wildfires, expansion of shrubs, and ocean-atmosphere methane flux (together with atmospheric chemistry) would make it possible to model atmospheric methane concentration as a dynamic variable and the bi-directional coupling between climate change and natural methane emissions.	C, F, M	S	M	2, 4
Coupled chemistry-climate models are computationally very expensive to run. Yet, inclusion of processes representing the oxidation of methane, and other climate-chemistry interactions, is crucial for modelling atmospheric methane concentration dynamically and for making a complete assessment of the effect of changes in anthropogenic methane emissions. Climate-chemistry interactions not only include those related to changes in ozone and stratospheric water vapor that are caused by changes in methane emissions, but also feedbacks such as the increase in methane oxidation in a warming climate (e.g. Denisov et al. 2013).	A	S	M	2
Regarding the effects of ozone produced from methane, uncertainties lie both in the ozone change itself (e.g. Fry et al. 2012, and discussion in Sect. 8.3.2.1) and in the climate response to ozone change. The latter will also depend on feedbacks involving the biosphere (e.g. Sitch et al. 2007b; Collins	A	S	B	2, 4

et al. 2010), which have not been taken into account in the present study. Further research is needed for a more accurate assessment of the climate response to future ozone changes.				
Uncertainty in the calculated temperature response to the maximum technically feasible reduction of methane is relatively large, especially in the Arctic, as reflected by the difference between the results from the three ESMs used in this study. A detailed investigation of the various factors contributing to this variability in model results is also likely to contribute to a better understanding of the effect of the changes in natural and anthropogenic methane emissions on the Arctic climate.	A	S	B	2
Annual-mean surface air temperature is not the only relevant climate parameter. For the Arctic region in particular, changes in other high-impact climate variables including sea-ice extent, snow cover, evaporation and precipitation, and ocean circulation are also relevant. Additional analyses that focus on the benefit of reduction in SLCFs including methane will benefit from an assessment of the response of these other high-impact climate variables.	A	S	B	1, 2
On a more general note, uncertainties with respect to modelling the regional climate response remain large, and this is of particular relevance for studies aimed at the Arctic region. Improved regional climate modelling with a focus on the Arctic region deserves increased attention in this respect.	A	S	B	1, 2

Table 9. Radioactivity in the Arctic (AMAP)

Web source: https://www.amap.no/documents/download/2772/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Climate effects (principally warming) on the behavior of NORM/TENORM in the Arctic could have implications for human and environmental health and this requires further research.	-	C	B, O	-

Abbreviations: NORM = Naturally-occurring radioactive material; TENORM = Technologically-enhanced naturally-occurring radioactive material

Table 10. Chemicals of Emerging Arctic Concern (AMAP)

Web source: https://www.amap.no/documents/download/3003/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Fate and transport models for PPCPs need to be developed for Arctic conditions	-	C	M	5
Continued refinement of geospatial models supported by environmental measurements will aid efforts to identify sources and pathways of PAHs to the Arctic.	-	C	M	5
Further work is needed to improve models of air-water gas exchange for halocarbons in the Arctic and to quantify their production/release at air-snow-ice interfaces and in melt ponds. Participation of marine and terrestrial dissolved organic matter, and bacteria in the synthesis of halocarbons in the Arctic Ocean should be investigated.	A, C, F, M, T	C	M	5
Monitoring programs should be expanded to extend spatial trends for CECs, in particular to cover additional areas in Russia, Alaska, Sweden, Finland and Iceland.	-	C	O	5
Baselines should be established for temporal trends, with a view to implementing well-designed temporal trend monitoring for priority CECs; specimen archiving should also be undertaken to allow the possibility for retrospective temporal trend studies of CECs as methods and QA/QC advances allow.	-	C	O	5
Such monitoring should include POPs added or under review for listing under the Stockholm Convention in existing temporal trend monitoring studies (air and biota).	-	C	O	5
Monitoring supported by research studies is needed to provide greater knowledge on the presence of microplastics in the Arctic and potential to act as ‘carrier’ of other chemicals, including a route of dietary exposure to animals, and associated effects.	-	C	B, O	5
(AMAP) monitoring strategies should be adjusted to make it possible to examine the presence in the Arctic of contaminants with local sources as well as long-range transported substances.	-	C	O	5
Wider application of (target and non-target) analytical screening is needed for additional CECs, different media, and additional geographical locations (including areas with potential influence of local sources).	-	C	O	5
Broader screening is needed for CECs in Arctic human biomonitoring studies.	H	C	O	5, 9

Abbreviations: CEC = Contaminants of Emerging Concern; PAH = Polyaromatic hydrocarbons; POPs = Persistent Organic Pollutants; PPCP = Pharmaceuticals and personal care product.

Table 11. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) (AMAP)
Web source: https://www.amap.no/documents/download/2987/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
WCRP Grand Challenge: Assembling the most reliable observational data on sea ice and snow, and using these data to evaluate and improve climate model simulations of the remarkable changes that have already been observed and to enhance confidence in future projections.	C	K	M	1, 2
WCRP Grand Challenge: Assembling glacier and ice sheet models for use in projecting melt rates and corresponding sea-level rise. Shrinking glaciers will also have profound and direct impacts on millions of people whose water resources depend on the summertime storage provided by mountain glaciers.	C	K	M	2
WCRP Grand Challenge: Quantifying the amount of carbon available in permafrost areas, evaluating the potential for release of this carbon, and improving our capability to simulate the response of permafrost thaw, and its connection to the global carbon cycle.	C	S	M	2
Overarching knowledge gap: Despite qualitative progress, the overarching knowledge gap is poor quantification of the timing, magnitude, and risk of future Arctic change, especially for those changes that involve multiple Arctic feedbacks.	-	-	-	1, 2
Changing climate system: Determine the amount of global warming that would trigger an unstable abrupt shift in the Arctic system (sea ice, Greenland ice sheet, permafrost, boreal forest). Better document and project changes in storms, precipitation/evaporation, Arctic vegetation, moisture fluxes, and the influence of freshwater-marine coupling on the Arctic and through teleconnections to the North Atlantic.	C, T	B, K	B, M, O	1, 2, 4
Declining sea ice: Improve timing estimates for future loss of regional sea ice and increase understanding of the change from multi-year sea ice to first-year sea ice. Determine the impacts of sea ice loss on Arctic and mid-latitude weather, climate variability and predictability. Data gaps impede projections of the ice-associated ecosystem response to a changing climate.	C	B, K	B, M, O	1, 2
Thawing permafrost: Investigate how changes in permafrost affect coastal erosion, ecosystems, and infrastructure on local and regional scales. A major unknown is quantifying the strength of the positive feedback between thawing permafrost and warming climate in terms of natural carbon emissions.	C	K, S	B, M, O	1, 2

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Melting ice sheets/glaciers: Quantitative rates are needed for the processes (ice dynamics, subglacial meltwater, ocean interaction) that accelerate melting. Also needed is a more complete quantitative evaluation of the contribution of the Greenland ice sheet and Arctic glaciers to future sea-level rise relative to non-Arctic contributions.	C	K	B, M, O	2
Shifts in terrestrial ecosystems: Improve understanding of snow-land type-hydrologic changes coupled with ecological feedbacks that together transform Arctic landscapes. Scaling challenges arise because many landscape changes occur at small scales but their aggregate changes have regional and global impacts. Develop syntheses of pan-Arctic observations of wildfire characteristics (frequency, intensity, severity, size).	C, F, T	K	B, M, O	4
Observations: All aspects of Arctic research can benefit from better monitoring and satellite interpretations, and improved coordination between monitoring efforts, process studies, and modeling.	-	B, K	B, M, O	-
Modeling: How to use climate model results in future climate and risk assessments is a significant scientific issue in itself. Improvements include the need for better approaches to multi-model evaluations, determining confidence levels in model projections for different variables, development of strategies for using model ensembles to assess probabilities and uncertainties, and using downscaling techniques to add resolution and uncertainty estimates.	-	K	B, M, O	1

Abbreviation: WCRP = World Climate Research Programme

Table 12. State of the Arctic Marine Biodiversity Report (CAFF/CBMP)

Web source: https://caff.is/monitoring-series/431-state-of-the-arctic-marine-biodiversity-report-full-report/download

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Combine national monitoring with collaborative approaches that allow for sufficient integration and standardization to conduct syntheses across the circumpolar region.	M	B	G	4
Standardize how data are collected, managed and made available. This is a key component in ensuring circumpolar Arctic comparability and should be an important consideration in the implementation of monitoring plans.	M	B	D	4
Ensure that Arctic monitoring programs are ecosystem-based and include as many CBMP FECs as possible to include functionally important taxonomic groups and improve our understanding of how the ecosystem functions, and how its components are related. Such monitoring programs can serve to underpin management of human activities in the Arctic marine environment.	M	B	A	4
Standardize methodology, including taxonomic identification in order to allow production of comparable data and results.	M	B	A	4
Ensure training of personnel performing sampling and analyses.	M	B	A	4
Use TLK within the design and implementation of monitoring plans. The TLK of people living along and off the Arctic Ocean is an invaluable resource for understanding changes in Arctic marine ecosystems and its inclusion should be supported by national governments.	M	B	I	4
Increase engagement and partnerships with local residents and easy to access technology in monitoring programs. Indigenous communities are important 'first responders' to catastrophic events. More importantly, their knowledge systems provide a wealth of knowledge that should be involved in the analysis of collected data for increased understanding of current trends and filling historical gaps.	M	B	I	4
Increase the span of networks in the CBMP to include Community-based monitoring networks.	M	B	I	4
Encourage the monitoring of relevant physical parameters alongside some FECs that are particularly sensitive to their effects, including sea ice biota and plankton.	C, M	K	O	4
Expand monitoring programs to include important taxonomic groups and key ecosystem functions. These gaps are likely due to logistical challenges or lack of expertise in specific fields.	M	B	O	4

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Expand monitoring programs to include those utilizing both TK and science; involvement of Indigenous organizations and build capacity to provide a co-production of knowledge platform.	M	B	O	4

Abbreviations: FECs = Focal Ecosystem Components; TK = Traditional Knowledge; TLK = Traditional and Local Knowledge

Table 13. Arctic Ocean Acidification (AMAP)

Web source: https://www.amap.no/documents/download/3055/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
The effects of ocean acidification, in combination with other stressors such as warming, are highly uncertain. That uncertainty is compounded when other environmental, social and economic responses and trends are also considered. There is a need for multi-stressor research into how Arctic species are likely to respond.	M	B, P, S	B, O	4, 8
Ecosystem changes should be monitored in such a way that allows for the identification and differentiation of the impact of each stressor on the ecosystem, as well as the potential synergistic effects of multiple combined stressors.	M	B, P, S	B, O	4
Monitoring should also be intensified in the North Atlantic, given the biological, commercial and subsistence importance of fisheries in these waters and the impact of outflow of increasingly acidified water from the Arctic Basin. Regional fishery management organizations, OSPAR and the Arctic Council should cooperate to do so.	M	B, P, S	O	4, 8
There is a need for more Arctic-specific research into ocean acidification and its effects, whether regarding impacts on species, habitats or economic consequences. Currently, the lack of such research means many findings are extrapolated from research undertaken experimentally or in other geographic regions.	M	B, P, S	B, O	4, 8

Table 14. Biological Effects of Contaminants on Arctic Wildlife and Fish (AMAP)
Web source: https://www.amap.no/documents/download/3080/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Certain Arctic regions, such as Russia, Fennoscandia and Alaska, are not adequately represented in the monitoring of wildlife and fish exposure and effects, despite relevant studies in the Russian Arctic in particular having been called for in all previous AMAP assessments since 1998.	F, M, T	C	O	4, 5
There are a number of invasive and migratory wildlife and fish species, including killer whale and capelin (*Mallotus villosus*), which are not represented or are under-represented in Arctic monitoring and research addressing biotic changes due to the changing Arctic climate.	F, M, T	C	B, O	4, 5
Further pan-Arctic harmonization is required in relation to target species, sampling frequency and season, and methods applied for the measurement of contaminants and associated biomarkers and biological endpoints that are applicable to effects assessment. In doing so, there is a need for increased communication and collaboration with local and indigenous people	F, M, T	C	I, O	4, 5

Table 15. State of Arctic Freshwater Biodiversity Report (CAFF/CBMP)

Web source: https://www.caff.is/monitoring-series/488-state-of-the-arctic-freshwater-biodiversity-report-full-report/download

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Future Monitoring Methods: Further harmonize sampling approaches among countries, and select appropriate sampling methods and equipment to balance between maintaining consistency and comparability with historical data and alignment with common methods used across the circumpolar region.	F	B	A	4
Future Monitoring Methods: Develop supplementary monitoring methods that provide better standardized estimates of biodiversity to maximize the likelihood of detecting new and/or invasive species.	F	B	A	4
Future Monitoring Methods: Use a regionalization approach based on ecoregions to guide the spatial distribution of sample stations and, ultimately, to provide better assessments.	F	B	A	4
Future Monitoring Methods: Ensure that spatial coverage of sampled ecoregions is sufficient to address the overarching monitoring questions of the CBMP across the circumpolar region, maintain time series in key locations, and fill gaps where monitoring data are sparse.	F	B	A	4
Future Monitoring Methods: Ensure the number of monitoring stations provides sufficient replication within ecoregions and covers common water body types.	F	B	A	4
Arctic countries should establish a circumpolar monitoring network based on a hub-and-spoke (intensive-extensive) principle in remote areas.	F	B	A	4
Experimental design for the hub-and-spoke network should largely focus on addressing the Impact Hypotheses developed in the CBMP freshwater plan to increase focus on assessing biotic-abiotic relationships in Arctic freshwater systems.	F	B	A	4
The Freshwater Steering Group of the CBMP should continue to serve as the focal point for the development and implementation of pan-Arctic, freshwater biodiversity monitoring.	F	B	G	4
There should be a focus on continuing monitoring efforts at stations with existing time series, as these stations form key sites for future evaluations of temporal changes.	F	B	G	4
Resources must be provided to maintain and build the freshwater database for future assessments in order to maximize the benefits of this database	F	B	D	4
Arctic countries should make better efforts to document and preserve data from short-term research projects and research expeditions, as well as from industrial, university and government programs.	F	B	D	4

Table 16. Desktop Study on Marine Litter including Microplastics in the Arctic (PAME)

Web source: https://pame.is/index.php/document-library/pame-reports-new/pame-ministerial-deliverables/2019-11th-arctic-council-ministerial-meeting-rovaniemi-finland/423-desktop-study-on-marine-litter-including-microplastics-in-the-arctic/file

Topic	Sphere	Theme	Activity	European Polar Research Priorities
With regards to entanglement, knowledge was abundant on pinnipeds during the 1980's and 1990's in the Bering Sea and Gulf of Alaska, but monitoring efforts have since been reduced. In the rest of the Arctic, knowledge is fragmented and covers only some groups or species, such as whales. Studies on interactions between biota and marine litter in the Arctic have mostly focused on the interaction and effects at the individual level, and information on the effects at the population level are lacking, even for the better-studied species.	M	C	O	4, 5
Plastic additives or adsorbed environmental contaminants can be potentially toxic to marine organisms, but as of today, it is not possible to determine a level for safe environmental concentrations for microplastics (OSPAR Commission, 2017). Current evidence indicates that the risk to human health appears to be no more significant than via other exposure routes, but an understanding of exposure, bioaccumulation and impacts at different food web levels is still lacking (UNEP, 2016).	M	C	B, O	5, 9
The knowledge on distribution of marine litter, including microplastics,in the Arctic is geographically skewed due to information being mostly available for the Barents and Norwegian Sea and for the Bering Sea. Few data are available for the Central Arctic Ocean and the coastal areas aroundit in Siberia, Arctic Alaska, mainland Canada,and the Canadian Arctic Archipelago.	M	C	O	5
Despite a growing number of studies, plastic ingestion and entanglement in the Arctic have been studied and documented at the individual level for only a limited number of species and even less with regards to microplastic interaction.	M	C	O	4, 5
Developing a monitoring program as part of, or parallel to, the development of a regional action plan is of great importance in gaining further knowledge on litter distribution and composition, as well as informing decision-making.	M	C	O	5

Abbreviations: RAP = Regional Action Plan (RAP) on marine litter in the Arctic

Table 17. Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Arctic Health and Wellnes (D1.8) (EU-PolarNet)

Web source: https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP1/D1-8_Minutes_of_International_Stakeholder_Workshop_at_ASSW.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Priority issues				
Mental health, vectorborne infections, contaminant cohort studies	H	D, C	O	5, 9
Modeling ecological changes such as range shifts of plant and animal species,	-	B	M	4, 9
Temperature changes and changes in precipitation	A	K	O	1, 9

Table 18. Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Research Needs on Arctic Ecosystems and Ecosystem Services (D.12) (EU-PolarNet)
Web source: https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP1/D1.12__Minutes_of_workshop_with_international_partners_and_stakeholders_at_a_relevant_Arctic_Conference.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Coordinated measurements are needed of key properties and processes in representative areas of Arctic shelves and basins. Among important research needs are improved remotely operated observatories, targeted long-duration time series studies of primary and secondary production and the cycling of bioactive compounds, and the development of coupled biogeochemical models that use Arctic-appropriate parameterizations.	M	B, P	M, O	4
There is need to establish a more comprehensive all-year network of monitoring stations in the Arctic Ocean as well as deployment of drifting and moored platforms in both the surface and deeper waters.	M	-	A	4
The seasonal ice zone: physical-biological interactions, ecosystem characteristics, including timing and productivity, acidification and contaminants.	C, M	B, C, K, P	B, O	2, 4
Investigation of the effects of increasing amounts of freshwater in Arctic Ocean surface waters on, for example, circulation	M	K	O	1, 4
Analysis of species composition and fish stocks in the marine areas currently accessible, both pelagic and benthic, as a basis for long-term monitoring programs for key species and ecosystems	M	B	O	4
Screening for new chemicals arriving in the Arctic via long-range transport	-	C	O	4, 5
Studies of the distribution and effects of plastics and microplastics in Arctic ecosystems	-	C	B, O	4, 5

Table 19. Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Research Needs on Climate-related Effects on the Arctic Cryosphere and Adaptation Options (D1.15) (EU-PolarNet)

Web source: https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP1/D1_15_Minutes_of_workshop_with_international_partners_.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Monitoring climate-related changes in the Arctic cryosphere at the system level and across disciplines is very important and requires a consistent commitment from funding agencies for long-term monitoring, which is vital given the rapid changes in these systems owing to changing stressors. Funding for the development and maintenance of interdisciplinary networks is also crucial.	C	K	G, O	2

Table 20. Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Research Needs on Arctic Biology and Terrestrial Ecosystems (D1.19) (EU-PolarNet)

Web source: https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP1/D1_19_Minutes_of_Stakeholder_Workshop_at_Arctic_Conference.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Across scientific practice, there is a need for harmonizing sampling methods and taxonomic nomenclature as well as an intercalibration of methods for use in monitoring freshwater and terrestrial ecosystems. Challenges in relation to monitoring efforts include different monitoring standards between countries, large gaps in geographical coverage of monitoring efforts, and differences in taxonomic lists and misidentification of specimens. There is a very strong need for common standards for methods and taxonomy	F, T	B	A	4
There is need to develop better insight into the taxonomy and biodiversity of Arctic freshwaters that can be used to identify new indicators of change and new tools for the assessment of the ecological status of Arctic aquatic ecosystems according to EU's Water Framework Directive	F	B	O	4
A strategic goal of future biodiversity monitoring in Arctic freshwaters should be harmonization of efforts among Arctic countries to obtain adequate sampling across representative ecoregions that will support the detection of spatial and temporal trends.	F	B	O	4
Access to data that are of high quality and inclusive is crucial for future assessments of change in Arctic ecosystems. Arctic countries should develop joint efforts to secure existing monitoring efforts and expand them to cover the entire circumpolar region.	-	B	D	4
There is a clear requirement for better storage of data and better data structures	-	B	D	4
New approaches for long-term ecological research and monitoring should be implemented, including DNA-barcoding and environmental DNA (eDNA) for better taxonomic resolution of complex groups that are key components of food webs in Arctic aquatic ecosystems	-	C	B, O	4

Table 21. Set of white papers addressing priority questions in polar research and targeting funding agencies and policy makers (Deliverable 2.8) (EU-PolarNet)

Web source: https://www.eu-polarnet.eu/fileadmin/user_upload/www.eu-polarnet.eu/Members_documents/Deliverables/WP2/D2.8_Set_of_white_papers_addressing_priority_questions_in_polar_research_and_targeting_funding_agencies_and_policy_makers.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
The coupled polar climate system: A more accurate understanding of the coupled Polar climate system has to be reached. An improved understanding of key processes can be achieved through intensive measurement campaigns to study processes controlling the exchange between the different components of the Polar system and through careful analysis of existing data from long term measurements from coordinated observation infrastructures. Strengthening the Polar observation infrastructures through joint networks and standardized measurement methods is essential in order to carry out a more precise model initialization and for obtaining comparable data set circumpolar.	A, C	K	A, B, O	1
The coupled polar climate system: We need to coordinate existing data into common databases. A first step is to integrate different data among disciplines at different time scales and spatial resolution to understand modern and past environmental dynamics and processes	A, C	K	D	1
Footprints on changing polar ecosystems: Lead concerted international actions (involving EU countries and countries worldwide) to establish coordinated research and subsequent science-based and scenario-based advice for fast action in management and international policies. In the Arctic, cooperation between the EU, its Arctic member states (Sweden, Finland, Kingdom of Denmark) and other Arctic Council member states (Norway, Russia, Canada, Iceland and the US) and implementation of the Trans-Atlantic Research Alliance between EU, US and Canada, are necessary for ensuring coordinated activities (research, monitoring, management) at a pan-Arctic scale. In addition, fostering the involvement of indigenous Arctic peoples and local communities across national borders is crucial for sharing all useful information and experience with them, and for ensuring their broad involvement in ecosystem assessments.	-	B	B, O	4
Managing human impacts, resource use and conservation of the Polar Regions: Identify gaps in knowledge and initiate or enhance monitoring activities to strengthen future predictions of environmental impacts and trends in Polar Regions.	-	-	O	5, 7
Managing human impacts, resource use and conservation of the Polar Regions: At policy-relevant spatial scales, integrate available environmental and societal knowledge to model future scenarios.	-	-	M	5, 7, 8

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Advancing operational informatics for Polar Regions: Consider how best to link measurements of the natural environment with models, allowing better forecasting and prediction capabilities.	-	-	M	-

Table 22. Initial Requirement Report (D1.1) (INTAROS)

Web source: https://intaros.nersc.no/content/initial-requirement-report

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Essential Variables to Observe				
Atmosphere	A	S	O	1
Terrestrial: Snow, vegetation, the Arctic carbon balance, permafrost and freeze-thaw cycles, soil moisture and surface water, the freshwater balance of Arctic hydrological systems and the export of fresh water and nutrients into the Arctic Ocean	T, F	K, P	O	2, 4
Croysphere: in situ/near surface variables, satellite-derived variables	C	K	O	2
Sea ice	C	K	O	2
Ocean/Physical: Temperatures, salinity, currents, heat fluxes, sea ice	M	K	O	1
Ocean/Biogeochemical: Oxygen, nutrients, inorganic carbon, dissolved organic carbon, suspended particulates	M	P	O	4
Ocean/Biological: Primary production, secondary production, fish abundance and distribution, marine mammals and polar bears, marine biodiversity	M	B	O	4

Table 23. Report on present observing capacities and gaps: Ocean and sea ice observing system (D2.1) (INTAROS)

Web source: https://intaros.nersc.no/content/report-present-observing-capacities-and-gaps-ocean-and-sea-ice-observing-system

Topic	Sphere	Theme	Activity	European Polar Research Priorities
There are many gaps in the data coverage in the Arctic, but the gaps in biogeochemical observations (oxygen, nutrients, Chl-a, Carbon/pH) are particularly important. Specifically, one can mention: • Deep ocean observations are sparse, especially under the ice • General lack of RT/NRT data in the Arctic • Argo observations of temperature in the upper 10 m of ocean are needed	M	K, P	O	1, 4
Gaps in data availability: In the Arctic there are limiting factors in accessing data in the same way as in other regions • Some data originators have strict data policies and are simply unable to share. • Data are handled by military institutes and hence are not made available. • R&D data where data originator wants to publish before sharing. • In some institutes data are sold and hence they are not willing to share data that would compromise business. • Some organizations and scientists express concerns about "incorrect interpretation of environmental data"	M	-	D	-

Abbreviations: RT/NRT = Real time/Near Real Time

Table 24. Report on present observing capacities and gaps: Atmosphere (D2.4) (INTAROS)

Web source: https://intaros.nersc.no/content/report-present-observing-capacities-and-gaps-atmosphere

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Lack of all types of atmospheric observations over the Arctic Ocean. This is in particular the case when it comes to observations of the vertical structure of the atmosphere.	A	-	O	1

Table 25. Report on present observing capacities and gaps: Land and cryosphere (D2.7) (INTAROS)

Web source: https://intaros.nersc.no/content/report-present-observing-capacities-and-gaps-land-and-cryosphere

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Observations of greenhouse gases	C, T	S	O	1
Soil freezing and thawing observations	C, T	K	O	2
Snow observations	C, T	K	O	2
Glacier and ice sheet observations	C, T	K	O	2
Geological observations	C, T	G	O	6
River discharge observation	C, T	K	O	2

Table 26. Observational gaps revealed by model sensitivity to observation (D2.12) (INTAROS)

Web source: https://intaros.nersc.no/content/observational-gaps-revealed-model-sensitivity-obser-vations

Topic	Sphere	Theme	Activity	European Polar Research Priorities
The ocean observing system	M	K, P	D, O	1
The atmosphere observing system	A	K	D, O	1
GHG fluxes observing system	A	S	O	1

Abbreviations: GHG = Green house gasses

Table 27. Community based monitoring programmes in the Arctic: Capabilities, good practice and challenges (D4.1) (INTAROS)

Web source: https://intaros.nersc.no/sites/intaros.nersc.no/files/D4_1_updated_1.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Good practises				
Establishing CBM programmes	-	-	I, O	-
Implementing CBM programmes	-	-	I, O	-
Sustaining CBM programmes	-	-	I, O	-
Obtaining impacts through CBM	-	-	I, O	-
Connecting and cross-weaving with other approaches	-	-	I, O	-
Ensuring the quality of knowledge products	-	-	I, O	-
Addressing the rights of Indigenous and local communities	-	-	I, O	-

Table 28. Arctic Social Indicators- a follow-up to the Arctic Human Development Report

Web source: http://library.arcticportal.org/712/1/Arctic_Social_Indicators_NCoM.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Recommended set of Arctic Social Indicators: 1. Infant Mortality (Domain: Health/Population) 2. Net-migration (Domains: Health/Population and Material Well-being) 3. Consumption/harvest of local foods (Domains: Closeness to Nature and Material Well-being) 4. Per capita household income (Domain: Material Well-being) 5. Ratio of students successfully completing post-secondary education (Domain: Education) 6. Language retention (Domain: Cultural Well-being) 7. Fate Control Index (Domain: Fate Control	H	E	-	8, 9
Recommendations				
1. Design the Arctic Social Indicator monitoring system to meet the following objectives: 1. Data are available at a regional level; 2. Data are available separately for indigenous and non-indigenous populations; 3. Data are available on at least a five-year reporting period	H	E	A	8, 9
2. Encourage national statistical agencies to participate in development of a metadatabase identifying ASI indicators that are already monitored by a national agency and published in hard copy or electronic form.	H	E	A	8, 9
3. Encourage establishment of an international task force composed of national statistical agency analysts and Arctic researchers to identify the special tabulations required to produce comparable ASI indicators and to recommend approaches to produce these special tabulations.	H	E	A, G	8, 9
4. Encourage the collaboration of ASI with researchers who are funded through national research councils to collect primary data.	H	E	G	8, 9
5. Reduce duplication of effort by promoting collaboration among monitoring projects in the Arctic, notably but not confined to, Arctic Observing Networks, (AON), Sustaining Arctic Observing Networks (SAON), and Arctic Social Indicators (ASI).	H	E	G	8, 9

Table 29. SIOS Infrastructure Optimisation Report

Web source: https://www.sios-svalbard.org/sites/sios.metsis.met.no/files/common/D3.4_SIOSInfrastructureOptimisationreport.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
The proposed overarching approach of the SIOS monitoring programme				
Involve as many of the nations operating there as possible in the monitoring programme	-	-	O	-
Integrate the monitoring of vertical coupling through the entire atmosphere, down to the Earth surface and into the ocean	-	-	O	1
Integrate measurements of horizontal transfer of Earth System relevant variables across the archipelago and within the surrounding ocean	-	-	O	-
Monitor changes in the land-based environment and its biodiversity	F, T	B	O	4

Table 30. Evaluating the Antarctic Observational Network with the Antarctic Mesoscale Prediction System (AMPS); Karin A. Bumbaco; Joint Institute for the Study of Atmosphere and Ocean, University of Washington, Seattle, Washington

Web source: https://journals.ametsoc.org/doi/full/10.1175/MWR-D-13-00401.1

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Observations are particularly limited in West Antarctica. Combined with the shorter temperature correlation length scales, this implies that West Antarctica is a compelling location for implementing an objective, optimal network design approach.	A	K	O	1

Table 31. EU Seventh Framework Programme: ARCRISK: Arctic Health Risks: Impacts on health in the Arctic and Europe owing to climate-induced changes in contaminant cycling

Web source: https://www.amap.no/documents/download/1901/inline

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Models are useful and continue to be improved, but further improvements are needed	H	C	M	4, 5, 9
Food-web models have been developed to examine the transfer of contaminants into and through food chains, and potentially the influence of climate change on this process. However, an incomplete understanding of the underlying processes means that such models are currently unable to produce reliable projections of future development	H	C	M	4, 5, 9
Studies of human health outcomes in relation to contaminants are seldom conclusive and it is difficult to link health effects to specific contaminants. If cohort studies addressing health effects of contaminants were conducted according to agreed protocols this would increase their suitability for meta-analyses.	H	C	A, O	5, 9

Table 32. 3rd International Conference on Artic Research Planning (ICARP III)

Web source: https://icarp.iasc.info/images/articles/downloads/ICARPIII_Final_Report.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Observing and Predicting Future Climate Dynamics and Ecosystem Responses				
Establishing a robust, sustained, co-designed and participatory observing system of systems, as reflected in the ongoing efforts of Sustaining Arctic Observing Networks (SAON), relying on existing and new networks and infrastructure and innovative experiments to generate environmental and socio- economic observations to improve our ability to predict local, regional and global processes.	-	-	O	-
Establishing flagship observatories as part of this observing system of systems to provide comprehensive measurements over the entire Arctic region.	-	-	O	-
Developing an international agreement for standards and maintenance of key observing systems.	-	-	G, O	-
Supporting international efforts to make Arctic data and metadata easily accessible, such as the SAON/ IASC Arctic Data Committee (ADC).	-	-	D	-
Facilitating knowledge transfer between environmental, socio-economic and traditional and local knowledge, making use of platforms, such as the CryoNet component of the Global Cryosphere Watch (GCW), the International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT) and the Circumpolar Arctic Coastal Communities Observatory Network (CACCON).	-	-	O	-
Supporting the development and deployment of new technology to improve our understanding of the physical, ecological and social environments of the Arctic, including unmanned vehicles, remote sensing, autonomous systems and telemedicine, among others.	A	-	O	-
Focusing on fully coupled modeling, i.e., air-ice-sea interactions, in order to provide reliable weather forecasts, decadal predictions and rapid prediction of extreme events as a major contribution to the Year of Polar Prediction (YOPP), allowing the development of tools required to facilitate rapid decision-making at local, regional and global scales.	-	K	M	1
Fully integrating ice-shelf dynamics, permafrost, ecology and economics into existing modeling frameworks, including models used in the Intergovernmental Panel on Climate Change (IPCC) framework, allowing improved representation of complex processes.	-	-	M	1, 2, 4, 8

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Making more effective use of traditional and local knowledge by engaging northern and indigenous communities and involving local, regional and global stakeholders in the co-design of sustained observation systems and models to help define mitigation and adaptation strategies.	-	-	I, O	8

Table 33. ICC Alaska Food Security Report

Web source: https://iccalaska.org/wp-icc/wp-content/uploads/2016/03/Food-Security-Summary-and-Recommendations-Report.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Establish ecological baseline data rooted in IK. For example, there is a need to identify highly sensitive ecological areas through IK. Additionally, close attention needs to be given to how such information is categorized and shared.	-	B	O	4, 9
Enhance monitoring of pollutants throughout habitats.	-	C	O	5, 9
Enhance monitoring programs throughout all Alaskan Inuit communities; enhance monitoring programs based on both IK and scientific methodologies; enhance monitoring programs through the use of modern technology (e.g., recorders, cameras, etc.).	-	-	O	9

Abbreviation: IK = Indigenous Knowledge

Table 34. International Quiet Ocean Experiment. Science Plan

Web source: https://www.itk.ca/wp-content/uploads/2018/03/National-Inuit-Strategy-on-Research.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
1) International Year of the Quiet Ocean	M	-	M, O	-
2) Long-term measurements of sound	M	-	O	-
3) Observation efforts to support regional “experiments”	M	-	O	-
4) Arctic study comparison	M	-	O	-
5) Antarctic study comparison	M	-	O	-

Table 35. Antarctic Near-shore and Terrestrial Observation System

Web source: https://www.scar.org/scar-library/search/science-4/physical-sciences/antos/3446-2015-antos-workshop-report/file/

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Terrestrial systems				
Biodiversity (5 yearly)	T	B	O	4
AWS	T	K	O	1
Aeolian Collections	T	K	O	4
Respiration	T	B	O	4
Biological activity	T	B	O	4
Soil Geochemistry (5 yearly)	T	P	O	6
Limnetic systems				
Hydrology	F	K	O	2
Biological activity	F	B	O	4
Marine component				
Physical	M	K, P	O	1
Colonisation	M	B	O	4
Diversity	M	B	O	4
Distribution	M	B	O	4
Function	M	B	O	4
Genetic/genomic	M	B	O	4

Abbreviations: AWS = automatic weather station

Table 36. CliC/AMAP/IASC, 2016. The Arctic Freshwater System in a Changing Climate

Web source: https://www.amap.no/documents/doc/the-arctic-freshwater-system-in-a-changing-climate/1375

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Recommendations for policy-makers				
Supporting the efforts of the research community in improving the observation of key processes that affect the hydrological cycle in the Arctic and sub-Arctic regions.	A, C, F, M, T	-	B, O	2
Promoting the understanding of the inter- linkages between key processes, such as the effects of changing freshwater fluxes into Arctic oceans on currents and climate, and the effects of reduced river and lake ice on atmospheric and ecological processes.	A, C, F, M, T	-	B, O	1, 2, 4
Facilitating deeper understanding of the physical, biological, ecological and climatic consequences, over the short, medium and long terms, of a more intense freshwater cycle.	A, C, F, M, T	-	B, O	1, 2, 4
Working to better understand the likely key socioeconomic consequences of changes to the Arctic freshwater system, with particular regard to how the ecosystem services it provides are likely to be affected, and to the development of tools for stakeholders to use to adapt to these changes, especially when planning and managing infrastructure in the region.	A, C, F, H, M, T	-	B, O	1, 2, 4, 8

Table 37. Polaris. User Needs and High-level Requirements for the Next Generation of Observing Systems for the Polar Region. Summary Report (Polar View)
Web source: https://www.arcticobserving.org/images/pdf/RMTF/20190603/Polaris_Summary_Report.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Polar Information Gaps				
Sea ice	C, M	K	O	1, 2
River and lake ice	C, F	K	O	1, 2
Ice sheets	C	K	O	1, 2
Glaciers	C	K	O	1, 2
Snow	C	K	O	1, 2
Icebergs	C	K	O	1, 2
Permafrost	C	K	O	1, 2
Ocean	M	B, K, P	O	1
Land	T	B	O	1
Atmosphere	A	K, P	O	1

Table 38. Southern Ocean Modelling: Status and observational data requirements
Web source: http://soos.aq/resources/reports?view=product&pid=57

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Identifying the needs for better interdisciplinary ocean modelling	M	-	M	-
Developing data quality control procedures and data-model fit software	M	-	D, M	-
Designing and Performing Observing System Simulation Experiment	M	-	M	-

Table 39. A review of the scientific knowledge seascape off Dronning Maud Land, Antarctica

Web source:
https://www.researchgate.net/profile/Andrew_Lowther/publication/327051373_A_review_of_the_scientific_knowledge_seascape_off_Dronning_Maud_Land_Antarctica/links/5b75241292851ca65063d7b2/A-review-of-the-scientific-knowledge-seascape-off-Dronning-Maud-Land-Antarctica.pdf?origin=publication_detail

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Physical structure				
Ice shelf characteristics	C	K, P	B, O	2
Geology of the seafloor and continental margin	M	G	B, O	6
Paleoceanography	M	H	B, O	3
Sea ice	C	K	B, O	2
Ocean circulation	M	P	B, O	1
Ocean biogeochemistry	M	P	B, O	1
Ecosystem structure				
Macrobenthos	M	B	B, O	4
Plankton, krill and sea ice biota	M	B	B, O	4
Fishes	M	B	B, O	4
Flying seabirds	M	B	B, O	4
Penguins	M, T	B	B, O	4
Marine mammals	M	B	B, O	4
Pollution	-	-	B, O	5

Table 40. Canadian National Inuit Strategy on Research

Web source: https://www.itk.ca/wp-content/uploads/2018/03/National-Inuit-Strategy-on-Research.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
1. Advance Inuit governance in research	-	-	I, G	8
2. Enhance the ethical conduct of research	-	-	I	8
3. Align funding with Inuit research priorities	-	-	I	8
4. Ensure Inuit access, ownership, and control over data and information	-	-	D, I	8
5. Build capacity for Inuit Nunangat research	-	-	I	8

Table 41. User Requirements for a Copernicus Polar Mission

Web source: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC111068/2018.1802_src_polar_expert_group_-_phase_2_-_final_report_20180726final2.pdf

Topic	Sphere	Theme	Activity	European Polar Research Priorities
Floating-ice parameters	C, M	K	O	2
Glaciers, caps and ice-sheet parameters,	C	K	O	2
Sea level/SLA parameters,	M	K	O	1, 2
All weather SST	A	K	O	1
Surface albedo,	-	K	O	1
Surface fresh water	F	K	O	1
Snow	C	K	O	2
Permafrost	C	K	O	2

Abbreviations: SLA = Sea Level Anomalies; SST=Sea-Surface Temperature