EU-PolarNet
connecting science with society

INTEGRATED EUROPEAN POLAR RESEARCH PROGRAMME

Photo: Ronald JW Visser

Contents

Photo: Diane Erceg

Executive Summary

The poles are subject to multiple stressors, including environmental, economic, political, cultural and societal changes, which have regional impacts but also affect the entire globe through multiple and complex connections. While the changes, especially climate change, are particularly evident at the poles compared to other regions of the globe, they are by many aspects poorly understood in terms of driving processes, interconnection between each other, actual impacts on the socio-ecological systems and their potential to shape or constrain the future of the society at local, regional and global scales.

Europe has a leading role to play in the development of the Polar Regions to ensure safe, sustainable and prosperous Polar Regions. Europe's efforts aim at defining strategies for adapting to climate change, protecting the environment and promoting the emergence of new knowledge through innovation, international scientific cooperation and integration of diverse knowledge systems on the Polar Regions (see e.g. the EU Arctic Policy[1]). In this respect, the EU-PolarNet project has played a key role by fostering the coordination of polar research through networking between research institutions and organisations, by strengthening the link between the scientific community and the stakeholders to define their research needs and expectations and by proposing ways forward to optimise the existing research infrastructures, including those in charge of data management.

A prerequisite for Europe to achieving its ambition in the Polar Regions is to promote research that will advance the understanding of the functioning of these regions and their influence on Europe and the global system. The European Polar Research Programme (EPRP) was therefore developed with the mission to identify research priorities which have direct relevance to the most pressing societal challenges that local and indigenous communities, polar stakeholders and, more generally, all regions including Europe are facing as a result of the changes in the Polar Regions.

The EPRP is the outcome of a five-year process of co-designing and co-developing a future research agenda for Europe which has been performed within the EU-PolarNet consortium. One of the challenges consisted in the careful collection of the highly diverse polar stakeholder needs by implementing a series of engagement actions. Another key challenge was to translate these needs into prioritised research questions. This work was achieved by involving a wide range of polar experts and combining their expertise. In addition, the EPRP was subject to a thorough review by different scientific and polar specialists in and outside the EU-PolarNet consortium.

The enormous amount of information on the current stakeholder needs was provided directly by the various stakeholders thanks to several dedicated surveys and communication events, a major one being a survey which was launched in 2017. This survey has been translated into eight different languages, and largely contributed to the elaboration of the structure of the EPRP document. The EPRP structure indeed builds on the analysis of the large corpus of answers which has been received during this survey and could be categorised under a few major overarching research areas, named Research Needs, corresponding to the main domains of polar stakeholder's expectations. A group of international scientific experts was subsequently convened to a dedicated meeting to identify and discuss the appropriate research questions related to each chapter, the drafting of each chapter of the document being then entrusted to a subset of authors with particularly relevant expertise for this chapter.

The content of the EPRP is organised in six main chapters dealing with overarching, cross-cutting research issues which should lead to major advances in the understanding of the Polar Regions. In total, the chapters highlight a number of research issues ranging from improved characterisation and understanding of the physical, environmental, societal, cultural and economic conditions, and the current changes and evolutions in the Polar Regions to better definition, prediction and projection of their future conditions, thus supporting adaptation and resilience to the changes. Major challenges identified in the EPRP relate to the actual implementation of research in terms of co-creation of knowledge, leveraging resources and enhanced international cooperation for the benefit of society at large.

While altogether the Research Needs of the EPRP identify a large variety of key research questions from different disciplinary perspectives, they all address several overarching research challenges in relation to:

- Understanding the processes controlling the different polar systems, including the climate system, the socio-ecological system structure and functioning, and the different knowledge systems and their multiple interactions,

[1] EC JOIN/2016/21: "An integrated European Union Policy for the Arctic".

- Identifying and characterising the connections between the Polar Regions and the global system, and their implications in terms of coupling and feedback across all scales and disciplines,
- Assessing the current changes, including defining the relevant indicators of these changes, predicting their evolution, anticipating the future with regard to climate, environmental and socio-ecological conditions and designing a sustainable future for the society and community development in response to the socio-ecological changes,
- Evaluating the impact of human activities on the polar environments and socio-ecological systems, addressing the future evolution of local and Indigenous communities under increasing environmental, economic and cultural pressures, and defining the relevant governance system and policy frameworks for resilient socio-ecological systems facing just, safe operations in the Polar Regions,
- Enhancing the quality and quantity of information, through expanded observations, and knowledge on the Polar Regions by identifying the mechanisms for integration of different (scientific and non-scientific, Indigenous and western) knowledge systems and knowledge co-production,
- Identifying the necessary steps to optimise the chain of information linking research outcomes to decision-making through adequate brokering of scientific information, identification of relevant indicators of baseline states and changes, improved access to knowledge, including the FAIR data management requirements, and the design of relevant tools for the different polar stake- and right-holders,
- Advancing the technology and enhancing the infrastructure capacity in support of more efficient research, more sustainable polar operations, and development of the local communities,
- Designing education and training systems for better information of stake- and right-holders and increased awareness of the society on the value of the Polar Regions.

There is a general consensus across the different EPRP chapters that essential knowledge can be gained from contrasting the two poles and understanding their similarities and differences. While the two Polar Regions differ by their geographical characteristics and their history of human presence and economic development, they do have many features in common, though responding differently to the current changes and posing different scientific, geopolitical and logistical challenges.

As a natural result of the EPRP development strategy, the research priorities which are proposed in this document should contribute significantly to answering some of the major societal expectations regarding the Polar Regions. The relevance of the EPRP to these expectations has indeed been validated though a review of the document by a stakeholder panel specially appointed by the project. While the societal relevance of the research would differ depending on the different challenges that stake- or right-holder communities are facing, the research questions which are highlighted in the EPRP share common relevance to some major societal issues related to:

- Assessing and predicting the changes and the vulnerability of natural polar environments,
- Preserving the polar environments and the cultural vitality of Arctic communities,
- Identifying mechanisms that can sustain improved well-being and quality of life,
- Improving knowledge of environmental, technical, and societal factors controlling safe, sustainable, and just operations in the Polar Regions and evaluating the associated risks,
- Accessing environmental and socio-economic data, and improving interoperability, and
- Raising awareness on the value of Polar Regions.

The following chapters demonstrate how cross fertilisation between disciplines and knowledge systems and active cooperation between the research and stake- and right-holder communities have the potential to create significant advances in the knowledge of the Polar Regions for the benefit of their sustainable future.

I. Scope

The Polar Regions may seem remote, but the observed rapid changes currently affecting both the Arctic and Antarctic regions result in significant consequences in lower latitudes, including Europe (IPCC, 2019). Environmental, economic, and societal changes are now occurring at greater speed and scale than ever before and in increasingly interconnected ways. These environmental changes, particularly in the Arctic, are a clear indication of the impending shifts that will increasingly affect the European environment, society, and economy.

Both Polar Regions are also experiencing significant developments and, in particular, unprecedented levels of human activity that include research, tourism and new forms of resource extraction such as the expansion of oil and gas activities into the Arctic Ocean or the krill fishery in the Southern Ocean. Parts of Antarctica have been subject to transient human presence for almost 200 years but only in the past 65 years has this presence, mainly by researchers, become substantial. In comparison, the Arctic is home of a variety of human communities that exist under divergent economic and legal conditions. However, all of them share a common view that they are not simply onlookers and demand participation in the design of strategies for safeguarding the region's future.

Changes in the Polar Regions are at the root of societal challenges, but also economic opportunities for Europe and the world. Science is a vital tool in understanding the observed rapid changes and their drivers at high latitudes. Research is also necessary to make our climate models and forecasting tools more realistic by identifying and reducing important sources of uncertainty that may impair reliable prediction and future scenarios.

The integrated European Polar Research Programme is the outcome of a five-year process of co-designing and co-developing a future research agenda for Europe, which has been performed within the EU-PolarNet project. The integrated European Polar Research Programme represents a bottom-up community effort, which has been built on the challenges and needs raised by all stakeholders[2] who are affected by the ongoing changes in the Polar Regions. It has been designed using a truly transdisciplinary approach and it aims to bridge the knowledge gaps in and between the natural and social sciences, the economy and society in the Polar Regions. The outcomes of the research needs, which are put forward here, shall support the European Commission, national decision makers and businesses in making evidence-based decisions for the benefit of the Polar Regions and their inhabitants.

II. The need for an integrated European Polar Research Programme

European-funded research has made significant contributions to understanding the consequences of global change and the structure and functioning of ecosystems in both Polar Regions and their global interconnections. In the past 5 years, EU-PolarNet has investigated the research interests and operational capacities of the European polar research community, performed gap analyses for important research domains (e.g. data management, monitoring and modelling) and also gave recommendations for improvement (see Appendix I. I). The results of these analyses show how European polar research contributed to the development of a strategic agenda on innovation, while proposing solutions to mitigate and adapt to the ongoing changes in the Polar Regions. Formulating research questions in support of these actions is instrumental in achieving and demonstrating the EU's contribution to the generation of knowledge with relevance for society, economy, environment, and policymaking.

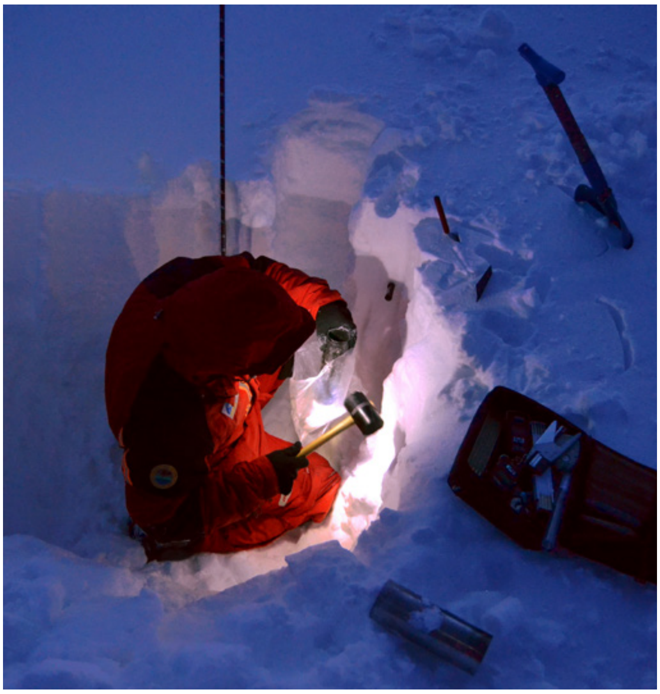

Photo: Federico Dallo

[2] Stakeholders are those who are potentially affected by, concerned about, interested in, important to, or having any influence on the Polar research agenda or will be end-users of polar research outcomes. Stakeholders include a wide variety of public and private sectors including policy, business, governmental and non-governmental organisations (NGOs) and the wider society, including local and Indigenous Peoples (rightholders).

THE ARCTIC: A JIGSAW OF MULTIPLE ACTORS

A unique and precise physical, political, or juridical definition of the Arctic region does not exist. Eight Arctic states[3] have sovereignty and sovereign rights but almost all of them have their political centres far to the south of the region. In this context, the Arctic Council plays a major role in fostering circumpolar cooperation amongst Arctic states and other actors. The Arctic Council is not an international organisation based on a treaty but is rather an international political forum. It has been credited with playing a role in peace and security in the Arctic, particularly as its mandate does not address military security issues[4]. Today, thirteen non-Arctic States are observers in the Council. With more observers wishing to join, and the growing economic presence of those engaging with the Arctic economically, the definition of an Arctic state is being re-examined in terms of identity building and practical circumpolar diplomacy. Thus, Arctic politics and security thinking have expanded well beyond the Arctic states themselves. It is therefore important to understand whether and how the growing array of security questions will result in new forms of state and sub-state dialogue, including how the Arctic Council would cope with security issues between its members. There is a risk that current developments in diplomatic relations across the Arctic may threaten security in the Arctic as a whole, but also marginalise considerable security concerns on other issues, especially in regard to Indigenous Peoples, the environment, economic development, and socio-economic questions.

Regional politics, since the Arctic sea ice recorded a remarkable low in 2007, have been marked by an increasing trend to asserting the primacy of the states (i.e. The Ilulissat Declaration[5]) and intensified state military investments in the region. Some of the Arctic states are also questioning how the changes in the Arctic will affect their politics and finances. In addition, numerous non-Arctic States have also formulated their Arctic policies using different methods, with some pointing to their scientific and exploration prowess, others towards their maritime expertise, and others focusing on the enormous economic and policymaking weight that the region will likely have in the future. Such initiatives reflect the large variety of political interests in the Arctic and demonstrate that, beyond the regional perspective, the Arctic is shaped significantly by global governance developments, and economic and environmental challenges. Regarding environmental issues, this vision is supported by the research activities within the Council working groups, which offer the opportunity for non-Arctic states and observers to contribute to and take up new challenges for future research actions.

Photo: Ronald JW Visser

The possibility of an scramble for Arctic resources was the subject of much of the speculation when the region began to be seen as a potential economic powerhouse. However, it faded due to dropping commodity prices and the logistical challenges that many nascent extractive industries in the region are still facing in their efforts to operate in the extreme environment. At the same time, regional agreements including the Polar Code[6], prohibitions on fishing in the Central Arctic Ocean and the moves towards an agreement to forbid heavy fuel oil in the Arctic, demonstrate further progress towards multilateral solutions to current, and a precautionary approach to emerging, governance, and socio-ecological challenges.

THE ANTARCTIC: A PROTECTED REGION UNDER INTERNATIONAL GOVERNANCE.

The Antarctic is a continent under international governance through the Antarctic Treaty System (ATS), which is a unique example of international governance. The ATS provides the legal framework for cooperation in Antarctica. It has maintained peace within the continent for almost 60 years and concluding a period of territorial claims in the first half of the 20th century. Eleven EU Member States are among the 29 Consultative Parties that take decisions on the governance of the Antarctic at the annu-

[3] Canada, Kingdom of Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States.
[4] Art. 1 of the Ottawa Declaration, 1996.
[5] The 2008 Ilulissat Declaration was adopted at the Arctic Ocean Conference in Ilulissat, Greenland on 28 May 2008.
[6] MEPC 68/21/Add.1 Annex 10, page 3: "International code for ships operating in polar waters (POLAR CODE)".

al Antarctic Treaty Consultative Meetings (ATCMs). The Parties have agreed to protect the natural and scientific values of the Antarctic Treaty area (the Antarctic continent and the Southern Ocean south of 60°S).

Once the Treaty entered into force in 1961, various traditional security interests were mitigated: military activity was prohibited along with the testing of nuclear weapons and disposing of nuclear waste. The Treaty sets aside the continent for peace and science. Article IV of the Treaty is the very cornerstone of international collaboration under the Antarctic Treaty. This provision preserves the *status quo* of the territorial claims asserted by states regarding their right of sovereignty. No party may be considered to have renounced any claim, nor may any new claims be asserted based on activities carried out while the Treaty is in force.

Spurred on by the 1973 OPEC oil crisis and assuming the mineral wealth of Antarctica, a Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA) was established in 1988, which would have allowed for mining and oil extraction in Antarctica. However, this Convention has never been ratified and never entered into force. Instead, in an unprecedented 180° turn, the Antarctic Treaty members established in 1991 the Protocol on Environmental Protection to the Antarctic Treaty (The Madrid Protocol), which entered into force in 1998. This Protocol declares the Antarctic south of parallel 60°S a natural reserve, devoted to peace and science, and prohibits any activities relating to mineral resources. The Protocol makes provisions for enabling a review not sooner than 50 years after its coming into force (2048), but until such a process is initiated, the prohibition on Antarctic mineral resource activities continues indefinitely.

As a response to increasing commercial interest in Antarctic krill resources and a history of over-exploitation of several other marine resources in the Southern Ocean, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) was established by international convention in 1982. Nine EU Member States and the EU itself are members of CCAMLR.

THE WAY FORWARD: SHAPING THE FUTURE OF POLAR REGIONS IN A RAPIDLY CHANGING WORLD

Perspectives of security in both Polar Regions call for a vision beyond state-centric configurations. Today's security threats, such as climate change, transcend states and economies, and are becoming relevant beyond the Polar Regions and reach national and global settings. A **comprehensive security assessment is** necessary to better grasp the ways in which different perceptions of security interact, and perhaps conflict, between states, human, societal, and international security perspectives, in addition to better understand how security issues are addressed and which policies are designed to that effect.

An improved understanding of the evolving and increasingly globalised nature of Arctic and Antarctic peace and security is needed. It shall focus on the **interaction between the poles and the rest of the world** and its continuously evolving contexts, both outside as well as within the Polar Regions.

Both the Arctic and Antarctic are rich in natural resources and the focus of increasing economic interest as access to these regions increases. An **assessment of the economic relevance of the Polar Regions** at local, national, regional, and global levels, and of the tension between economic, environmental and human security interests, would be needed.

In the Arctic, the Arctic Council must be able to adequately respond to existing and emerging challenges, most of these being shared with non-Arctic states and actors. The Council must focus on finding ways for further inclusion of those actors in the scientific research of its working groups, which serve as the main generators of ideas and projects for further actions.

The Antarctic Treaty itself is facing important challenges. The discussions at the ATCMs over the last decades have shown that countries involved in Antarctic governance, as well as stakeholders (e.g., environmental conservation groups, tourism operators, etc.), have different ideas about what precisely ATS agreements shall achieve with respect to regulating and managing human activities in the Antarctic. Consequently, these stakeholders may have different perspectives and economic considerations when asked the questions, to what extent are changes to the ATS desirable, and what governance actions, if any, are needed? To be able to engage in this discussion and to give whole Europe a voice, the EU should be **more involved in the ATS and encourage all its Member States to become Parties to the Antarctic Treaty.**

Photo: Ronald JW Visser

The integrated European Polar Research Programme (EPRP) aims to identify knowledge gaps, which need to be addressed to provide a better understanding of polar changes and to answer the current pressing needs and expectations of European societies regarding the Polar Regions. The methodology developed for this programme aimed to organise the EPRP around a limited set of overarching, cross-cutting themes, each of them being identified based on a comprehensive review of polar stakeholder needs.

Polar Regions are vulnerable and critical realms in the climate system and are currently facing the most rapid changes on the Earth. Climate change and increased human activities, occurring locally and across the world, are altogether responsible for this rapid evolution. Among others, there are some critical examples of the rapid environmental changes:

- The drastic decrease in Arctic seasonal sea ice and snow cover,
- Possible instabilities of the Antarctic and Greenland ice sheets in response to enhanced surface melting, ice-shelf collapse, and marine-terminating glacier retreat,
- The warming and increased thawing of the permafrost,
- The higher concentration levels of atmospheric and oceanic pollutants, and
- The changes in biodiversity and species distribution.

Despite these strong signals, knowledge of the environmental system in the Polar Regions is still too incomplete to allow anticipation of the scales and pace of the changes and their consequences and to facilitate the creation of a holistic theoretical and observational framework in support of future scenarios.

At the same time, climate change at the Poles is appropriately seen as a global issue. Polar Regions play a particular role in the global equilibrium and budgets of the Earth's climate and, as such, maintain strong connection to it through a wide variety of interaction and feedback mechanisms, which are rooted in the specificities of the natural polar environment. Examples of such linkages are the declining extent of the marine and terrestrial polar cryosphere, which is contributing to polar amplification of surface warming, acceleration of sea level rise and modifications of marine and terrestrial ecosystems, and associated fluxes of carbon dioxide and methane. Several of these processes exhibit tipping points and may imply irreversible changes with dramatic consequences on the global climate. Yet, knowledge about the potential impacts of such processes is still extremely poor.

Rapid changes in the environmental conditions, increasing global demand on polar natural resources and transportation routes, and growing geopolitical interests in the Polar Regions threaten these regional ecosystems. These changes may have tremendous consequences on individual livelihoods and the well-being of communities across the circumpolar North. Associated with these impacts are pressing needs to better understand interlinkage between ecosystems and society at different levels through the inclusive concept of socio-ecological systems. This will allow a better understanding of the valuation of ecosystem services for the residents and enable the society taking up the challenges of vulnerability, conservation, adaptation, and resilience. A full account of these aspects should contribute to improving baseline knowledge of broad scale variations of drivers and responses of species and biological communities, thereby contributing to better assessment of changes and appropriate environmental monitoring. Valuable insight can be gained from contrasting the Arctic and Antarctic regions on many issues. These are related to, e.g., the connectivity of their ecosystems to mid-latitudes, the history of colonial settlements, the current political power relations, their societal and economic development as well as more generally, how differences between the two poles modulate the impacts of global changes and human activities on these regions.

Indigenous Peoples, local communities and circumpolar governments are affected in a variety of ways by the changes brought about by a warming climate, increasing economic activities and urbanisation and potentially intensified migration from the South into the Arctic. To understand how population diversity, demographic factors and traditional livelihoods modulate the impact of changes, better knowledge is needed about the complex nature of the couplings between Arctic socio-ecological, political, cultural and economic systems. New methods are to be developed and applied together with the polar communities to understand and envision their future. In particular, mechanisms of transition to sustainability in these regions where the resource-based economy, durable infrastructures and cultural vitality are at risk need to be understood. This knowledge will form the necessary baseline on which to build governance scenarios for adaptation and resilience to the changes addressing both plausible and desired futures at local, regional, and global levels.

Increasing human activities pose challenges not only to local communities but also to business operators who need to become aware of the impact of their activities. To ensure safe, sustainable and just operations in the Polar Regions, enhanced knowledge of the factors influencing operating costs in the long-term are needed. The impacts of new commercial activities in the Polar Regions should be rigorously evaluated against pressures on the environment. In the Arctic interests of local and Indigenous communities and in Antarctica scientific, historical, aesthetic and wilderness values need to be taken in account as well. Research should aim at concrete knowledge of the societal value of ecosystem goods and services and help promoting technological and methodology developments in support of sustainable operations.

Polar Regions are still sparsely covered by observation networks although sustained observations are essential for predicting the evolution of changes in the Polar Regions and their impacts at local to global scales. The remote location and harsh conditions make operations in polar areas both expensive and complicated. Cross-cutting research to develop new methodologies and practices for data acquisition and interoperability is required for supporting and ensuring the most inclusive, cost-effective, and efficient data collection. Access and sharing of knowledge imply enhanced research cooperation, equal consideration and improved understanding of differences between Western and Indigenous knowledge systems, better use of the existing observational capacity, better connection with stake- and right-holders, including development of new methods of knowledge brokering, and innovative education and training methodologies for developing new skills.

III. Societal Relevance

The ambition of the EPRP is to identify those important knowledge issues regarding the Polar Regions that are of high concern to polar communities and global societies. The high degree of connectivity of both Polar Regions with the rest of the world calls for improved understanding of the relative importance of local, regional, and global (both natural and social) factors that influence their evolution. Regionally, the challenges are vast: Indigenous Peoples, local inhabitants and also polar ecosystems face environmental and economic pressure, as well as needs that are particularly difficult to satisfy in their extreme environment. Globally, the challenges are to fully understand the central role of the Polar Regions in the global climate system, while acknowledging that these regions will increasingly be under pressure as providers of food and resources in a world with a fast-growing population.

While, by definition, the outcomes of the EPRP should contribute to a better understanding of the societal and environmental vulnerabilities in the Polar Regions, they should also support important ongoing global initiatives such as:

- The UN 2030 Agenda for Sustainable Development by making the Sustainable Development Goals (SDGs) and their indicators relevant for the Polar Regions and other areas, the people living in the Arctic and all stakeholders with activities in the Polar Regions (Figure 1),
- The achievement of the Paris Conference (COP21) climate change targets at the global level,
- The EU Green Deal, which commits the EU to implement both the Paris Agreement and the United Nations 2030 Agenda for Sustainable Development,
- Major international scientific assessments, including the IPCC and Arctic Council reports, as well as EU and national adaptation strategies and plans,
- The Sendai Framework for Disaster Risk Reduction 2015-2030, and
- The UN binding agreement in preparation on Biodiversity of Areas Beyond National Jurisdiction.

In addition, the Research Needs identified in the EPRP aim at answering a suite of cross-cutting societal needs related to:

- Closing knowledge gaps in the understanding of various Polar processes. Advancing fundamental Polar research is essential to close several critical knowledge gaps in the understanding of the functioning of the Polar Regions and its effects on societies in the Polar areas and beyond. The EPRP recommends observing and research efforts, which are suitable to meet the demands for comprehensive and integrated information on polar environments and their role in influencing climatic and other process at lower latitudes. Increased assessments of polar processes are needed to increase confidence in models and predictions. Some of those research topics may not have a direct societal relevance now but are expected to generate knowledge that will indirectly contribute to inform major societal issues,
- Assessing and predicting changes in local and regional natural environments, and the vulnerability of the Polar Regions to these changes. The aim is to anticipate the societal implications of physical changes like increased natural hazards, increased accessibility to the region or modified local freshwater pathways, to prepare for adaptation procedures and to support informed decision-making. Beyond these regional impacts, there is a need to assess the value of the Polar Regions for the global climate, including their role as potential hosts for mitigation pathways,
- Assessing baseline state, changes, and future threats concerning polar ecosystems and their relation to the socio-ecological systems and society. The aim is to strengthen future predictions of environmental impacts, feedbacks, and trends in Polar Regions to propose scenarios for mitigation and adaptation and to develop societal and environmental resilience for these systems. This includes enhancing knowledge integration that can be incorporated into strengthened regulatory and management practices for ecosystem protection in marine and terrestrial environments, resource conservation, traditional food sourcing, water security, or guide responses to health and related life quality issues within the One Health concept,
- Identifying mechanisms that can sustain improved well-being and quality of life in a context of rapid change and increased self-determination and Indigenous participation in regional and local governance. The aim is to enable the economic, social, and cultural prosperity of Arctic communities and a just transition to sustainability. This implies developing new indicators for wellbeing and sustainable development in Polar Regions, in complementarity with the UN-SDGs, and new regional economic development models that ensure local sustainable value creation and well-being,
- Improving knowledge of environmental, technical, and societal factors that control and shape the ability to develop and maintain safe, sustainable and just operations in the Polar Regions, and their integrated effects on natural and social environments. This includes developing more accurate methodologies

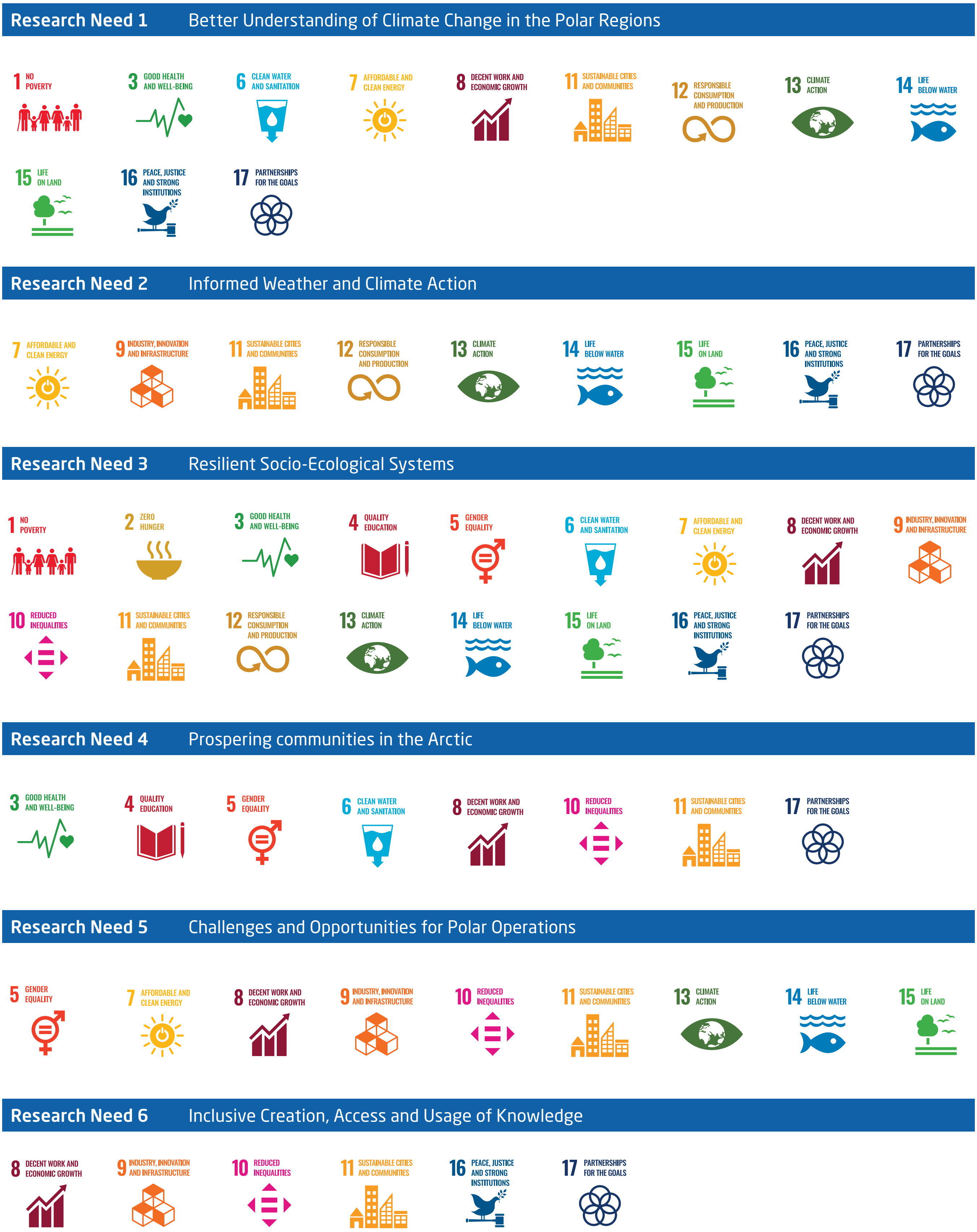

Figure 1. Relation of the EPRP Research Needs to the UN-SDGs

and procedures to define and manage environmental risks, and enhancing knowledge enabling Arctic communities and Antarctic commercial operators to participate in the development of a sustainable, profitable green economy,
- Enhancing the searching and access to available environmental and socio-economic data and improving their interoperability, designing methods that promote co-design and co-production of new data and providing recommendations for enhanced collection of new data and monitoring activities. The aim is to enrich the amount of information that is needed to assess systematic impacts upon polar environments and societies and related human activities,
- Developing new methodologies to optimise the full processing chain from identification of information needs to transfer of research results into relevant tools for stakeholders. Methodologies should integrate different knowledge systems, including community-based knowledge, at policy-relevant spatial and temporal scales. The aim is to improve the availability and meaningfulness of information for societies at large to support the co-design of future scenarios and decision making, and
- Developing innovative education and training systems that integrate different knowledge sources and will contribute to building the skills needed for sustainability, enhanced participation of society and strengthened public understanding and awareness of the value of Polar Regions.

IV. Methodology

1. Identification of research Needs

The integrated European Polar Research Programme was developed as a commitment of the EU-PolarNet consortium to deliver a research programme to the European Commission, which should be co-designed with representatives from polar stakeholders. The objective was to ensure that future European research outcomes would be directly relevant to society. The research programme is therefore structured according to overarching societal needs that could be identified through a regular dialogue with the polar stakeholder community including a range of dedicated events and online surveys. Engaging a large variety of stakeholders (including government policy-makers, business, NGOs, Arctic residents, Indigenous Peoples, research funders and scientists) in regular dialogue was instrumental to collecting their needs and views on the priority issues concerning polar research. Yet, account or representation of all the relevant stakeholder groups likely remained imperfect, e.g. because of the limited access to events and online material that some stakeholder groups might have faced.

Concomitantly, several initiatives have been accomplished by the EU-PolarNet project to support the development of the EPRP. The major outcomes have been the subject of several deliverables, which are detailed in Appendix I. I. In particular, the necessity to build on existing experience of national and international polar-related bodies in establishing priorities of relevance to Europe was taken into account through a desk analysis of available research strategy documents addressing priorities in polar science but also in polar infrastructures, observation and data facilities and, more generally, societal research needs (Appendix I. II). Another particularly relevant deliverable is the set of five EU-PolarNet White Papers, which were published in February 2019. This document, which was drafted by a group of more than 50 scientific experts and polar stakeholders, outlines the most pressing polar research priorities and related implementation challenges. In addition to the review of existing polar research strategy documents, the input material, which was used to prepare the synthesis of the stakeholder research needs that form the basis of the EPRP structure, falls into two main categories: stakeholder on-line consultations, and dedicated workshops and/or side events during international assemblies. The full list of input material can be found in Appendix I. Even though the engagement was comprehensive, international, and ongoing, there are possible biases in the data caused by e.g. the selection of source materials for the desk studies,

Photo: Ronald JW Visser

none-responses to surveys, and workshop design. However, as the responses to the surveys and participation to workshops included at least one representative from all major groups of polar stakeholders broadly defined, we are confident that the results represent the shared European societal and industrial needs in the Polar Regions.

1.1. Stakeholder surveys

Three surveys were specifically dedicated to collecting stakeholder research needs (Appendix I. III).

The first survey was launched in winter 2016 and reached out to the research community, which was asked to express its views on the compilation of research priorities and related societal challenges originating from the desk study on European polar research priorities. Through this consultation, it has been possible to verify the completeness of the original compilation and to narrow the number of overarching topics down to ten.

The second survey reached out to several polar stakeholder communities to investigate their possible engagement in polar research. The questionnaire was initially distributed in association with stakeholder workshops (section 1.2) and then launched online in April 2017. The results of the questionnaire facilitated initial science-stakeholder dialogues with the perspective of managing expectations and identifying needs from the onset of future partnerships.

The third survey, launched for two weeks in spring 2017, was designed to enable the polar community and stakeholders to identify priority areas for future polar research. The survey was conducted in eight different languages and distributed via various channels, including over a thousand individual emails that were sent to various countries. The results of this survey formed a fundamental basis for the set of five polar white papers, which in turn were an important step towards the integrated European Polar Research Programme.

Two other public surveys were launched in the context of the EU-PolarNet project with the aim to obtain overviews of the existing polar research data systems and infrastructures (targeted to data system managers), and polar commercial infrastructures (targeted to the business community). The information, which was collected through these surveys, provided valuable inputs to the EPRP to define urgent requirements in terms of information and infrastructures.

1.2. Stakeholder events

The objectives of the stakeholder events were to inform recommendations on how to conduct mutually beneficial stakeholder engagement for addressing the societal challenges in the Polar Regions[7]. More specific objectives were:

- To learn from stakeholders what their research needs and knowledge gaps are, and to determine the needs and challenges that society is currently facing in the Polar Regions,
- To bring different research disciplines together to share knowledge and to discuss the possibilities and benefits of doing multidisciplinary research, and in particular transdisciplinary research with the local and Indigenous communities in the Arctic, and
- To find the best strategies for communication and exchanges with the different stakeholders.

[7] A full list of stakeholder events can be found in the EU-PolarNet Public Deliverable 4.14.

Photo: Andrea Spolaor

2. Integrated European Polar Research Programme Structure

The next challenge in developing the EPRP was to translate stakeholder concerns and views into research questions. The first efforts focused on drafting a stakeholder needs document which represented a synthesis of the collected stakeholder information.

A preliminary categorisation was undertaken aiming at broad categories that would highlight issues that are recurring in the White Papers while being relevant to several stakeholder communities, therefore offering potential for future interdisciplinary research.

The additional input from the stakeholder research priorities survey and the workshops and events was used to revise the preliminary categorisation and to cluster the issues into overarching thematic areas, each of them containing several (6 to 11) topics with a wide range of underlying sub-topics. The full information and structure were preserved in a mind map (Appendix II) and formed the basis of the future work.

The stakeholder needs that had been identified were based on the issues and research interests of a large variety of stakeholders ranging from international researchers to policy-makers, Indigenous Peoples and local communities, business and NGO representatives and scientists who formed the majority of contributors. For the sake of completeness, it was decided to review the stakeholder document by a group of stakeholders via the EU-PolarNet Stakeholder Panel. The comments of the panel were then included in a revised version of the document.

The structure of the EPRP document was ultimately organised along six overarching Research Needs (Figure 2), each of them making a separate EPRP chapter. The underlying information, which had been identified under each of these research needs, was synthesised into key questions (Table 1). A template for each chapter of the research programme was then developed and proposed to the drafting team as the initial framework of the EPRP document.

The drafting of the EPRP chapters was delegated to a group of experts. Those experts were nominated and selected by the EU-PolarNet consortium and were invited to contribute to the EPRP in spring 2019. Each chapter was assigned to a list of experts led by two lead authors. The full EPRP draft was reviewed both internally and externally as explained in Appendix I. IV.

Photo: Elena Barbaro

Research Need 1
Better Understanding of Climate Change in the Polar Regions

Photo: Elena Barbaro

Research Need 2
Informed Weather and Climate Action

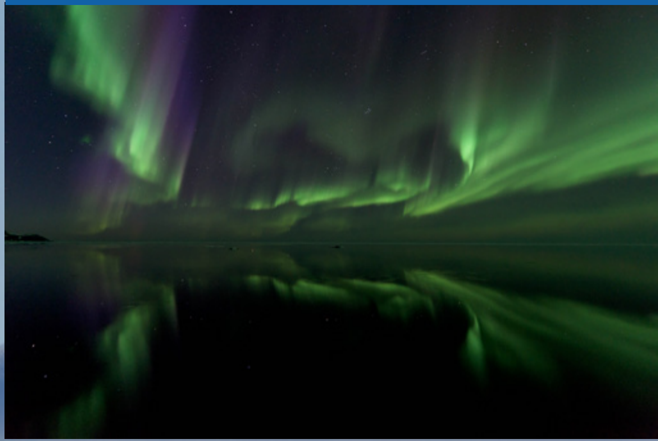

Photo: Ronald JW Visser

Research Need 3
Resilient Socio-Ecological Systems

Photo: Ronald JW Visser

Research Need 4
Prospering communities in the Arctic

Photo: Kirsi Latola

Research Need 5
Challenges and Opportunities for Polar Operations

Photo: Stefan Hendricks

Research Need 6
Inclusive Creation, Access and Usage of Knowledge

Photo: Thomas Steuer

Figure 2. The six Research Needs identified within the EPRP

V. Research Needs

Table 1. Final setup of the Research Needs and the Key Questions relevant for the EPRP.

RESEARCH NEEDS	KEY QUESTIONS
1. Better understanding of climate change in the Polar Regions and its links to lower latitudes	1.1: Key processes in polar-specific components of the climate system. 1.2: Polar coupling and feedback processes at the regional and global scales. 1.3: Modelling and predicting the polar climate system. 1.4: Assessing the impact of human activities on polar climate.
2. Informed weather and climate action	2.1: Identifying relevant indicators of polar climate change. 2.2: Designing new approaches to test the chain of processes from climate indicators to decision making. 2.3: Supporting decision making through predictions and projections of polar climate and socio-ecological systems. 2.4: Assessing the added value of the Polar Regions in relation to climate change and human activity impacts.
3. Resilient socio-ecological systems	3.1: Understanding key issues of polar ecosystem structure, functioning, and change. 3.2: Designing a healthy socio-ecological system. 3.3: Expanding observation of socio-ecological systems. 3.4: Ecosystem-based management, governance and transformative solutions toward a sustainable future.
4. Prospering communities in the Arctic	4.1: An infrastructure plan in support of sustainable community development. 4.2: National and sub-national governance challenges in the Arctic Regions. 4.3: Economic innovations for sustainable development of Arctic communities. 4.4: Education as a tool to expand the capacity of Arctic residents to respond to changes. 4.5: Learning from the past for a socio-economically balanced and gender-equal development of the Polar Regions. 4.6: The demography of the future Arctic population. 4.7: Cultural vitality for prosperity in the Arctic.
5. Challenges and Opportunities for Polar Operations	5.1: Understanding the impacts of changing environmental conditions and operations on risk and vulnerability. 5.2: Minimising the environmental impacts of polar operations. 5.3: Understanding and promoting the concept of social license for polar operations. 5.4: Identifying policies, frameworks and governance which ensure safe, sustainable, and just operations.
6. Inclusive creation, access and usage of knowledge	6.1: Developing new technologies and improved capacities in observation, modelling, and research in the Polar Regions. 6.2: Co-production of knowledge as a benefit to societal stakeholders. 6.3: FAIR data management principles for polar data collections. 6.4: Ensuring knowledge access and capacity building in Polar Regions. 6.5: Exploiting knowledge to inform decision making for the Polar Regions.

Research Need 1.
Better understanding of climate change in the Polar Regions and its links to lower latitudes

1. Introduction

Polar Regions are both vulnerable and critical in the climate system. The Arctic is the fastest warming region in the world. Arctic seasonal sea ice, land ice and snow cover in spring are decreasing, and permafrost is warming with increased thawing and subsidence. The region is a receptor of atmospheric and oceanic pollution both of local origin and from lower latitudes. The declining sea ice extent and thickness and dramatically changing ecosystems are only two examples of Arctic features that are threatened under a changing climate, impacting local and Indigenous communities. Climate change also impacts regional populations through access to food and resources, vulnerable infrastructures and changes in lifestyles. At the same time, the remoteness of the Polar Regions causes them to be poorly covered by the observation networks that form the basis for scientific research on climate issues.

The interconnection between polar processes and the global climate is such that climate change at the Poles is a truly global issue. The Antarctic and Greenland ice sheets play a crucial role in global climate and are losing mass, causing sea level rise. These ice sheets may experience instabilities in response to enhanced surface melting and ice-shelf collapse and marine-terminating glacier retreat. Large areas of ice shelves have collapsed in recent years (e.g. Pine Island and Thwaites Glaciers), allowing inland glaciers to flow faster into the ocean. Antarctic ice shelf collapse and glacier retreat are linked to ocean circulation, temperature and heat transport. The circumpolar Southern Ocean, warming at depth, is an important driver in the carbon cycle and the redistribution of heat across the global oceans. The influence of the Atlantic water in the Arctic Ocean is currently increasing with potentially important consequences for the sea ice, the climate, and the regional ecosystems.

The Arctic and Antarctic are connected to global climate through several feedback mechanisms, such as changes in the surface albedo and changing terrestrial ecosystems that lead to changes in fluxes of carbon dioxide, methane, nutrients and contaminants. Melting glaciers and ice sheets cause additional freshwater input to the ocean with possible feedback through the global thermohaline circulation. Several of these processes exhibit tipping points, which mean that once they are fully triggered, they can dramatically and irreversibly change the global climate on a human time-scale (e.g. methane hydrate release in a warming Arctic Ocean, permafrost thawing and release of carbon). The potential evolution and consequences of such processes are still under investigation.

The research identified in this chapter also aims at increasing predictability and reducing the uncertainty associated with key processes that affect climate change and people. The scientific research needed involves a portfolio of disciplines targeting different environmental compartments and methods, ranging from satellite and in situ observations to coupled numerical modelling. Models dedicated to the Arctic and Antarctic require specific developments and validation with novel and enhanced observations and methods, including data science techniques.

Photo: Mario Hoppmann

Photo: Peter Prokosch

2. Societal Relevance

Inhabitants of the Polar Regions are among those most directly affected by climate change. However, natural physical processes occurring in the Polar Regions regulate environmental conditions across the globe and directly impact Europe. Future changes in climate mean that many of these processes may be altered in intensity and their effects may induce changes throughout the Planet with significant impact on lives and livelihoods. Understanding the polar processes and improving predictability through modelling will benefit people, environmental policy, ecosystem management, and businesses well beyond the Polar Regions. Thus, a better understanding of climate change in the Polar Regions and their links to lower latitudes is urgently needed to better address the following societally relevant effects of climate change.

SOCIETAL RELEVANCE GLOBALLY:

- Global sea level rise,
- Ocean warming and global circulation changes,
- Changes in polar sea ice cover,
- Changes in the occurrence of extreme weather events,
- Changes in atmospheric composition,
- Changes in freshwater flows to the ocean,
- Changes in the ecosystems on land and in the ocean,
- Increasing resource extraction in the Arctic,
- New shipping lanes, and
- Changing international geopolitical arena.

SOCIETAL RELEVANCE AT THE REGIONAL/LOCAL SCALE:

- Traditional food sourcing issues, traditional lifestyles,
- Changes in landscape (coastal erosion, subsidence, mass movements and thaw lake dynamics) due to permafrost degradation,
- Threat to infrastructure from thawing permafrost and changes in the snow/ice season,
- Increase of natural hazards,
- Changes in freshwater flows in the local environment, and
- Increased accessibility that may impact economic activities (e.g. shipping, extractive industries, tourism and fisheries).

To transfer physical model results into policy tools, new methods, such as hazard and risk assessment and mapping at regional and local scales, must be developed by integrating socio-economic variables and community-based knowledge. It will thus be important to include local stakeholders and researchers from social sciences and humanities.

An integrated programme is needed that supports community-based decision-making based on the best possible observations and understanding of the coupled climate system at all scales and for key communities. The impact of such a programme will be an improved ability of society to mitigate and adapt to polar climate change.

3. Research Questions

Key Question 1.1. Key processes in polar-specific components of the climate system

While the development and continuous availability of high-quality data and modelling efforts have allowed critical observations of ongoing processes, many unresolved issues related to the behaviour, interaction, and feedback processes of the polar-specific components remain unanswered. To improve our understanding of the physical behaviour of the Polar Regions under transition, it is a key priority to provide an integrated focus on the multi-timescale variability in the cryosphere, atmospheric and ocean dynamics and the land-ocean and land-atmosphere interactions. In addition to present day observations, paleoclimate data are crucial to validate model simulations of the climate system over longer timescales and provide useful insights into current changes from enhanced assessment of past climates. The key components to study are:

Polar land ice

For polar land ice, there is a need to understand key processes related to surface mass balance and ice dynamics and to improve our understanding of the governing mechanisms such as glacial hydrology, glacier calving and ice discharge, and marine ice sheet instability through in situ monitoring and remote sensing. While the ice sheets and glaciers play a major role in predicted contribution to sea level rise, assessment of changes in time and space of glaciers distinct from the polar ice sheets remains also a priority to gauge local and regional freshwater runoff and for evaluating the representation of their respective mountain ranges. This is an overarching key priority to assess ongoing changes in a long-term context through terrestrial and marine geological records and improved understanding of geomorphological processes. This will also provide a linkage to accurately quantifying solid earth deformation, which is important as it directly feeds back to geodetic observations used to monitor the state of the polar land ice.

Permafrost

The increasing temperatures during recent decades have already had a direct impact on permafrost distribution and consequently led to terrain deformation and erosion. Both terrestrial and sub-sea permafrost degradation impacts carbon dioxide and methane release into the atmosphere. With projected increasing warming it is a key requirement to assess the thermal state and extent of the permafrost and to understand the feedback mechanisms influencing permafrost stability and the exchange of greenhouse gases with the atmosphere.

Precipitation and terrestrial hydrological cycle

Changing precipitation patterns and increasing temperatures are influencing the snow cover in the northern hemisphere. Snow cover shows large declines in springtime while rain is increasing, impacting the length of snow melting season, river discharge and amount of freshwater input, especially to the Arctic Ocean. Also, the extent of lake and river ice formation have a direct impact on freshwater runoff. It is a priority to document changes and improve understanding of the rapidly changing precipitation patterns. An enhanced hydrological cycle and river discharge will also increase freshwater fluxes from melting glaciers, while ice sheet dynamics have potentially severe impacts on coastal ocean patterns and marine and terrestrial ecosystems.

Atmosphere and clouds

As processes in the atmosphere, and their on-going changes, have a direct impact on large-scale global energy circulation, it is a key priority to provide a full understanding of the interactions and feedback processes between the components at play. An essential requirement is to resolve the physics and chemistry associated with polar cloud formation and boundary dynamics. Moreover, the impact of moisture and aerosols on direct and indirect radiative processes, including volcanism as a climatic forcing, remains among the largest research priorities in climate modelling.

Sea ice and ocean

With the changing sea ice cover observed during the past decades, it is a main priority to improve the understanding of the main processes related to sea ice formation and distribution, new sea ice dynamics, the linkage to riverine and ice sheet freshwater runoff, and the impacts on the ocean thermohaline circulation and thus the global energy budget. An improved understanding of the ocean circulation and physical structure is a key requirement as these also directly affect the distribution of ocean properties, the sea ice cover, and the marine glaciers and ice shelves as well as the carbon pump and oceanic uptake of greenhouse gasses through biogeochemical air-sea interactions. These processes also influence the microbial primary production with cascading effects across the entire polar food web, including key species such as Antarctic krill, and other ecosystem services on which local and Indigenous Peoples rely (RN 3).

HUMAN PRESSURE

Human pressure on the poles is generally both increasing and transitioning from long-range influence of mid-latitude forcing to increasingly local anthropogenic pressures. Exploitation of ores, oil and gas, land use, and fisheries are leading to increasing population in the Arctic, whereas in the Antarctic, increased tourism and research station numbers also show potentially increasing impacts on the environment.

Key Question 1.2. Polar coupling and feedback processes at regional and global scales

There will be a growing need for an improved understanding of polar systems at process level. It is essential to move forward with studies related to processes acting at the interfaces between the different media (e.g., air-sea-ice interactions) and a better grasp on the impacts of permafrost thawing on nutrient release from terrestrial to freshwater and marine ecosystems, the impact of the snow cover melting on carbon storage and release and light transmission through sea ice into the ocean, the impact of the marine biosphere on the biological carbon pump relating the atmosphere dynamics and chemical compounds along the biogeochemical cycles.

At the same time, processes specific to the Polar Regions play a key role in the global climate system. Deep-water formation occurring at high latitude modulates the ocean thermohaline circulation. Polar Regions contribute to global sea level rise through melting land ice and ice sheets, and also to carbon sequestration. Furthermore, polar amplification of global warming is a large-scale feedback loop that impacts weather and climate and their extremes at all latitudes. For Europe, it is particularly important to better grasp the impact of decreasing sea ice on mid-latitude weather patterns.

Understanding the role of the Polar Regions in the global context includes improving knowledge of the key processes linking the polar climate processes to the Earth climate system, especially those affecting atmospheric and oceanic long-range connections, weather patterns and extremes, the transport of properties between the polar and mid-latitude areas, and the global carbon cycle. It is also important to have a clearer picture of the impact of changes in polar ecosystems and geomorphological processes on lower latitudes. In this regard, comparative studies of the Arctic and Antarctic regions should provide additional information about the sensitivity of the Polar Regions to specific climate components.

The expectation that polar environments will experience dramatic changes over the next decades to centuries in response to and coupled with global warming is a particular challenge to properly allocate research efforts and monitoring programmes. The representativeness of observations should be considered in this context, including the creation of an extensive and carefully designed fit-for-purpose *in situ* programme as well as satellite data. These will facilitate a better understanding of the coupling and feedback processes, and contribute with essential climate records from all spheres (ocean, atmosphere, cryosphere, and biosphere). It is of particular importance to target key climate and ecosystem services (e.g. greenhouse gas related), thereby integrating and advancing knowledge of thresholds (multiple stressors) and the possibility of cascading tipping elements, for example, in the food webs.

Key Question 1.3. Modelling and predicting the polar climate system

Numerical models aggregate and test our understanding of the Earth system and its components. Models are widely used to explore the limits of predictability, carry out future change projections, and provide guidance for the optimal design of the observing system. Despite recent progress, major shortcomings remain as model biases may confound signals of interest.

Current climate models underestimate predictable state variables of the climate system and this is also true in the Polar Regions. In particular, the high predictability of the ocean in these systems does not transfer to atmospheric circulation to the expected extent, and predictability over continents appears too low. Improvements in understanding of key physical processes are necessary to reduce model biases and improve forecasts and scenarios. Skill improvement may also be achieved through the development of methods to combine high-resolution and low-resolution ensembles and optimally use multi-model ensembles, and approaches to blend dynamical and machine-learning ensembles. Regional models, such as MAR or RACMO, dedicated to Polar Regions and combined with global models offer a huge potential for an improved understanding of processes related to cryospheric compartments and processes. Results from such efforts may assist and target developments at process level in models and inform the design of laboratory and fieldwork studies, including polar-targeted satellite missions.

Progress in modelling hinges on the improvement of parametrisations of critical subgrid-scale processes and increases in resolution in Earth System Models (ESM). Examples of processes, for which advanced parameterisations are urgently needed, include boundary layer processes in the atmosphere and upper ocean. Increases in resolution will also open new windows in simulating important phenomena, such as ocean eddies and sea ice leads, thus reducing the need to rely on current parametrisations. The scalability of processes determines our capability to implement higher resolutions in models and hence defines our ability to generate seamless prediction, which is useful for policy and climate action. In fact, the strong coupled nature of the system calls for seamless coupled modelling systems that can be used from weather to climate time scales.

Improving model's interfaces between compartments will allow a fully coupled representation of the Earth system. Examples of coupled processes, which need to be urgently addressed, include air-sea ice-ocean interaction and atmosphere-ice shelf interaction. It will also be critical to extend ESMs to allow capturing of major instabilities and tipping points. Furthermore, interaction between physical, chemical, and biogeochemical processes need consideration. Specific challenges at the interfaces currently include aerosol feedbacks, carbon feedbacks involving permafrost and wetlands, ocean primary production as well as ice sheet instabilities.

Model evaluation and diagnostic capacity are a core requirement to identify modelling issues, determine the origin of model errors and monitor progress in model development. This capacity need also includes easy access to all available observations while fostering new observational data collection and promotion of open-access databases. Models are validated against, or assimilate, remote and *in situ* observations, which are generally of insufficient spatial and temporal coverage in the Polar Regions. Our ability to generate seamless predictions depends on the development of coupled data assimilation capacity to improve forecast initialisation, model error diagnosis and observing systems design.

The development of fit-for-purpose regional models is a specific challenge for the Arctic and Antarctic. The application of mid-latitude models requires careful consideration for the poles themselves (e.g. the singularity in the mesh). All models need to consider the dynamics of the increasing anthropogenic pressure accounting for global and local influences and include polar-specific processes.

Ensemble prediction is another area that will need to be addressed, given the central role that uncertainty quantification plays in decision making. Here, development of trustworthy representation of underlying uncertainties in the initial conditions but also model formulation will be key.

The modelling community will urgently need to consider emerging technological challenges arising from the end of Moore's law. The next-generation of high-performance computing systems – so called exascale systems – will provide unique opportunities to push the limits of resolution; yet these systems are so complicated that we will not able to exploit them unless major technological investments are made in making ESMs and associated work flows (e.g. including data analysis) exascale-ready (RN 6).

Finally, it is important to recognise that the coupled nature of the Earth system in Polar Regions calls for improved collaboration to advance ESMs between different communities among the Earth system community and new partners to tackle further technological challenges. The development of climate-socio-economical models considering the specificities of stakeholders in a polar context will further bring the climate research results closer to usage by authorities and communities.

Research Need 1. 1. The need for a polar observing decade – providing model validation data and enhancing the Arctic and Antarctic observing networks.

Photo: Peter Prokosch

There is a need for a coordinated European and international platform for decadal scale observations across all scientific disciplines to understand better the processes of climate change in the Polar Regions at sub-decadal time scales and enhance our ability to predict their impacts from local to global scales.

There is a lack of long-term records of glaciological, terrestrial, oceanic, and atmospheric parameters especially at the interfaces between cryosphere, land, biosphere and ocean – coastal areas, glacier outlets, permafrost areas where exchanges of heat, greenhouse gases, nutrients and freshwater are occurring and where Arctic communities live. An effort of intensifying the observation network during 10 years would allow a time-limited effort to collect observational data on a wide range of disciplines. These will enhance the development, validation and their assimilation in Earth System Models with a sufficient coverage of interannual variability to enable trend detections. There are many areas in the Antarctic, the Southern Ocean, the Arctic margin and the Central Arctic Ocean, which are still unexplored because they are too remote and too harsh to be accessed considering the financial, technical and logistical capacities of the national polar programmes.

A European polar observing decade building upon the existing national monitoring programmes, community-based observations, and European integrating activities from space agencies and research infrastructures should provide an enhanced and integrated data foundation. Here the modelling efforts focused on understanding how climate change in the Polar Regions influence global climate and living conditions for both Arctic communities and the population at lower latitudes will improve understanding of the processes. This effort would also build upon and extend the Year of Polar Prediction effort, and would launch the collection of new observables on a systematic basis. Regarding the polar oceans, such a synoptic approach might also provide a valuable contribution to the upcoming UN Ocean Decade initiative in which these oceans are recognised among the key regions where a dedicated action should be supported.

In parallel, an effort to collect new paleoclimate data for understanding the response of the Polar Regions to climate change on the longer time scale should be initiated.

Key Question 1.4.
Assessing the impact of human activities on polar climate

Besides climate change, the fragile polar environment is impacted by local and remote human activities through harmful pollutants and other anthropogenic pressures arising from various human activities such as, for example, tourism, waste management, extractive industries and fishing (RN 5).

A wide range of human perturbation to the natural environment are affecting the Polar Regions. Short-lived climate forcers and greenhouse gases are impacting polar and global climate, but there is still a lack of understanding about past and current change, the relative roles of natural and anthropogenic components and how their variability is perturbing the climate system. Local and remote sources of pollution to water, air, soils, and organisms are likely to increase as a result of combined socio-economic drivers and climate change, especially in the Arctic. Development of sustainable adaptation and mitigation strategies to minimise risks requires a clearer picture of the sources, processing and fate of different greenhouse gases and pollutants, in atmospheric, marine, and terrestrial compartments. Potential effects of emerging greenhouse gases and pollutant sources such as shipping, natural resource extraction, fishing, tourism, and associated urbanisation on air, water quality and the environment require improved assessments.

A pressing challenge is to understand the magnitude and trajectory of remote and local sources of long and short lived climate forcers and pollutants, as well as their impact on global and regional climate, and on the health, well-being, and food security of Arctic societies and on polar ecosystems at large. This challenge cannot be tackled without considering the complex interplay of anthropogenic pressure and natural processes. The predictability of changes in response to future climatic, environmental, and socio-economic drivers remains also low. An improved understanding of the interactions between the changing climate system and pollutant burdens is needed, which should include climate-driven ecosystem changes affecting natural emissions such as wildfires or pollutant deposition. Remote sources of pollution including contaminants such as mercury, disease vectors and persistent organic pollutants or microplastics, transported to the Polar Regions via atmospheric, terrestrial, and marine pathways are known to be also harmful for human and ecosystem health through polar food webs. Improved quantification of these effects, as well as emerging contaminants and re-emission of legacy contaminants due to melting cryosphere or thawing permafrost is compulsory to avoid new threats to human well-being. In addition, food security is a huge concern for Arctic residents with diets mostly relying on "country food" (RN 3 and 4).

Assessing and quantifying these drivers of change requires a synergistic approach working at interfaces and building on physical climate system knowledge and local and Indigenous knowledge. Interactions between the physical climate system, living ecosystem components and the exposure and functioning of Arctic societies need to be considered as well. Exploration of potential future pathways to minimise risks and impacts requires the development of climate change predictions coupled with socio-economic models. It will also involve exploration of synergies between pollutants and greenhouse gases, as well as interactions between the different environmental compartments.

Conversely, climate knowledge, which will be gained from research interaction between climate-scientists, local and Indigenous communities as well as societal stakeholders, should be made available to local residents in support of their actions and decision-making.

Photo: Ronald JW Visser

Photo: Anna Karin Landin

4. Resource Requirements

The research and development necessary to significantly advance the understanding of the coupled polar climate system will require (RN 6):

- Enhanced and integrated observing systems in the Polar Regions building upon existing and new environmental research infrastructures including near-real time data transmission. Current environmental research infrastructures not dedicated to the polar areas should be encouraged to develop their activity and spatial coverage to the polar and subpolar environments,
- New advanced sensor and platform technologies to perform measurements compliant with relevant standards under harsh, cold, and remote conditions,
- Earth System Models development and sustained supercomputing facilities,
- An improved support of new data acquisition through future multi-year fieldwork programmes and observatories,
- The promotion of FAIR (Findable, Accessible, Interoperable and Re-usable) data management systems, and
- Interdisciplinary research on polar climate effects and feedbacks based on stronger circumpolar and interdisciplinary collaboration within Europe and beyond, as well as an enhanced sharing of access to polar infrastructures (EU-PolarNet Deliverable 3.7).

International and better coordinated initiatives need to be promoted, especially those aiming at the Polar Regions. Europe should develop and reaffirm its leadership and further strengthen excellence in these international initiatives as the capability becomes available. Expanded networks of young scientists need to be further developed through the European Research Area and through capacity building.

Research Need 2. Informed weather and climate action

1. Introduction

Science has the duty and responsibility to inform society of the different trajectories of environmental changes in the Polar Regions and their socio-cultural, economic, geopolitical, and environmental implications. This information will contribute to identifying mediation and mitigation pathways in relation to climate change and its impacts on society. As such, informed weather and climate action underpins priorities of several major international programmes and assessments such as, for example, the World Climate Research Program (WCRP) and Global Climate Observation System (GCOS) as well as the Essential Climate Variables (ECVs) identified therein.

Relevant stake- and right-holders in the Arctic and Antarctic need to be included at an early stage of any research proposed to ensure alignment with societal needs and bilateral knowledge transfer. For regions with Indigenous and local communities there is much to be gained from exchanges of perspectives, motivations, and cultural values. It is also important to emphasise the conservation of the Polar Regions for humanity and future generations, both for their extrinsic and intrinsic values to local and global communities.

The expected outcomes from research in this cluster should improve ecosystem and societal impact assessments of change in the Polar Regions, contribute to environmental monitoring and strengthen the development and maintenance of long-term datasets capturing the many dimensions of change in the Arctic and Antarctic.

2. Societal Relevance

Local and regional northern communities and economies are already affected by climate-change impacts, ranging from permafrost thawing and coastal erosion to changes in species abundance and diversity, with direct effects on health and well-being – in a physiological, but also psychological and sociocultural sense. In many ways, the Arctic and its communities, but also the Antarctic environment, are "canaries in the coal mine" for societies at lower latitudes.

In order to better understand how changes in the Arctic and Antarctic affect the rest of the globe, both at micro- and macro-levels, the use of a broad array of scientific tools and observations are needed. These range from improved downscaled climate projections to better environmental monitoring and integrative research that draws on multiple elements within the complex socio-ecological system in order to better understand and anticipate environmental changes and their societal implications (Figure 3).

Thus, the research needs are to:

- Understand the current status and predict future changes in the Polar Regions to allow for near and far field societal adaptation,
- Engage constructively and iteratively with policy-makers at all stages of the research, with a focus on the existing and likely future threats to polar ecosystems, stake- and right-holders,
- Identify available sources for environmental and socio-economic data that are needed to assess systematic impacts upon Arctic and Antarctic environments as well as related human activities,
- Identify gaps in knowledge and initiate or enhance monitoring activities to strengthen future predictions of environmental impacts, feedbacks, and trends in Polar Regions, and
- At policy-relevant spatial and temporal scales, integrate available environmental and societal knowledge to develop a suite of future scenarios.

Figure 3. The interconnected polar environment: The pictured example showing thermokarst erosion, caused by soil warming, developing in the foreground along the bank of the river leading out into the fjord and ultimately the open ocean (Zackenberg, NE Greenland). This is an avenue for transport of stored soil carbon in permafrost that through thawing is vulnerable to removal as dissolved material to the oceans. Both on land and along the way there are also important exchanges of greenhouse gases taking place with the atmosphere. Research concerning these elements of the natural carbon and water cycles in the Arctic, which see disruption by climate warming, is extremely important for understanding both local effects and global implications. *Photo: Lars Holst Hansen.*

3. Research Questions

Key Question 2.1.
Identifying relevant indicators of polar climate change

Systematic monitoring of the Polar Regions is essential in order to develop informed weather and climate actions in the fight against climate change and to mitigate the consequences on local communities and ecosystems. Against this background, and following the concept of Essential Arctic Variables that is being promoted by SAON as broad observables in support of Arctic societal benefit, there is a need to identify a suite of Essential Climate Variables (ECVs) and indicators that can be used to characterise changes in the Polar Regions and assess the impact of climate change on the Earth system (e.g. atmosphere, cryosphere, ocean, biosphere, terrestrial environment), local communities, infrastructure, and ecosystems.

Indicators tailored to the Polar Regions should generate information about the changing regional climate across relevant multi-disciplinary Earth system domains and temporal-spatial scales. Candidate indicators (some of these are consistent with WMO/GCOS) include: temperature and energy, atmospheric composition, ocean and water, the cryosphere, terrestrial phenology, biosphere, and extremes, as suggested in Table 2. The indicators should be broadly communicated and tell stories about climate change in the Polar Regions in a clear and concise way that can be understood by non-experts. The number of indicators should preferably be limited and, as emphasised by WMO/GCOS, ensure compliance with the following factors:

- Relevance: Broad impact to user communities, from national via regional to global values,
- Representativeness: Manifest distinct changes in the Polar Regions,
- Traceability: Be estimated using an internationally agreed (and published) approach, and
- Timeliness: Be regularly updated, at least on an annual timescale.

These indicators could also be tailored to the three natural cycles, namely energy, carbon (including biogeochemical cycles) and water as shown by the pink, green, blue colours, respectively, in Table 2, as well as the light brown colour that implies relevance for both the water and carbon cycles. The listing of the ECVs (related to physical, biogeochemical and biological variables or a group of linked variables defined by WMO/GCOS) emphasises how these variables critically contribute to the characterisation of Earth's climate, and hence the cycles and the indicators. Moreover, the observations of the ECVs are based on feasible technology and sound methods.

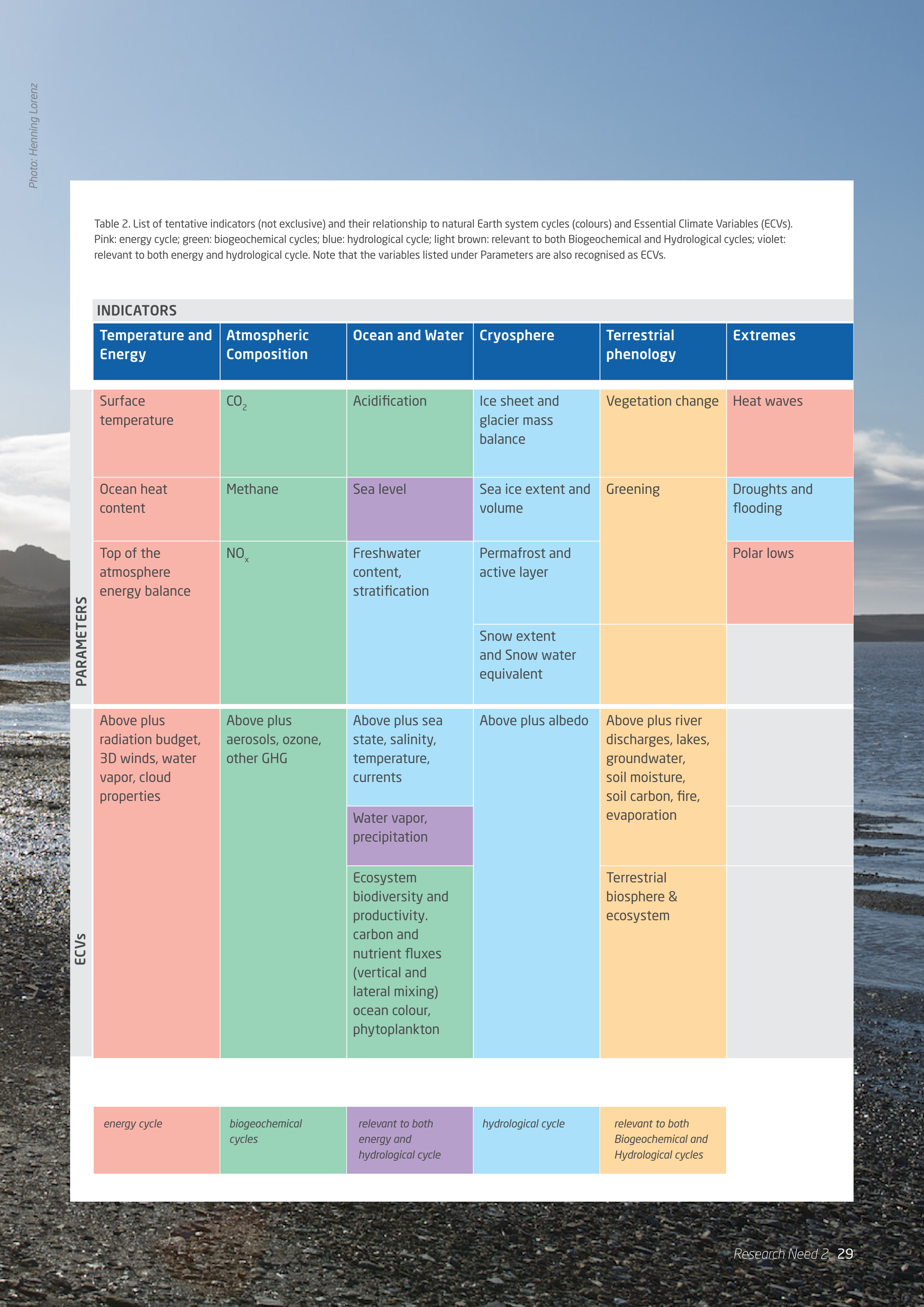

Photo: Henning Lorenz

Table 2. List of tentative indicators (not exclusive) and their relationship to natural Earth system cycles (colours) and Essential Climate Variables (ECVs). Pink: energy cycle; green: biogeochemical cycles; blue: hydrological cycle; light brown: relevant to both Biogeochemical and Hydrological cycles; violet: relevant to both energy and hydrological cycle. Note that the variables listed under Parameters are also recognised as ECVs.

INDICATORS	Temperature and Energy	Atmospheric Composition	Ocean and Water	Cryosphere	Terrestrial phenology	Extremes
PARAMETERS	Surface temperature	CO_2	Acidification	Ice sheet and glacier mass balance	Vegetation change	Heat waves
	Ocean heat content	Methane	Sea level	Sea ice extent and volume	Greening	Droughts and flooding
	Top of the atmosphere energy balance	NO_x	Freshwater content, stratification	Permafrost and active layer		Polar lows
				Snow extent and Snow water equivalent		
ECVs	Above plus radiation budget, 3D winds, water vapor, cloud properties	Above plus aerosols, ozone, other GHG	Above plus sea state, salinity, temperature, currents	Above plus albedo	Above plus river discharges, lakes, groundwater, soil moisture, soil carbon, fire, evaporation	
			Water vapor, precipitation			
			Ecosystem biodiversity and productivity. carbon and nutrient fluxes (vertical and lateral mixing) ocean colour, phytoplankton		Terrestrial biosphere & ecosystem	

energy cycle	*biogeochemical cycles*	*relevant to both energy and hydrological cycle*	*hydrological cycle*	*relevant to both Biogeochemical and Hydrological cycles*

The core ECVs that spatially and temporally influence the water cycle include: water vapor; clouds; wind; precipitation; snow cover; glacier and ice sheet growth and/or melting; permafrost; soil moisture; river discharges; ground water; vegetation cover and species composition; surface temperature; sea surface salinity and sea level. Moreover, the water cycle involves the exchange of energy, which leads to changes in heat fluxes and temperature. When water evaporates, it takes up energy from its surroundings and cools the environment. When it condenses, it releases energy and warms the environment. The water cycle is linked to changes in sea level and the ocean circulation and is also coupled to the carbon cycle, with increasing atmospheric CO_2, methane and temperatures that subsequently influence the cloud properties and strength and distribution in precipitation and evaporation. The direct interconnections between these overarching cycles are schematically illustrated in Figure 4.

Figure 4. The global cycles of water, carbon, and energy (courtesy of GCOS).

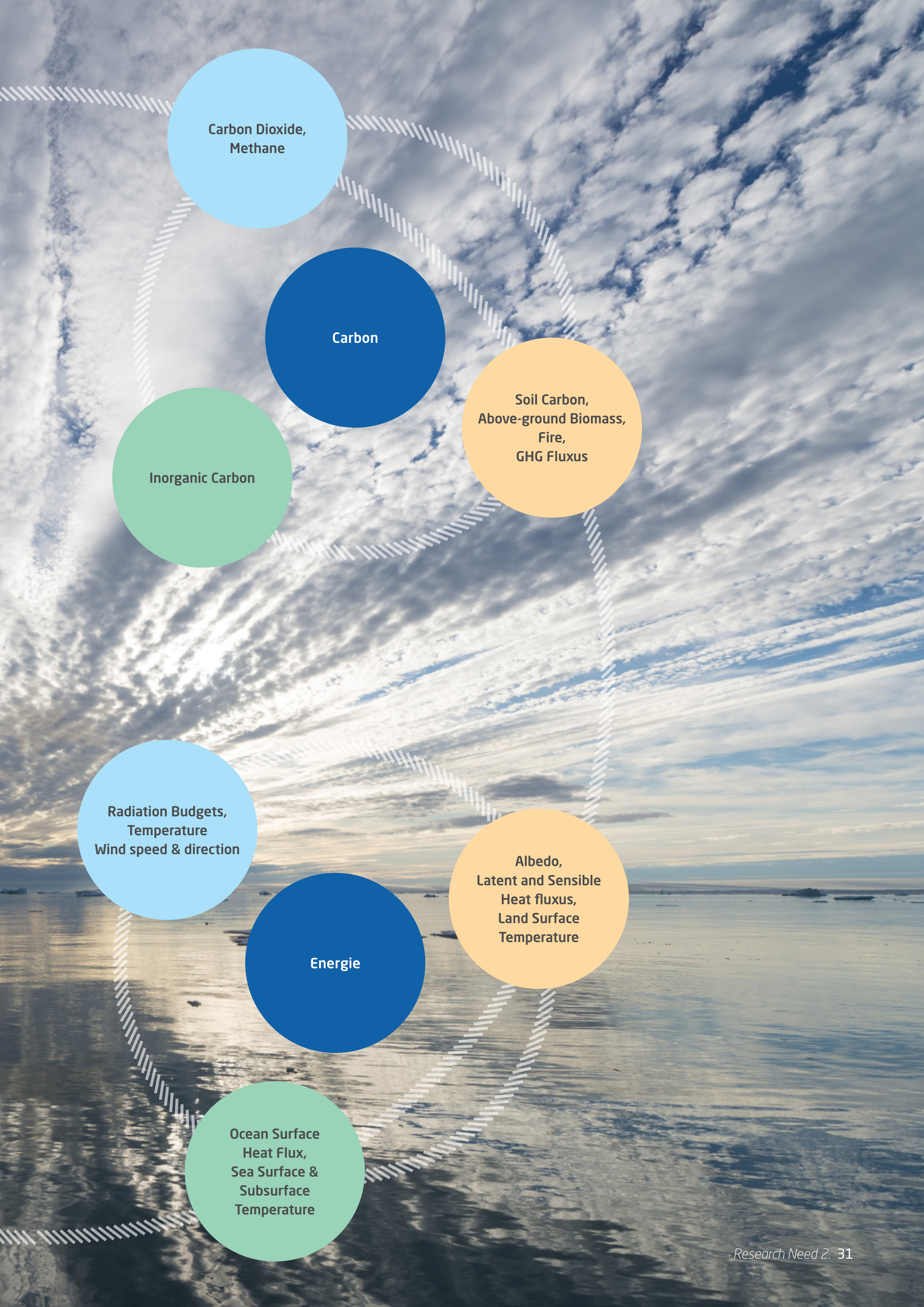
Carbon Dioxide, Methane
Carbon
Soil Carbon, Above-ground Biomass, Fire, GHG Fluxus
Inorganic Carbon
Radiation Budgets, Temperature Wind speed & direction
Albedo, Latent and Sensible Heat fluxus, Land Surface Temperature
Energie
Ocean Surface Heat Flux, Sea Surface & Subsurface Temperature

Photo: Peter Prokosch

Key Question 2.2. Designing new approaches to test the chain of processes from climate indicators to decision making

A balanced combination of explorative science and sustained long-term observations is required to improve our ability to understand and predict changes in Polar Regions and their subsequent global impact. Likewise, there are many examples where long-term measurements have led to the discovery of large-scale connectivity in natural systems. Both types of research serve to provide the necessary insight and data to improve model predictions, which are ultimately used to provide society with a sound foundation for management, planning and adaptation.

For policy-makers to make informed decisions on how to alter current practices or adapt to future changes it is necessary that a suite of climate indicators is derived (KQ 2.1). Ideally, these should be aligned across paleological, historical and modern observations. Moreover, they should be complemented with model extrapolations to ensure increased temporal and spatial coverage. This is, however, highly challenging due to the sparsity in observational networks, limitations of available paleo proxies and the complex and vast range of temporal- and spatial scales that characterise Earth system variability (Sørensen, et al. 2019).

European long-term polar observation networks (terrestrial field stations, repeat marine hydrography and ecology programmes, meteorological, permafrost and glacial sensor networks) are typically supported by national contributions and private foundations. Hence, they are subject to fluctuating priorities with respect to funding, the measurement parameters encompassed and data availability. This hinders the full potential of these activities from being realised. However, these networks provide vital data for climate indicators, feed the further development and validation of regional and Earth System Models, and represent an existing infrastructure investment from which much can be gained. Global Polar science would benefit greatly from a coordinated European effort, which could be linked to established initiatives such as SAON and SOOS. A selection of EU long-term polar research initiatives each collecting data for climate indicators across major polar environmental compartments (atmosphere, cryosphere, terrestrial, marine and geological) and contributing to explorative research would represent a major opportunity for European science, innovation, service development, policy regulations and deliver societal benefit. Integration of the data and research findings to current Earth system modelling, as well as results from observing system simulation experiments, is also a vital component for these initiatives (Sørensen, et al. 2019).

Such initiatives would also provide a sustained coordinated European contribution that aligns well with existing North American and Asian polar programmes as well as internationally coordinated efforts under SCAR and IASC. The location and focus of these initiatives are best developed using a bottom-up consortium creation process. There are several existing national programmes examining specific biomes where the first initiatives can be expanded easily to host broader European involvement.

Research Need 2.1. Long term observations combined with a transect approach

Figure 5. Possible transects in the high latitude seas and Arctic Ocean and along the Antarctic Peninsula.

Sustained long-term observational data series are pivotal for improved understanding of polar environmental responses to climate change. These are, however, often restricted spatially to local sites and leave questions relating to representativeness for larger areas/regions. This problem can be solved by a combined effort, with transect measurements during short time periods (one-three years) filling in geographical gaps between long-term autonomous (or semi-autonomous) observational platforms. These should be supported with repeated visits (annually or biannually) by campaign-based mobile infrastructure that, in turn, have the capability to conduct measurements and analysis along gradients with shorter time windows needed at individual locations.

Such coordinated efforts may cover transects that can serve the purpose of studying scientific questions adopting, e.g., the "space for time" approach in which spatial gradients are used to explore temporal changes, in particular future trends or shifts linked to climate change. Geographically, in the case of the high latitude seas and Arctic Ocean (as shown in Figure 5) valuable information could be gained from documenting the north-south gradient along the east coast of Greenland, the east-west gradient across the Nordic Seas and from the central part of the Arctic Ocean towards northernmost Greenland and Svalbard. As indicated in Figure 5, similar transects could be envisioned following gradients e.g. along the Antarctic Peninsula to South Georgia, or to explore the land-sea continuum from the ice sheet to the deep Southern Ocean across the Antarctic continental shelf.

Coordinated research efforts along such gradients in the Arctic and Antarctic will benefit from coordinated and shared logistics with ships, airborne and autonomous platforms and remote sensing-based sensors (More information on polar infrastructures can be found in the EU-PolarNet Deliverable: D3.2 European Polar Infrastructure Catalogue and its database).

Photo: Ronald JW Visser

Key Question 2.3. Supporting decision making through predictions and projections of polar climate and socio-ecological systems

Anticipated increases in ship traffic, resource exploitation, tourism, and other activities call for accurate and reliable weather and climate analysis, predictions, and projections for safe and efficient operations in the Arctic and Antarctic. Polar predictions will be improved when new observation-based knowledge is transformed into better informed decision-making for users. Despite improvements in Arctic and Antarctic forecasting skills in recent decades, existing numerical weather prediction (NWP) and coupled global climate model projections do not fully meet existing user requirements (KQ 1.3).

Interactions and collaborations between research and operational departments is crucial for reaching the common goal of providing high quality services to end-users. Organisational (infra) structures should be built which allow an efficient and effective transitioning of new technologies and observations into operational systems. A strong research-to-operations (R2O) interaction is essential to implement newly developed (pilot) products that have been co-produced through an iterative and interactive process with users, and to embed short-term (project-based) collaborations into long-term strategic relationships aiming to increase the users' capacity to responsibly use tailored services and actionable information. Observation and field campaigns should also benefit the operational real-time services without compromising the observation-based research. The EU funded Copernicus Earth Observation Programme[8] builds on this rationale and approach, and provides information services freely and openly accessible to its users. Its further development should continue to be user driven.

NOVEL DISSEMINATION AND VISUALISATION SERVICES FOR ARCTIC AND ANTARCTIC USERS

The increasing number of polar maritime operators, the hazardous sea ice and weather conditions, and the sparse telecommunication infrastructure put great demands on the provision of environmental monitoring and forecasting services. Up-to-date weather, sea state, icing, iceberg, and sea ice information is essential to maintain safe navigation in ice infested waters. Moreover, adequate iceberg and sea ice information for all activities in the high latitude seas and Arctic Ocean is a mandatory requirement for safe operations, enforced by the Polar Code, which was introduced on 1 January 2017. Large amounts of satellite observations and model forecasts are available from Copernicus and governmental services in real-time. The Antarctic has no coordinated ice/weather agencies and significantly fewer SAR capabilities than the Arctic. In any case, the uptake by users of satellite data is limited by the expertise to handle and interpret the data and information products and by the low bandwidth limitations of satellite communication in the high latitudes. Novel approaches to adapt to the limited communication capacity in the Polar Regions will be needed jointly with visualisation systems to provide the multitude of information from satellites and forecasting systems in real-time to polar operators.

[8] https://www.copernicus.eu/

Key Question 2.4.
Assessing the added value of the Polar Regions in relation to climate change and human activity impacts

When discussing the value of the Polar Regions we should be aware that this umbrella term comprises both extrinsic (or instrumental) values – those that are means to an end and include economic and resource values – and intrinsic values, which describe aspects of the regions that are valued in and of themselves, such as wilderness or aesthetic beauty. In the Antarctic region, a range of intrinsic values, including aesthetic and wilderness values, as well as extrinsic values such as the value of the region for scientific research, are explicitly recognised as worthy of protection through the Protocol on Environmental Protection to the Antarctic Treaty.

In a climate-change context, the significance of both Polar Regions as barometers of global change as well as significant moderating forces, e.g. drivers of thermohaline circulation through the production of cold, dense bottom water and the Earth's largest frozen freshwater stores, cannot be overemphasised. At the same time, global temperature change is amplified in the Polar Regions, especially in the Arctic, where the impact of climate change has consequences not only upon local environments and populations but also on the lower latitudes through global teleconnections.

Increased human activities in both Polar Regions are generating local and global impacts. In the Arctic, these come from increased tourism, transport and activities aimed at securing both finite and renewable natural resources. In the Antarctic, these impacts arise from increased human presence through expanding tourism, fisheries, and research activities, including the establishment of additional research stations and infrastructure. In the Arctic, reductions in sea ice promise to open new sea routes that must be managed to ensure that networks of marine protected areas are preserved and protected. In all instances, both the lack and the construction of infrastructure for long-term and transient human presence present challenges.

4. Resource Requirements

In order to investigate the major element cycles with the purpose of improving the knowledge base for decision making in relation to better informed weather and climate action, the following set of international efforts are needed:

- Transect based coordinated large-scale targeted programmes. These should take advantage of shared logistics and organisation for answering key scientific questions,
- New technologies should be deployed that will ensure that proper information can be collected. These should be in the form of autonomous platform carried sensors, automated distributed sampling hubs, increased use of emerging remote sensing capabilities, and advances in bandwidth capacity (RN 6),
- Existing long time-series of ecosystem monitoring data. These should be utilised to their maximum and expanded with greater spatial coverage using mobile comparative and complimentary measurement platforms (RN 3),
- Novel model development and innovative approaches. At a variety of scales, from processes to regional climate prediction, models, data assimilation, Machine Learning and Artificial Intelligence should be applied and developed in close conjunction with the improved measurement capabilities as well as through use of emerging long-term observational datasets for validation (RN 1 and 6),
- Educational aspects. These need to be included at all levels, both in the form of internal exchange between researchers and technicians involved, and beyond the projects with educational and training programs for schools and the wider public to be developed in consort with the research efforts (RN 4), and
- Commercial, industrial, and social developments. There is a need for collaboration between academia, Indigenous organisations, local communities, governments and industries to enhance technology developments, new jobs, safer operations, better sustainable economies (transport, fisheries and industry), and capacity building in Polar Regions (RN 4 and 6).

Research Need 3.
Resilient socio-ecological systems

1. Introduction

Understanding the changes in structure, functioning, and biodiversity of polar ecosystems in the Arctic and Antarctic poses some common challenges. Both Polar Regions are hard to access and difficult to study because of their remoteness and scant infrastructure. Long-term observational systems, necessary for better future predictions, are mainly operated within the more accessible geographical sites, sectors, and ecoregions, such as the Bering and Barents Sea in the Arctic and the West Antarctic Peninsula Region in Antarctica. Lack of baseline knowledge of broad scale variations of drivers and the dynamic responses of species and biological communities (i.e., spatial ecology) poses significant constraints on detecting and evaluating climate-induced ecosystem changes, or assessing the cumulative impacts of multiple drivers.

In the Arctic, the permanent residents are directly affected and need to adapt to the consequences of a changing climate. Although the majority of Arctic residents in northern Europe inhabit modern cities, they strongly rely on services provided by ecosystems and are culturally deeply rooted in their local environment. Studying climate change impacts in a socio-ecological context is therefore pivotal. Integrating science with local and traditional knowledge and observation systems, and including a diversity of perceptions and values to set priorities for monitoring socio-ecological changes, can provide a better understanding of the complex interlinkages between ecosystems and society at different levels.

Antarctica, although now exclusively dedicated to science and environmentally protected, has received major human impacts from sealing, whaling industries, and, to a lesser degree, from the fishing industry, all powered by industrialisation in the nineteenth and early twentieth century. Especially the impact of fishing on the highly specialised and unique Southern Ocean marine ecosystems and Antarctic food webs continues today, and continued monitoring is essential to assess ecological consequences. These impacts on the marine and coastal Antarctic ecosystems are regulated by the Convention for the Conservation of Antarctic Seals (CCAS), the International Whaling Commission (IWC), and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). In addition, coastal Antarctic ecosystems are under the jurisdiction of the Antarctic Treaty Consultative Meeting´s Committee for Environmental Protection (CEP).

Ultimately, past, and present human interferences shape ecosystem structure and functioning in both Polar Regions and need to be accounted for in past, present and future biodiversity assessments and analyses of spatial ecology to guide conservation measures.

The concept of socio-ecological systems (SES) conveys that human societies cannot be understood as separate from polar ecosystems, but are active agents of ecosystem change, which feeds back directly or indirectly to the people depending on these ecosystems. Global connectedness also increasingly influences polar systems and changes the local socio-ecological dynamics. Resilience, i.e. the ability of the systems to absorb and cope with these changes, the vulnerability of social groups or communities exposed to "surprising" changes, extreme events, and unexpected stressors (Pershing, et al. 2019), and their adaptive capacity to respond to such changes, are inherent to the SES concept. Rapidly changing climate and weather conditions and increasing regional and global impacts necessitate more than projections and predictions of trends in polar areas, and instead call for scenario models that can envision both plausible and desired futures. Ecosystem-based management of SES also needs to consider the multiple values, diverse knowledge systems and complex interactions between local and global interests as the Arctic is changing. In the Antarctic, the grade of accomplishment of existing conservation measures needs to be revised and updated in the face of climate change and increasing human pressure on marine and terrestrial ecosystems, and of the changed global geopolitics.

Figure 6. Resilience and vulnerability of socio-ecological systems (SES).

Research Need 3.1. Consequences of climate change: Arctic vs. Antarctic

From an ecological perspective, the major differences between both Polar Regions relate to the long-lasting biogeographical isolation of Antarctica and its extremely cold climate. Whilst Antarctic terrestrial biotas are highly endemic and predominantly consist of a few dominant groups of lower plants and invertebrate fauna, a higher marine biodiversity is attributed to the genetic isolation of the Southern Ocean marine communities. Long-term isolation of both marine and terrestrial biotas in an extreme cold environment has fostered adaptive changes of molecular, structural and physiological capacities, leading to the evolution of highly specialised organisms that form large populations in the Antarctic (e.g. krill), but are also highly sensitive to the vagaries of environmental variability and change. With several important groups not well represented (e.g. fish) or entirely missing in freshwater bodies, Antarctic marine ecosystems and food webs are highly specialised to meet the environmental conditions and constraints caused by permanent or seasonal ice cover. Their response to climate change needs further investigation, from organismal to community and to ecosystem level, and with respect to connected ecosystem services. The large Antarctic krill swarms, and the seabirds, whales and seals depending on them, are good examples that show the response to change of sea ice dependent communities. Under pressure from climate change and the target of a major Antarctic fishery, krill accelerates carbon draw down to the deep ocean, sustains large populations of charismatic top-predators and, hence, provide provisional, regulatory, and cultural ecosystem services. These are massively at stake if climate warming continues unabated (Further reading: Bennett, et al. 2015; Rogers, et al. 2019).

On the contrary, the stronger connectivity between the Arctic and boreal regions combined with a much younger ecosystem means that there are generally fewer endemic species in the Arctic compared to the Antarctic. The connectivity to lower latitudes also enables poleward migrations and range shifts of temperate species and lowers physical barriers for dispersal of non-native species (NNS), including pathogens. The ecosystems in the Arctic have also been exposed to multiple waves of resource exploitation in the past that have impacted the communities. Extended ice and snow free periods alter light availability that lead to substantial shifts in productivity and phenology and alter ecosystem structure and food webs. For example, the loss of sea ice has been estimated to increase ocean productivity in some regions, and expansion of Atlantic water into the Arctic has driven range expansion of several temperate commercial fish stocks.

Photo: Ronald JW Visser

Photo: Ronald JW Visser

Research Need 3.2. Human footprint in the Arctic and Antarctic

A major difference between both Polar Regions is linked to the historical human colonisation and the accelerating societal development and urbanisation of the Arctic.

Humans have relied on living resources in the Arctic for thousands of years, and substantial impacts upon the ecosystem started at least 400 years ago when European whalers decimated populations of several Arctic marine mammals, which have never recovered. Commercial fisheries in the Arctic are substantial. They contribute about 10% to the global catch and are concentrated in the Bering Sea, Norwegian Sea, Barents Sea, and the West Greenland shelf. Examples of local overfishing of commercial stocks started in the 1970s, and extensive trawling has undoubtedly resulted in expansive changes, especially in benthic biodiversity. In recent decades, an increasing number of studies have documented how temperate flora and fauna are expanding north. Similarly, melting of sea ice provides access to new areas for fisheries. The Central Arctic Ocean Fisheries agreement has been promoted as an example of precautionary ecosystem-based management. It prevents the signatory Parties to engage in unregulated commercial fishing in the high seas of the Central Arctic Ocean for a specified duration of time. In addition, the increased fishing activity further north of the EEZ and the pressures of multiple human activities impacting the coastal socio-ecological systems have been studied only to a limited degree. The terrestrial ecosystems also lack general baseline data due to lack of monitoring in these areas.

Photo: Ronald JW Visser

In contrast, the remoteness and the absence of native human populations in Antarctica has until recently minimised direct human impact on the continent. However, human presence in form of the Antarctic fishing industry, tourism industry, and national scientific and logistic activities is increasing with potentially negative consequence for Antarctic ecosystems. For example, ship traffic has increased by 5-10 times since the 1960s, commercial visitor numbers having increased to ca. 60,000 tourists annually, and the continent now supports over 100 research stations, camps, and runways. These activities may increase local pollution, disturbance of wildlife and the risk of non-native species (NNS) introductions to marine and terrestrial environments. At present, the great majority of Antarctic human footprint, in the form of tourist visitor sites and research stations, is concentrated on ca. 6,000 km^2 of ice-free land near the coast, and in particular around the Antarctic Peninsula, as this affords ready access by ship. However, this same area supports much of Antarctica's terrestrial vegetation, as well as seabird colonies and seal haul out sites, which have in some cases been destroyed or displaced in locations where human activities have taken priority. Contrary, although krill *(Euphausia superba)* and the Antarctic toothfish *(Dissostichus mawsoni)* are the largest ongoing fishery in the Antarctic, their catch limits are strictly controlled by CCAMLR.

One of the greatest threats to Antarctic marine and terrestrial environments is in the introduction of NNS (McCarthy, et al. 2019; Hughes, et al. 2020). Within short reach from South America, the West Antarctic Peninsula (WAP) is receiving 99% of the Antarctic tourism and the major part of logistic support travel for the land stations operated here. In addition to trampling and littering the environment, humans visiting Antarctic coastal areas facilitate introduction of NNS. Most of the introduced organisms are still not able to survive under Antarctic environmental conditions. However, as terrestrial and ocean temperatures warm, migration of organisms and exchange of larvae and algal propagules between South America and the WAP becomes more likely. In the Arctic region 34 non-native marine species have been introduced since 1960 (Chan, et al. 2019), a low number compared to other regions in the world, but high compared to the Antarctic.

2. Societal Relevance

The research proposed here addresses knowledge gaps in the understanding of ecosystems and the services they provide, and illustrates their importance for human health, well-being, community identity and culture, quality of life, and subsistence economies. The polar ecosystems are an important element in the cultural heritage of Indigenous as well as non-Indigenous Arctic communities. Their well-being strongly relies on the ecosystem for subsistence hunting and for food and water security, especially in rural regions. The strong interlinkage between ecosystems and human communities creates specific demands with respect to ecosystem conservation and management that sets the baseline to support Arctic societies in finding their ways to cope with climate change and globalisation in the Polar Regions (Figure 6).

The term "One Health" (OH, see also KQ 3.2) describes a multidisciplinary approach to health risks in humans, animals, plants, and the environment. It considers traditional and local knowledge and uses the experience to identify and respond to health issues.

In order to understand how changes in the terrestrial and marine ecosystems in the Arctic and the Antarctic are influencing the socio-ecological system at local, regional and global scale, we need to understand the structure and functioning of the polar ecosystems, more clearly identify the hierarchy of drivers and stressors, and determine how they influence the ecosystems. In doing so we can better understand the relations between ecosystems on the one hand and human health and well-being on the other, and infer how ecosystem change impinges on the socio-ecological system.

With this knowledge, we can address societal challenges like:
- Protecting the fragile marine and terrestrial polar ecosystems by developing proper management tools.
- Assessing the main health risks for human and animal populations in the changing polar environment.
- Improving the quality of life in rural and urban Arctic communities and including its multidisciplinary integration into the OH concept to address changing polar socio-ecological systems.

3. Research Questions

Key Question 3.1.
Understanding key issues of polar ecosystem structure, functioning, and change

Climate change and increasing human pressure at a global scale cause rapid and irreversible changes of ecosystem structure and functioning in both Polar Regions. Warming of the Arctic and Antarctic results in melting of their ice sheets, thawing of permafrost layers, loss of sea ice, and glacier retreat. This leads to shifts or loss of habitat for polar species and complex impacts on biogeochemical cycles, biodiversity, ecosystem structure, as well as productivity and carbon cycling (ecosystem function). In addition, pollutants from local and distant sources are taken up by organisms and incorporated into polar food webs, with the highest concentrations building up in the apex predators. Warming allows temperate species to move and expand their dispersal ranges toward the poles, where they compete with native polar biotas. Furthermore, human shipping and visiting activities on land increase the risk of introducing invasive non-native species (NNS) and disease vectors. Thus, polar ecosystems are exposed to a multitude of forcing factors, from general large-scale drivers that affect entire Polar Regions, to more specific processes acting at local scale, including changes in the physical environment, ocean acidification, changing coastal matter fluxes, reduced oxygen availability, extraction of living and non-living resources, and arrival of new pathogens that may threaten the wildlife, human beings and livestock. Combined, these drivers create a mosaic of multiple and mutually reinforcing anthropogenic stressors

Photo: Doris Abele

Figure 7. Layers of dying krill beaching on King-George Island, West Antarctica. The krill has been exposed to glacial melting and dead animals had ingested sediments from subglacial in the coastal environment erosion (Fuentes, et al. 2016). *Photo: Doris Abele.*

acting on the unique and highly vulnerable polar ecosystems. To improve our capability to quantify and predict changes in polar ecosystem structure and functioning in response to macro-scale and local drivers, and to allow timely adaptation to, and mitigation of disturbances, we must improve our capacities to analyse and quantify changes in polar ecosystems, and further our understanding of the combination of stressors that drive these changes. Goals should include:

- To develop standardised biological baselines for the biodiversity and ecosystem structure of polar ecosystems and develop suitable indicators and observing programmes to monitor health and rates of ecosystem change, and
- To obtain better understanding of major drivers across geographic regions/sectors and improved process understanding of the resulting changes in polar ecosystems and across different habitats, including the cumulative effects of multiple drivers.

Development of coordinated circumpolar observation systems combined with other initiatives such as the Distributed Biological Observatory[9] or the Synoptic Arctic Survey[10], including data on both environmental drivers and ecosystem responses, is essential to support this research. Ecosystem change research must include knowledge derived from biogeochemical and biological archives and take into account the evolutionary history and adaptive capacities of polar species to allow projections into the future, and facilitate the development of standardised indicators and methods for Arctic and Antarctic ecosystem analysis. Importantly, we also need to improve methods for ranking stressor impacts and determine their combined impact across different ecological subsystems (habitats). Further knowledge gaps exist with respect to the regional hotspots and essential habitats[11] targeted by the anticipated impact. Hence, indicators need to be tested at different hierarchical levels and for different levels of complexity: from individual performance traits and markers for stress sensitivity/resilience, to community composition and structure, including migrating and introduced organisms, and demographic/ evolutionary traits of key species. Definition of desired ecosystem states and the development of management tools for impact mitigation and conservation in the future requires further advances in our understanding of how societies interact and respond to ecosystem changes. Participatory approaches require the inclusion of local and traditional knowledge in terms of provision of datasets and of an alternative understanding of the causality chain.

[9] https://www.pmel.noaa.gov/dbo/

[10] https://synopticarcticsurvey.w.uib.no/

[11] Essential habitats: important feeding or fishing/hunting grounds or other habitats of specific importance.

Figure 8. One-health concept based on Center of One Health Research (University of Alaska Fairbanks), which shows the different disciplines used to define it.

Key Question 3.2.
Designing a healthy socio-ecological system

Without a healthy ecosystem that maintains its intrinsic biodiversity, there is no human health (Figure 8). One Health (OH) is a concept that incorporates all atmospheric, terrestrial, and marine ecosystems, and all the life forms that inhabit them, including humans. It is the essence of traditional knowledge and since the beginning of evolutionary biology in the midst of 1800s, it has been a concept receiving acceptance particularly when faced with complex challenges such as climate warming, global migrations, infectious disease spread, and worldwide dispersal of contaminants by atmospheric cold condensation or oceanic transport. The dynamic processes, characterising ecosystems in constant change, demand efficient monitoring and surveillance across borders. Species facing climate change may go locally extinct and move poleward, or shift distribution range to higher elevations or into the deep ocean regions, and bring with them zoonotic infections that endanger other susceptible species and humans. Food and water security are at risk. With the increasing risk of cultural ruptures due to ecosystem changes, psychological stress and mental health problems are already affecting especially the Indigenous populations of the Arctic. The identity of Indigenous Peoples is strongly connected with well-being and good quality of life, turning culture into a proper tool to be used in health care to inspire mental wellness (RN 4). Increasing urbanisation, the importance of mass-media, especially social networks, the lack of wage-earning jobs, as well as intensified import of goods (including alcohol and drugs) exert additional pressures on local cultures, social structures and hierarchies adding to the stress for the inhabitants of human settlements and cities.

In the OH model the focus is on the link between healthy and productive ecosystems, biodiversity and human well-being and health, which is not so much used in all parts of the Arctic. The involvement of the local population in the monitoring, as an integrated part of ecosystems, is an essential element of the OH model. There is a growing need for education on different levels, from educational systems to the general public. Communication with decision makers as well as with the populations at large, including the business part of societies, is becoming increasingly important and necessary and should be emphasised in the approach, tasks, and deliverables of research consortia.

Photo: Anna Karin Landin

Key Question 3.3.
Expanding observation of socio-ecological systems

A primary challenge in polar systems consists in obtaining sufficient spatial coverage of quality controlled environmental and ecological data and knowledge that allows for process analysis of the dynamic changes in socio-ecological systems. There is a particular need to create observation systems that can effectively track changes of relevance to the sustainable development goals for the Post 2020 Biodiversity framework, and for enhancing adaptive capacity and resilience, reducing vulnerability, and contributing to sustainable development with respect to the Paris Agreement.

This requires improved and consistent sampling strategies of sufficient spatial coverage and temporal resolution, both in physical and biological parameters, in support of polar ecosystem modelling. This is becoming more important, since Polar Regions as terminal areas for the deposition of many historical and emerging pollutants, lay the cornerstone for monitoring and for assessing the effectiveness of regulatory measures within and outside the Polar Regions. Integrated approaches for environmental measurements and the analysis of the polar biota, the community structure, and species interactions need to be further developed. Advanced technological and analytical solutions are required for automated observation and repeated surveys of environmental and biological parameters in ice-covered and inaccessible environments. More generally, bio-logging and omic-based technologies are relevant tools to identify key habitats and pollutant hotspots, evaluate impact of human activities (fisheries, shipping routes) on biodiversity, and set-up protected areas. Enhanced spatial coverage is also required in polar socio-ecological system research for future predictions of human well-being, living conditions, and Polar community health (e.g., scattered data from field stations provide insufficient basis for terrestrial observation).

In addition, generic information systems are required for improved data management and accessibility, including visualisation of data and statistical requests in space and time for prompt recognition of research gaps and trends (RN 6).

Integration of ecosystem change analysis with the economy, social sciences and humanities is still weak. An additional major challenge is, therefore, in understanding the connectivity between ecosystem and societal change, including feedback loops of human interventions on the dynamics of polar socio-ecological systems at multiple levels. In this context, the collection and storage of human data also pose additional questions of ethics and security.

Photo: Henning Lorenz

Key Question 3.4. Ecosystem-based management, governance and transformative solutions toward a sustainable future

The widespread and accelerating changes taking place in polar ecosystems, their biodiversity and ecosystem services, embody fundamental challenges that ecosystem-based management and governance need to prepare for. In the search for ecosystem-based approaches that can manage resources and ecosystems sustainably, a diverse set of tools have been developed that can potentially address the complex interactions between ecosystems and society.

There are significant advances in developing management tools that enable us to implement ecosystem-based management (cumulative impact assessments, spatial planning, zoning, protected areas, etc.). The challenge is that these tools lack baseline data and constant observations. Furthermore, as the demand for ecosystem goods and services is increasing as polar ecosystems become more accessible, ecosystems functioning may be adversely affected by expansion of human interventions and interaction with the natural environment.

Managing the underlying drivers that are influencing the complex dynamic systems, including the current mismatch between social systems and ecosystem dynamics on multiple scales, requires coordinated governance regimes at the highest possible levels that can effectively respond to changes, despite uncertainties, by using precautionary approaches and science diplomacy.

Science can provide some support through innovative solutions for understanding the future sustainable pathways by drawing on information from the past, and by using scenario methodologies to predict, explore and to co-create desired sustainable futures with stakeholders holding diverse values and knowledge. However, enhancing resilience and creating sustainable futures is also more fundamentally about governance and collaboration between science, governments, civil societies, and markets to address future challenges. Implementing ecosystem-based governance, irrespective of political and other borders, requires the current powerholders to value and support ecosystem-based governance, even if it creates debates and conflicts about the required trade-offs.

Photo: Diane Erceg

A key challenge in the coming decades will also be related to transforming to a currently unknown future state of ecosystems and socio-ecological systems in the Arctic and Antarctic. Scenario approaches can help to build capacities to prepare for alternative plausible futures either by use of qualitative, story-telling approaches or through predictive modelling. The key to transforming societies to embrace sustainable management pathways requires partnership between governments, civil society, and businesses. For the Arctic, a constructive way of working with Indigenous and local people through co-design and co-production of knowledge can help building transformative solutions that are perceived as positive, constructive, and socially and culturally acceptable. Transformative changes also demand a multi-level perspective, including capacity building and recognising these capacities as legitimate for Arctic communities to act as an active agent for changing their own future. Developing integrated, adaptive, informed, and inclusive approaches for responding to these future ecological and societal changes is a major challenge for the coming decades. The key question is therefore: how can we transform to create sustainable pathways for the future?

4. Resource Requirements

In order to investigate the changes of socio-ecological polar ecosystems and the implications of these, there is an urgent need for:

- Improving the baseline knowledge of biodiversity and ecosystem functioning in Polar Regions at all levels of complexity, from microbes to plants and animals, to homogenise data across time and space and achieve better connection between marine, terrestrial, biological and atmospheric ecosystem facets, and social sciences. This will strengthen participation of communities and interest groups and their involvement in study design of major research activities to secure existing long-term biological surveys and demographic studies as well, and
- Advances in modelling and molecular techniques need to link broad-scale effects of drivers in socio-ecological systems to predict consequences for society and the natural environment at multiple scales. This will advance interdisciplinary and collaborative analyses of marine and terrestrial systems. The outcome will create plausible future trajectories of socio-ecological systems that allow for effective adaptation and decision-making.

Research Need 4.
Prospering communities in the Arctic

1. Introduction

Ongoing and projected climate and environmental changes, increased human activity, and growing geopolitical interest impact communities, industries and livelihoods in Polar Regions in different ways, but the most profound impacts are yet to come. Other drivers of change are especially affecting inhabitants in Arctic communities, including the accelerating urbanisation and intensified in- and out-migration that rapidly are transforming the human geography of many regions in the Arctic.

Research needs to consider the complexity of different Arctic populations, regions, and communities, with different political, cultural, religious, and economic systems. Men, women, youth, and elders are not equally affected by the changes brought about by globalisation, a warming climate, urbanisation, and migration. Thus, there is a need for better understandings of the gender and age dimensions of the impacts of change (Larsen, et al. 2010). The huge diversity of Arctic peoples calls for new and differentiated methods for understanding social and cultural processes and future developments for aiding local leaders, planners and policy-makers. In some parts of the Arctic, there are moves toward greater self-determination and autonomy, especially in regions demographically dominated by Indigenous Peoples, while other parts – such as the Russian Arctic – face centralisation and the abolition of regional autonomies. Many local and regional economies in the Arctic are resource-based, and there has been great dependence on extractive resource industries, which come with exposure to global market forces. To achieve sustainable communities, residents must have the knowledge, skills, and resources to create and implement new and innovative ways of addressing the challenges that researchers and Arctic inhabitants identify. The question is how education systems can develop these capacities (Larsen, et al. 2010; 2014).

The opening of new seaways in the Arctic raises the necessity for innovative and sustainable infrastructure; similarly, the receding cryosphere incurs challenges on land-based transport and other infrastructure, e.g. thawing permafrost (Arctic Council, 2009). As this chapter concerns social issues, it is mostly dealing with the Arctic. But when relevant, for instance when discussing industrial legacy, it also includes Antarctica.

2. Societal Relevance

The research proposed in this plan helps address knowledge gaps around how to enable the economic, social, and cultural prosperity of Arctic communities. Despite efforts to revive Indigenous cultures and languages, many are still under stress across the Arctic. More knowledge is needed to ensure that cultural vitality is enhanced. The ability of governance institutions to provide for soft security (food, water, energy) for Arctic citizens in an age of rapid change is also a matter of concern (Arctic Council, 2016).

The challenges many Arctic communities face in the transition to a less carbon dependent future is particularly acute compared to cities and settlements in the south, due to the long transportation routes for goods, greater heating needs, etc. At the same time, it is necessary to understand how a fair share of the burden tied to this transition can be determined (Skjöld, et al. 2019). There is thus a need for more innovations and knowledge about solutions for a just transition to low carbon energy solutions.

Additional examples of societal challenges this research need intends to address include:

- Developing stronger education systems that integrate western scientific knowledge and traditional knowledge,
- Understanding the relationship between improved well-being and quality of life and increased self-determination and Indigenous participation in regional and local governance,
- Developing new indicators for well-being and sustainable development in the Arctic to complement the UN-SDGs relevant to this Research Need (Figure 1), and
- Creating new regional economic development models that ensure local sustainable value creation and well-being from any increased industrial activity.

3. Research Questions

Key Question 4.1. An infrastructure plan in support of sustainable community development

Infrastructures, in the context of this document, are the basic physical structures needed for the operation of a society, and include such structures as roads, airports, harbours (transportation infrastructure) as well as the power grid, water supply and sewer systems (supply infrastructure), buildings and housing, telecommunication structures and navigational aids, as well as service and health infrastructures. Arctic communities are isolated and require a high degree of independence in terms of operating and maintaining infrastructure (Schweitzer, et al. 2017). Outside the European Arctic there is typically no or a seasonally limited regional road network, and most communities rely heavily on air or sea transport, and thus depend on airstrips, helipads, and harbour infrastructure. In the Barents region the problem is rather the lack of horizontal intra-regional transportation networks[12]. There is typically no regional power grid and water supply infrastructure. In addition, the pace of climate change in the Arctic creates significant threats:

- Thawing permafrost causes change in mechanical properties of soils, which in turn deteriorates stability and service-life of built infrastructure,
- In mountainous areas, slope destabilisation increases risk of slides, and at sea level, coastal erosion is enhanced by both more open water and thawing of coastal permafrost,
- The extent of Arctic sea ice is decreasing, the sea ice is warmer, thinner, weaker, and there are larger areas of broken ice than before, and
- Climate and environmental conditions are extreme and changing, and standard construction practices are typically not well adapted even to current conditions.

Many Arctic settlements experience challenges due to lack of adequate freshwater resources, accessibility by modern freight ships, stable ground for airstrips, etc. Such deficiencies may in turn slow or hinder infrastructure development; for example, the lack of adequate freshwater supply, may be a reason not to invest in piped water and sewer systems, as such infrastructures are known to increase household water consumption. At the same time, not every Arctic community wants infrastructure development, such as road connections to other villages and towns (Schweitzer and Povoroznyuk, 2019).

On this basis, we recommend supporting the following infrastructure research activities aimed at growing prosperity in Arctic communities:

- Understanding the complex interaction of adaptation choices in Arctic communities, where solutions to one problem may cause recession with respect to others. This includes identifying building types and construction methods better suited to Arctic environments,
- Exploring how to combine use of the best available technology with local involvement and capacity building to promote local ownership of solutions and create a feeling of responsibility for operation and maintenance, and
- Developing mechanisms for (i) mapping infrastructure barriers for business opportunities; (ii) linking infrastructure development to socioeconomic and physical well-being; and (iii) base policy and governance decisions regarding infrastructure development on community costs and benefits.

Photo: Peter Prokosch

[12] Barents Regional Transportation Plan

Photo: Peter Prokosch

Key Question 4.2. National and sub-national governance challenges in the Arctic Regions

The Arctic is governed by numerous institutional arrangements at multiple scales, from local municipal councils to international treaties. Still, there are some general characteristics that distinguish them: the distances are vast, and the communities are small, and even the local level of government might cover areas vastly greater than nation-states in the south. In this section we understand governance as the political systems at the national, regional, and local level that undertake public decision-making. Many governance institutions in the Arctic are influenced or run by Indigenous Peoples with their own languages and cultures. But the relatively small size of most communities and a colonial history implies a marginal position of many Arctic authorities in relation to the national state. This creates power asymmetries and affects northern peoples' opportunities to be represented and get their interests on political agendas. There has been a trend in the last decades of increasing devolution of power and increased autonomy at a regional level (e.g., Greenland, Nunavut, Finnmark). The increased self-determination brought about by legal empowerment of Indigenous Peoples is altering governance institutions at all scales. The establishment of separate political institutions for Indigenous Peoples has also led to overlapping governance structures. This can strain the capacity of inhabitants to participate in political processes as well as their economic resources for engagement (Larsen and Fondahl, 2014).

The rapid changes brought about by climate change, increased industrial activities, migration and urbanisation pose extraordinary challenges for governance at all scales in the Arctic. While the expectations of economic growth in the Arctic driven by resource extractive industries (petroleum, etc.) has not been fully met, the tourism industry is increasing rapidly at the poles, with profound impacts on local communities (Stepien, et al. 2014).

Arctic communities are also affected by the UN-SDGs and the expected transition to sustainability and carbon neutrality. The geography of Arctic communities, and their climate and economic resource base pose a tremendous challenge in that respect. It is thus important to keep in mind that "the hallmark of just transition is that it recognises and accommodates the needs of local stakeholders (in the Arctic, importantly the local inhabitants) and ecosystems" (Sköld, et al. 2019).

Based on the above-mentioned challenges, we recommend the following research priorities:

- Increased knowledge and institutional innovations to ensure that governance systems foster greater participation and engagement while growing self-determination and legal empowerment (Larsen and Fondahl, 2014),
- More knowledge about how the economic benefits from increased industrial activity can be combined with cultural and environmental protection, and how this challenge can be managed in a way that also ensures local participation, and
- More knowledge about how local and regional governance systems can enable just transition, in particular, by how it can engage local inhabitants and industries. (Sköld, et al. 2019).

Photo: Ronald JW Visser

Key Question 4.3. Economic innovations for sustainable development of Arctic communities

Arctic local economies have until recently been based on a few industries only, often within natural resource extraction, particularly petroleum, mineral extraction, and fisheries. This exposes them and makes them vulnerable to global changes in demand, particularly anticipating a future circular economy, requesting less of these resources. At the same time new service- and tech-based industries are of increasing importance for local economies. Tourism activities are growing rapidly in several Arctic regions, providing economic development opportunities, but also threatening fragile ecosystems and local cultures (e.g. Arctic Council, 2016). After a temporary drop in mineral prices after the financial crisis in 2008, the demand for minerals has again shot upwards, and there is yet again increasing extractive industry activity in the circumpolar North. Retreating sea ice is allowing for increased maritime traffic in the Arctic Ocean, with hitherto unknown consequences for local communities. The retreating sea ice is hampering traditional hunting practices, which again affect the availability of traditional foods in some communities (Hovelsrud, et al. 2017; RN 3). Subsistence activities constitute an important part of local economies, even though the importance varies greatly between regions. Climate- and ecosystem change does also have impacts on the relationship between subsistence activities and local industrial activity (Statistics Norway, 2015).

There is a lack of adequate indicators for measuring well-being and local economic development in the Arctic, taking their multi-level connectivity with global trends and changes into consideration. The UN-SDGs do not recognise the mix of industrial and traditional economic activities found in many Arctic regions (Sköld, et al. 2019).

On this basis, we recommend supporting the following research activities aimed at growing prosperity in communities in the Arctic:

- More knowledge about how economic activity can be sustained in peripheral Arctic communities and how it can contribute to welfare and desired demographic development,
- A better understanding about how the need for increased economic activity can be met while at the same time balancing the benefits of such development against its negative impacts, and for new business models that ensures sustainable local value creation from the increased activity,
- More knowledge about how the increased maritime activity affects local communities and how it can be utilised for sustainable local value creation,
- A better understanding of the interdependency between traditional subsistence activities and industrial activity – particularly with respect to the decline in food security caused by diminishing availability of traditional food, and how climate change affects this interdependency, and
- Develop a set of indicators that are representative of the Arctic, in order to understand and monitor the socio-economic developments.

Photo: Peter Prokosch

Key Question 4.4. Education as a tool to expand the capacity of Arctic residents to respond to changes

The role of education and knowledge transfer in supporting adaptation and sustainability in the face of rapid social, ecological, economic, and environmental changes have not been well explored. This is as urgent in the Arctic as elsewhere. In its SDG No. 4, the United Nations calls education "the key that will allow many other SDGs to be achieved". Moreover, many Arctic communities, especially the most rural and remote, are facing a loss of human capital, with the most educated youth leaving for southern or more urban areas (Hirshberg and Petrov, 2015). State-run education systems across the circumpolar north are not meeting the needs of many Arctic residents, especially Indigenous youth and those in the most remote and rural places. High dropout rates are a major concern in the Arctic both from secondary schools and higher education institutions, and especially among Indigenous students (Beaton, et al. 2019). There are persistent gaps in education outcomes across the north, including between the Arctic and southern regions, urban/industrial Arctic territories and the rest of the Arctic, between Indigenous and non-Indigenous populations, and in terms of the growing gender gap. Across most of the Arctic, but especially in rural and remote communities, girls and women are outperforming boys and men on standardised measures of achievement and graduation from secondary and postsecondary institutions (Beaton, et al. 2019).

The high mobility of human capital in the Arctic is a considerable challenge; across the North communities experience "brain drain" (loss of educated residents), "brain turnover" (intensive in- and out-migration of human capital), and "brain waves" (surges and dips of human capital associated with the boom-and-bust economic cycles) (Hirshberg and Petrov, 2015). We cannot assume that, without intentional attention to building needed skills among community members, as defined by those communities and not by outsiders, there will be a cadre of people ready to take on critical roles, whether governance, research, subsistence, social services or perhaps solving problems we cannot foresee yet.

The above-mentioned challenges and knowledge gaps call for the following research priorities:

- Increase knowledge about what kinds of human capacity development can better enable Arctic residents to develop, implement and operate economic, social and governance structures that move their communities toward greater well-being,
- Better understand why youth are dropping out from formal schooling, especially Indigenous students, and better understand why young people choose to leave northern communities and what encourages them to return,
- Better understand why Indigenous youth and young men are not succeeding in our formal institutions, and how we can transform the systems to better meet their needs, and
- Develop more effective education systems in the Arctic which must be based on systemic integration of western science knowledge and traditional (local and Indigenous) knowledge as many scholars and local Indigenous leaders in the Arctic argue.

Photo: Peter Prokosch

Key Question 4.5.
Learning from the past for a socio-economically balanced and gender-equal development of the Polar Regions

The task of governing the Polar Regions towards a socio-economically balanced and gender-equal future, without re-generating problems associated with colonisation and boom and bust economies, requires consideration of experiences from history, the role of legacies from the past in the Polar Regions in the present and development of new methodological and theoretical tools that allow to capture Arctic processes across temporal and spatial scales. In order to deal with the challenge of attaining sustainability in the Arctic, there is a need to understand the linkages between the past, present and future, in memory and narrative as well as materially. A key requirement is interdisciplinary research on the long-term development of large-scale extractive and other industries in the Polar Regions, and their consequences for environments and communities (Avango, et al. 2013). The Arctic and Antarctic bear the footprints of several boom and bust cycles of large-scale natural resource extraction, conducted by actors from outside. As an example, in the Arctic, European companies hunted and processed whales from the early 17th century at Svalbard (Hacquebord and Avango, 2009) and in the open seas off Greenland. The 20th century has seen the growth of oil and gas extraction.

The material and immaterial footprints of past resource extraction make up an important, yet poorly understood and therefore underestimated, component of cumulative impacts in resource rich regions in the Polar Areas.

Thus, the following research needs should be addressed to further community prosperity in the Polar Regions:

- Understand and assess cumulative impacts of present industrial activities and the role of material and immaterial legacies from the past that linger on as imprints in the physical and cultural landscape in both the Arctic and Antarctic,
- The industrial histories hold a great, yet largely untapped possibility for exploring the dynamics of resource booms in the Arctic and Antarctic. Given their relatively short lifetime, there is a need to get a better understanding of the extent to which extraction should be seen as a foundation for sustainable community development in the Arctic in the future,
- A third field of inquiry with large potential for improving the ability to govern new economic activities in the Arctic and Antarctic, concerns the history of environmental and social impacts of resource extraction. How did the different extractive industries change ecosystems and landscapes that make up the baseline of today? What legacies from the past linger on in the present, in terms of industrial debris, toxic waste, transformed landscapes and ecosystems and of difficult memories? And
- A complete mapping and understanding of the legacies from past extraction in the Arctic would greatly improve our ability to build more holistic and inclusive assessments of cumulative environmental and social impacts of new economic activities. This research requires multi- and interdisciplinary research collaboration, bringing together archaeologists, historians, anthropologists, geographers, and political scientists as well as climate researchers, hydrologists and ecologists, to work in close collaboration with stake- and right-holders.

Photo: Peter Prokosch

Key Question 4.6.
The demography of the future Arctic population

All Arctic regions are in economically and demographically advanced countries but differ considerably in population size, growth rates, and settlements structure as well as in fertility, epidemiological, and migration patterns (Heleniak, 2015). Indigenous and non-Indigenous populations also differ significantly in terms of demographics. Arctic Indigenous populations tend to have higher birth and death rates, larger families, younger age structures, and reside more in rural areas.

The size of the Arctic population[13] has stabilised but there are large regional disparities in growth rates with continued population decline in the Russian Arctic and increases in Alaska, Iceland, and the Canadian Arctic (Heleniak, et al. 2020). The trend of urbanisation and faster growth in larger settlements continues among the highly mobile Arctic populations. Arctic regions typically have rather high male sex ratios compared to other populations. These high male sex ratios are more pronounced in smaller settlements as, in some areas, women tend to move to larger settlements or out of the Arctic in greater numbers than males.

Projections of the future size, composition, and distribution of the populations of the Arctic states and regions are useful for policy-makers in planning (Heleniak, 2020). Global population size is forecasted to continue increasing from the current total of 7.4 billion to 10 billion in 2055. The population of the Arctic, as defined above, is projected to support an increase of just 1 percent. However, there will be considerable variation in growth rates among Arctic regions. Given the above-mentioned trends and issues, there is a need for the following research activities:

- Combine trends from natural and social science to better understand the future size, composition, and spatial distribution of the population of the Arctic,
- The population projections referred to above are the product of standard population projections. While these are useful and often used for planning, we need methodologies that take exogenous or non-demographic factors, such as climate change, into account,
- As small communities are sensitive to population changes, we need to better understand migration flows, including international ones, from and to Arctic communities, and
- In the end, demographic data need to be combined with other social, cultural, and economic factors, as well as with the aspiration of young people, to better understand the attractiveness of Arctic communities.

[13] We are using here a spatial definition of the Arctic as proposed in the Arctic Human Development Report (Larsen and Fondahl, 2014).

Key Question 4.7.
Cultural vitality[14] for prosperity in the Arctic

One of the results of the first Arctic Human Development Report was that "resilient cultures" and "modernity" do not have to contradict each other (AHDR, 2004). Contemporary Arctic residents have long known that the challenge is not to choose between "modernity" and "unchanging tradition," but to find a liveable combination of the two (Csonka and Schweitzer, 2004). The second AHDR found an ambiguous situation with, on the one hand, a trend toward revitalisation of Indigenous languages and cultures and the strengthening of northern identities. On the other hand, there is the perception of a growing "threat" to circumpolar cultures and identities through modernisation, globalisation and (urban) migration (Schweitzer, et al. 2014).

Apart from the above-mentioned trend toward cultural and linguistic revitalisation, there is increased Indigenous participation in academic discourses. Emerging northern identities and Arctic regional perspectives are not limited to Indigenous Peoples, as "Arctic culture" has become a trademark from Greenland to Iceland and northern Fennoscandia. Still, enormous differences remain within the Arctic regarding the social prestige of northern cultures and identities. Cultural and social marginalisation of Indigenous and mixed groups, as well as forms of racism remain a reality in some areas. If we talk about cultural vitality, cultural processes cannot be limited to the maintenance and retention of existing elements and characteristics of the culture. The notion of cultural autonomy – defined as "opportunities and resources necessary for a population with a distinct culture to pursue what it deems adequate for its cultural well-being and maintenance of its group identity" – entails not only that the wider society does not prevent a group from practicing culture but also that cultural innovation is a necessary prerequisite for cultural vitality.

Two dimensions of formal and informal northern economies seem to be particularly relevant in the context of culture. On the one hand, there is evidence that subsistence activities, which are never purely economic in scope, can contribute to cultural well-being and vitality. On the other hand, tourism, which is increasing in many Arctic Regions, can be a showcase for northern cultures, while the accompanying commercialisation of cultural items and practices can have negative impacts on cultural vitality.

Gender, age, and ethnicity are important aspects and parameters of Arctic livelihoods. Of these, indigeneity, respectively non-indigeneity, have received most attention in the literature. Gender, however, has not been sufficiently investigated through the lens of Arctic cultures and identities. While we know that traditional circumpolar cultures were characterised by gender-specific realms of activities, we know too little about the gender dimensions of contemporary cultural practices. Thus, more gender-sensitive research is needed. Likewise, the rapid changes of a globalised world are having and will have profound impacts on the younger generation (and future generations); thus, it is critical to understand the hopes and aspirations of the Arctic youth.

Thus, we recommend the following research activities:

- Understand the role of cultural revitalisation vs. cultural innovation in enabling prosperity in the Arctic,
- Explore the intersectionality of Arctic identities and cultural vitality to ensure that all groups and individuals have the opportunity of cultural expression, and
- Develop indicators of cultural vitality and/or autonomy that capture not only preservation but innovation as well, and include commercial and non-commercial aspects of culture.

Photo: Diane Erceg

[14] For a discussion of "cultural vitality" versus "cultural well-being" see the Arctic Social Indicators report (Larsen, et al. 2010).

Photo: Ida Kinner

4. Resource Requirements

For all the above-mentioned research needs, a co-production of knowledge approach should be sought, to ensure salience, relevance and credibility of the results. This requires the involvement of stake- and right-holders in the development and execution of research projects and application of relevant participatory methods. In addition, in order to respond to the research needs identified above, international cooperation is needed for securing the following resources:

- Resolution mechanism for conflicting data management regimes. The role of new technologies in Arctic research deserves to be contemplated. The increased online connectivity of Arctic regions will enable new forms of "remote sensing" in the social sciences and humanities of the Arctic. Data ownership, data sharing, privacy issues, etc., will thereby become even more prominent than they are now. International cooperation, which is an absolute necessity within Arctic science, can mean that different data handling regimes collide. There is an obvious role for European politics in making sure that these conflicting regimes do not impede Arctic research, while at the same time ensuring privacy rights of inhabitants of the Arctic, and
- Access to the Russian Arctic. Given that more than half of the population of the Arctic (and half of the region's land mass), are within the Russian Federation, it is crucial to have research access to the Russian Arctic. Most coastal settlements within the Russian Arctic are administratively located within the so-called "border zone", areas where Russian and foreign citizens need special permission to enter, which makes research access even more difficult than in other parts of the Russian Federation. Reciprocal access is stated by the recent Arctic Council agreement on scientific cooperation, but must become operational and open to scientists from non-Arctic Council countries.

Research Need 5.
Challenges and opportunities for Polar operations

1. Introduction

The overarching objective of this Research Need is to provide the EU with a framework for research that aims to increase knowledge required to underpin safe, sustainable, and just operations[15] in the Polar Regions in the long-term (Figure 9).

A major driver of this research is the influence that potential expansion of existing and new activities in the Polar Regions, whether as a consequence of climate change or simply from the ordinary development of such activities, may have on the natural environment as well as local societies.

Increased operations in the Polar Regions will pose both challenges and opportunities for local communities' present in the regions as well as for the operators themselves. An in-depth understanding of the triggers for these challenges and opportunities is of the essence.

Operators in the Polar Regions are generally committed to sustainable operations. Due to the high investment costs and high risks associated with failure, commercial operators engage in these areas with robust and long-term strategies (and not because of opportunistic choices). Many operators and companies invest millions of euros in research and development before commencing operations. It is pertinent that operators understand all factors influencing the costs and challenges of operating in the region.

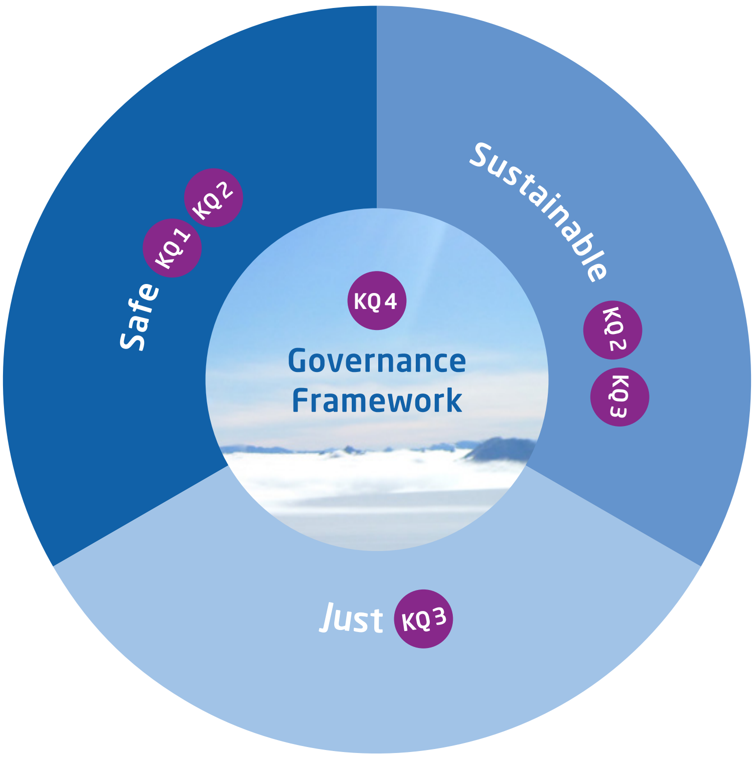

Figure 9. Connecting the Key Questions (KQs) discussed below (purple circles) to the goals of achieving safe, sustainable, and just operations in the Polar Regions.

[15] Operation refer to a broad range of activities in the Polar Regions, including commercial operations (oil and gas production facilities, mines, shipping, etc.), non-commercial operations, government operations (search and rescue operations, coast guard operations, etc.) and research operations (stations, vessels, research instruments, etc.).

Research Need 5.1. Commercial growing interest of Polar Regions

The Arctic is of growing interest for shipping and tourism, and potentially for resource exploitation. Ensuring that operations are developed and governed based on sound knowledge will enable responsible companies and operators to play a key role in the economic development of the Arctic region and beyond. Sustainable economic growth can stimulate job creation, increase the use of environmentally efficient technologies, and provide innovative solutions to developmental challenges in the region. At the same time, it is important to understand that economic growth may lead to new pressures on society that can challenge the sustainability of these communities and societies.

Antarctica, in contrast to the Arctic, does not host any Indigenous or permanent populations and settlements. While the level of activity in this region has been relatively low since the discovery of the continent 200 years ago, research and tourism activities have nevertheless grown in scope and extent over the past 70 years. While conditions in Antarctica will continue to be a limiting factor, new technologies will enable operations to evolve and expand. Research and tourism operations have generally taken place in the most productive and vulnerable areas of Antarctica.

Photo: Diane Erceg

Our current lack of in-depth knowledge about the peculiarities of the Arctic and Antarctic environments, the unique ecosystems and services they provide, as well as a failure to distinguish their value, could pose serious social consequences and result in losses of biodiversity and ecosystem services. Sustainable management of ecosystem goods and services requires foremost concrete knowledge of their societal value. Without this information, we would not be able to determine the impact on the Polar Regions from our continual expansion of operations.

All in all, new and expanding operations in the Polar Regions need to be balanced against the need to maintain the health and integrity of the environment and societies (and existing activities) in these regions, thus ensuring that activities are safe and just and do no harm to people and nature in any manner.

Further research and knowledge are needed to achieve such objectives. Our knowledge of the impact of economic activities and operations on both the environment and society is inadequate. Likewise, our understanding of cumulative and integrated impacts, and of resilience in natural and social systems, remains limited.

Research promoting technological developments underpinning sustainable Polar operations should be promoted. Research efforts enabling the efficient use of renewable energies (hydro, solar, wind), better water and waste management (disposal, reuse, recycling), better construction technologies, implementation of circular economy models, etc., in polar operations should also be encouraged.

2. Societal Relevance

Ensuring safe, sustainable, and just operations in the Polar Region has both region-specific and global societal relevance. Regionally, the challenges are vast and require economic development in a unique and changing environment, as well as the sustenance of existing activities and societies. In the Arctic there is a need to create more jobs and to develop a broader economic platform for the communities.

Globally the Polar Regions are resource-rich and will increasingly be providers of food and resources in a world with a fast-growing population. In the Arctic, operations related to hydrocarbon extraction, tourism, shipping (both bulk and trans-shipment), fishing and aquaculture, farming and agriculture, mining and forestry and the energy industry are among the location-specific operations that are likely to expand and diversify in the near future. Such operations need to be carried out in a way that complies with community expectations, desires, and benefits, and should include necessary support initiatives for local and Indigenous communities, while ensuring environmental integrity. Operations that may entail environmental and societal impacts need to be conducted in a manner that will have the least possible negative impacts. This is also true for Antarctic operations, although the type of operations in the southern Polar Regions are more limited and the societal context is also different to that of the populated northern Polar Regions.

There is a need to understand societal and environmental vulnerabilities in the Polar Regions to build societal and environmental resilience and develop mitigation and adaptation mechanisms and policies at the regional level. These matters will play an important role in achieving the UN-SDGs, several of which are directly relevant in the context of safe, sustainable and just Polar operations (Figure 1). Increased efforts will also contribute to the achievement of Paris conference (COP21) climate change targets at the global level.

The research outcomes are expected to contribute to:

- Better knowledge of the effects of operations on natural and social environments, with a focus on integrated effects, involving different environmental and social factors. Examples include effects of ship emissions on the composition of the atmosphere, impacting radiation and thereby climate, air quality and environmental pollution issues arising from an increase in operations or impact on marine ecosystems arising from an increase in fishing and aquaculture activities,
- Better understanding of the importance of local, regional, and global factors (both natural and social) influencing operations in the Polar Regions,
- Better grasp of environmental, technical, and societal factors that control and shape the ability to develop and maintain safe, sustainable, and just operations in the Polar Regions,
- Development of more accurate methodologies and procedures to prevent and recover from environmental damages caused by accidents and failures in Polar operations, and
- Knowledge enabling Arctic communities and Antarctic operators to be frontrunners in developing a circular economy achieving economic gains with sustainable solutions and benefit commercially from a green economy.

Photo: Diane Erceg

Photo: Ronald JW Visser

3. Research Questions

Key Question 5.1.
Understanding the impacts of changing environmental conditions and operations on risk and vulnerability

Climate change, as well as improved infrastructure and technological development, has made the Polar Regions more accessible and increased the potential for development of new activities with associated operations in these areas. However, both the societal structure and the environmental conditions in the Polar Regions are unique and need special attention in the context of safe and sustainable operations. Existing and expected new risks specific to these regions need to be taken into account.

An increased level of activity in more northern and southern waters will expose maritime operations to an increasing degree to cold climate, ice and icing, darkness, and atmospheric communication and navigation disturbances that have to be considered in order to ensure that safety is maintained at a high level, e.g. according to international regulations such as the IMO Polar Code. Furthermore, as a consequence of climate change, there may be an increased calving and thereby presence of icebergs in polar waters, which also affects navigational and operational safety.

On land, climate related changes such as the increased thawing of permafrost is a threat to present infrastructures (e.g. oil and gas pipelines supporting key energy operations in the Arctic). Other changes, such as landslides and coastal erosion may also impact existing operations.

Research and an expanded understanding are required to:

- Appreciate how the changing polar conditions and changing operations impact the type and level of risk and vulnerability, as well as what and where these risks and vulnerability are,
- Underpin the development of technologies as well as institutional mechanisms and operational competences to meet the challenges associated with increasing and changing risks and vulnerabilities,
- Develop appropriate responses in case of accidents to protect life, the environment and community values. There is a need to develop emergency response capacities to mitigate consequences of accidents and natural disasters, and
- Promote broad scale technological developments to ensure that existing and new operations in the Polar Regions are considering the risks associated with ongoing changes in polar conditions and operations. This should include mitigating the risks, meeting the risks, and responding to the risks.

Key Question 5.2.
Minimising the environmental impacts of polar operations

KQ 5.1 addressed the issue of risk and risk management in the context of a rapidly changing polar environment. Our understanding of the Polar Regions' environment and ecosystems need to be improved considerably in order to ensure realistic evaluations of impacts that existing as well as new operations can have on these environments and systems.

At the same time, it is fundamentally important to reduce uncertainties in future climate scenarios to better constrain impacts realistically. Stresses caused by impacts from existing and new operations will interact with the impacts of climate change. Furthermore, the operations themselves may amplify climate change itself. We need to have good knowledge of both components to be able to evaluate whether the polar environments are sufficiently resilient to sustain the combined impacts of changes.

Polar operations are likely to expand and diversify in the Arctic in the near future. In the Antarctic, fishing, tourism and research may expect to continue and expand. Most of these operations already carry potential risks to the environment and may pose new and additional risks when they expand in scope and their technology use changes and particularly when they move into new uncharted areas with new/unknown environmental parameters. The risks may be particularly high in the near-term when conditions are unknown, changing, and unpredictable.

The main route to reducing the risk of polar operation impacting the environment is to ensure a comprehensive understanding of the potential impacts these operations may have on environmental parameters and ecosystems. Understanding the impacts enable identification, development, and implementation of actions (technological, spatial, temporal, regulatory, etc.) that reduce these risks.

Understanding impacts on the environment requires an understanding of the environment itself, as considered under RN 3. The Polar Regions are still relatively poorly studied due to their extreme environment. Basic knowledge on most of the polar biodiversity is limited. Comprehensive data are generally available only for species important in the context of (commercial) harvest. The food web structures of polar biological communities are poorly known at temporal and spatial scales suitable to allow predictions of their response to environmental changes. The large knowledge gaps relating to biodiversity, environment and ecosystems in the (changing) Polar Regions, particularly in those regions that until now have remained largely inaccessible to polar operations, also indicate that there is a basic lack of knowledge about how such operations can impact the environment as they expand in scope and approach.

Understanding impacts is fundamental if we are to reduce the risk of any impacts that trigger unsustainability. Fundamental to counteract any environmental ramifications of new and expanding activities is a solid and robust understanding of the original and current state of the environment, and an understanding as to how various ongoing and potential impacts may affect the current state.

Natural variations in climate, anthropogenic climate change, long-range pollutants and ongoing activities impact the environment in the Polar Regions cumulatively and on multiple levels. An increase in polar operations will entail and add-on additional risks and impacts, some of which may be positive and some less so. Understanding the complexity of cumulative impacts and how new and expanding polar operations contribute to the risk of such cumulative impacts taking place is also of key importance.

Certain impacts/risks are considered to potentially have specific particularities in Polar Regions for which there still are large knowledge gaps that need to be filled:

- Invasive alien species and disease vectors enter and spread throughout the Polar Regions through several "pathways" (RN 3). Shipping (ballast water, hull biofouling) is an operation that is of particular concern in both the Arctic and Antarctic, while energy extraction and production installations and mineral exploration are operations that create additional risk of invasive species introductions in the Arctic. The Polar Regions are vulnerable to biological invasion due to a relatively low diversity of native species, the rapid warming and changing climate, and the expansion of human activity and operations into new areas of the regions (RN 3). Research and knowledge are required in a number of directions, including (i) risk assessments, (ii) introduction, (iii) avoidance and limitation, (iv) non-native species (NNS) identification and their status, (v)

Photo: Federico Dallo

distribution and impact of NNS, and (vi) eradication methods,
- Evidence about how anthropogenic noise (caused by vessel operations, marine-based energy extraction and production operations, etc.) that can affect marine life accumulates. While there is improved knowledge of the effects of noise on some species that occur in the Polar Regions, there remains a lack of research and long – term monitoring on endemic polar species, including little knowledge of population level effects and variations in effects with life stage. Due to the lack of fundamental knowledge, the effectiveness to current approaches to mitigation and management remain largely unverified. Marine mammals are to a larger degree than terrestrial animals dependent on their hearing for survival and are therefore particularly susceptible to noise disturbance. However, the impact of noise disturbance due to land - based operations on terrestrial biota is an area that also requires further knowledge, and
- Point sources of pollution in the Polar Regions vary. In Antarctica they are principally associated with shipping and individual terrestrial operations such as running and maintenance of research bases. In the Arctic they originate from a wide range of societal and industrial operations. The distributions and lifetime of operational pollution is furthermore affected by the unusual polar conditions, as further discussed under KQ 1.4 (e.g., long periods of darkness, cold, dry air, strong wind, ice cover, and permafrost), which affect the distributions and lifetimes of such operational pollutants that in turn impact species and ecosystem. Furthermore, point source pollution in the Polar Regions may also interact with climate processes and feed back into the climate system, for example soot falling out on the surface of snow and ice will decrease the ability of the originally white surface to reflect incoming solar radiation, in turn amplifying the melting of snow and ice cover, and by this contribute to accelerating climate change.

All in all, there is a large need to increase knowledge about the vulnerabilities in the environment to understand the resilience of the system through e.g. improved monitoring. Important is also to understand and assess the vulnerability of particular environmental values and of the polar ecosystems to new and increased operations.

Finally, there is a need to increase research related to operational technology that can contribute to reducing the impacts that may arise in the Polar Regions from the various types of operations. Best practice and available technologies developed for use in mid-latitudes need to be tailored for the particularities of the polar conditions.

Key Question 5.3. Understanding and promoting the concept of social license for polar operations

Climate change, globalisation and the desire for industries that are more sustainable are the main drivers for changing operations in the Polar Regions. These changing and increasing operations involve and affect many different stakeholders in different ways. In the resource extraction industry, it is common practice to conduct an impact assessment (IA). Traditionally the impact assessment is carried out to assess the environmental consequences of the operation, but nowadays the social aspects of the impact assessments are considered as well. In several Arctic countries conducting a social impact assessment is now mandatory or at least common practice.

The concept of Social License to Operate (SLO) is increasingly becoming a part of the IA process. SLO relates to the social risks of an activity, and it is usually defined in scholarly literature as the (ongoing) acceptance/approval of an activity or decision by the local communities, and other stakeholders that can affect its profitability. Trust building is regarded as central to obtaining a social license to operate, something which is created and maintained slowly over time. Traditionally there is a rather instrumental focus of the social license to operate on the local project context and the relation between a company and its local stakeholders, but it is important to relate it to more elements of today's increasingly interconnected and complex society. These elements include the roles of governments, regulatory frameworks, social media, regional, national, and international communities, etc. Using this broader concept of a SLO and deepening the understanding of the SLO concept can generate the insights that are needed to adequately address societal concerns and contribute to the successful implementation of an internationally debated activity.

SLO can be instrumental in dealing with some of the greatest challenges to sustainable development: the role of affected communities in shaping development trajectories, increasing expectations on industries from communities and governments, unequal power relations between key stakeholder groups, the complexity of building meaningful and lasting relationships between these groups based on mutual trust, and the challenge of finding a common language and approach among stakeholder groups to achieve deeper, more mutually acceptable ways of coexisting. SLO might also play a role in social justice considerations, referring to, among others, the rights of Indigenous Peoples, ethnic minorities, youth, and those marginalised on gender, sexual orientation or other grounds.

To answer this key question, it is important to obtain a better understanding of:

- Who are the stakeholders of the different operators and how they are affected by the operations,
- How the concept of SLO relates to different types of operations,
- How the conditions that influences the SLO differ between types of operations,
- What the desired futures of local communities and other stakeholders are and (i) What the conflicting interests are, (ii) What the beneficial interests are, (iii) How this relates to the different operators that are of influence, and (iv) How this relates to the social justice concept, and
- How the concept of SLO relates to social impact assessments and capacity-building.

Due to the particularities of the Polar Regions, there is considerable need to explore and understand the concept of SLO and social justice in the context of these regions, as well as location-specific issues related to the implementation of these concepts.

Photo: Peter Prokosch

Photo: Peter Prokosch

Key Question 5.4.
Identifying policies, frameworks and governance which ensure safe, sustainable, and just operations

The Polar Regions are gaining increasing political and economic significance. At the same time, climate and environmental changes and increased economic activity can set established administrative regimes under pressure. The geopolitical environment, the efficiency of established management regimes, as well as the conditions for international cooperation are therefore of importance. All stakeholders have a role in providing the framework for movement of goods, knowledge, and people, and understanding these factors are of importance.

There is a need for research-based understanding that can underpin further development and discussions relating to the following policy and governance aspects relevant to operations in the Polar Regions:

- The political and commercial interests in different Polar Regions are changing, making it necessary, in a political context, to map the national, international, and commercial stakeholders in the different regions. One must look into the potential mismatch between emerging interests and activities and the international agreements, national laws and regulations in the specific regions,
- There is room for expanding our understanding of existing international regimes in the context of internationally governed regions, in order to consider how potential new operations in new areas create new challenges, including those for environmental protection, emergency preparedness, search and rescue, principles for resource allocation and access,
- Increased interest in mineral and petroleum operations in the Arctic represents administrative challenges. There is a need for research-based knowledge of how States relate to established and new collaborative regimes, and to what extent the regimes contribute to problem solving,
- There is a need to focus on the protection status of the regions and the limitations in operations related to different types of activity, including considerations for both the environment and the welfare of the local communities, and
- The operational demands of actors have to be met to counter the challenges of the region, including adequate safety precautions. An example is the IMO's International Code for Ships Operating in Polar Waters[16]. We need regulations both on land, air and sea covering areas such as design, construction, equipment, operational, training, search and rescue and environmental protection matters relevant to operators. This calls for R&D within both technology, business management, safety, security, and emergency response.

Many areas of the Arctic and Antarctic are data-sparse, and in some parts the paucity of observations is compounded by the lack of universal access to data. These shortfalls hinder the formulation of innovative strategies for managing social and environmental changes in the Arctic and beyond. Interoperability and exploitation of distributed data will provide useful information in a collective sense for science, society, industry, and operations in Polar Regions. Research and development within this field will greatly support the aim of safe, sustainable, and just polar operations in the long term.

[16] IMO´s Polar Code

Photo: Ronald JW Visser

4. Resource Requirements

In order to investigate the changes to and implications of existing and new operations in the Polar Regions, there is an urgent need for:

- A dedicated and comprehensive framework / platform for coordination and collation of research that will strengthen and make available the knowledge base required for society and governance to measure and regulate the "footprint" of operational activities in the Arctic and Antarctic, and to ensure that new operations take place within a responsible, safe and sustainable framework,
- commercial, industrial and social developments. There is a need for collaboration between academia, Indigenous organisations, communities, government, and industries to enhance technology developments, new jobs, safer operations, better sustainable economies (transport, fisheries and industry), and capacity building in Polar Regions,
- The deployment of new technologies such as autonomous platforms carrying sensors, automated distributed sampling hubs, increased use of emerging remote sensing capabilities, supporting not only safe and sustainable polar operations, but a wide range of research needs as also noted with regard to RNs 1, 2 and 6, and
- Engaging business operators in the collection of long time-series of ecosystem monitoring data. These should be utilised to their maximum and expanded with greater spatial coverage, engaging operators in using mobile, comparative, and complimentary measurement platforms.

Photo: Ronald JW Visser

Research Need 6.
Inclusive creation, access, and usage of knowledge

1. Introduction

Polar research comprises fundamental and thematic research across a wide range of disciplines. The remote and harsh weather and environmental conditions make operations in polar areas both expensive and complicated. Several crosscutting lines of research are therefore required for supporting and ensuring the most inclusive, cost-effective, and efficient data collection, dissemination and most widespread and meaningful use of research results.

In situ data collection in Polar Regions is expensive and complex, this prevents good spatial and temporal coverage and hampers the possibility of developing accurate models and ensuring adequate and long-term monitoring.

There is a need for applied and technology-oriented research to support the technological challenges of data acquisition in extreme conditions in polar areas. In addition, new and more efficient methodologies and practices for data acquisition, handling and analysis, and integration of different knowledge systems are imperative. Furthermore, with the expected increase in all types of human activities, it will be important to listen to and know more about all stake- and right-holders to find out how they will best cooperate. Appropriate consideration of different knowledge systems – the Indigenous knowledge and the scientific knowledge – is epistemologically beneficial and relevant for understanding and facilitating societal changes in times of changing environment.

Not only the various research disciplines could profit significantly from each other's research results, but all actors would benefit from adequate and tailored dissemination of research results to boost awareness about the Polar Regions, ensure easy access to research results and guarantee that the results are put to good use for the benefit of all. In addition, research and application of innovative and modern education and training methodologies could build capacity within and beyond the Polar Regions regarding the cultural and natural role of the Polar Regions and, at the same time, ensure that the demand for new skills and competences in a fast-changing world is met.

International research cooperation and coordination is, furthermore, a crucial tool to achieve the research needs. The interdisciplinary nature of polar science, the common challenges faced and the sensitivities in polar areas, also call for excellent science diplomacy to inform decision- and policy-makers in the best way. Connecting the international community and all stake- and right-holders is strongly required to ensure the optimal understanding and use of the different knowledge systems, existing expertise, infrastructure and human capacity around the world, and to operate in the most cost-effective way.

This chapter presents the technological and methodological crosscutting research needs and requirements for achieving optimal data, understanding and results, and facilitating their uptake and sustained use.

Photo: Federico Dallo

2. Societal Relevance

Data and knowledge from Polar Regions contribute to solving scientific and societal questions but also to timely evaluation of the impacts of change on climate, environment and society not only within the Polar Regions but – because of the connections between the poles and lower latitudes – on the entire global society.

In addition, a lot of data are not available in a systematic way, preventing combination of data from different sources and across communities to connect activities and establish a higher understanding of scientific problems. Satellite data can partially overcome this limitation but not all parameters are measurable from space or are available with enough accuracy (e.g., spatial resolution, minimum/maximum detectable value) with respect to the user needs.

Addressing these data and data coverage challenges will contribute to:

- More comprehensive understanding of the changes operating in the Polar Regions to support user needs,
- Improved accessibility to data and results, including improved interoperability. This will foster the usage of data and increase the societal relevance of research results by supporting knowledge-based management, sustainable development, and policy decisions, and
- Development of new technological solutions for generation, treatment, long-term preservation and sharing of scientific data. These will involve integration of information across different communities, countries, spheres, and disciplines. This will require a truly Big Data approach addressing volume, heterogeneity, and speed in data. The development of such techniques and methodologies could be beneficial also for other disciplines outside polar research.

However, sustainable solutions and new knowledge for policy-making cannot be found by scientific knowledge alone. In addition, in the Arctic impacts from global environmental change ultimately materialise at the "local" level – where local and Indigenous knowledge practices are used and developed. Embracing and enhancing cooperation between different scientific disciplines, as well as diverse stakeholders, and their different knowledge systems, including Indigenous knowledge, will benefit both the research community, the Indigenous communities and other stakeholders, because it will contribute to:

- Support the protection of Indigenous Peoples´ rights and their cultural identity as well as socio-economic and political self-determination,
- Increase the effectiveness and efficiency in the development of scientific knowledge using a diversity of cultural, social, geographic, and disciplinary perspectives that can provide guidelines to researchers,
- Improve methodologies for co-design and co-production of data, which may also alter initial classic research questions and put them on a more innovative level, and
- Provide a holistic framing for assessing impacts of, and possible solutions for coping with environmental change and its socio-cultural consequences to (i) improve human well-being and resilience of communities anticipating that the rate of change may be faster than social systems adaptation capabilities, (ii) support new economic activities and address new potential pressures, and (iii) enable sound, informed and effective decision-making by policy-makers.

Good communication and learning and skill development are important contributors to society. Transformation of education and training is therefore essential and will contribute to:

- Build the knowledge and skills needed for sustainability and sustainable growth, employment, and participation of the communities and the society at large, and
- Strengthen the public understanding of the relevance of Polar Regions in the global weather and climate system, and for the development and preservation of biodiversity and (lived) cultural heritage.

Photo: Ronald JW Visser

3. Research Questions

Key Question 6.1. Developing new technologies and improved capacities in observation, modelling, and research in the Polar Regions

Currently, the Polar Regions are characterised – both spatially and temporally – by an inadequate density and uneven distribution of observation data for many applications. This follows from the low density and poor coverage of the observation networks, the weak coordination of existing observing networks, and the limitations of data acquisition and transmission in remote and extreme environments. Even if the extreme conditions of the Polar Regions and their vastness call for enhanced use of Earth observation satellites, many of them are not able to observe at high latitudes. Moreover, some key parameters cannot be measured from space with required accuracy or cannot be measured at all because of a lack of adequate or dedicated sensors/satellites or in situ data, which are needed to validate them. In addition, while some satellites provide reliable products their long-time period availability is not yet secured by Space Agencies. Innovative experimental designs, new applications of existing technology, invention of next-generation technologies and development of novel air-, space- and animal-borne observing or logging technologies will be essential, not only to support ongoing science and operations, but to open the way to new investigations and scientific findings.

New innovative technologies are necessary to meet the special challenges (e.g., extreme environmental conditions, high deployment and maintenance costs, limited energy supply, limited communication abilities, etc.) of reliable and sustainable measurements (from micro- to macro- scale) but also to provide in situ and near-real time data to be used in modelling, forecasting and satellite calibration and validation activities.

Besides the development of new sensors that can measure polar-specific parameters there is a need to develop a new generation of observatory platforms capable of supporting different sensors that address multiple scientific objectives and allow for synoptic collection of data. This includes the development of a new generation of space-borne sensors specifically designed to observe Polar Regions.

At the same time, new observations capabilities must be developed and standardised in such a way that maximum synergy with existing observation networks and programmes (e.g. GCOS, Copernicus, SOOS, SAON) is achieved.

Overall, there is a clear need to:

- Support international efforts for measuring key indicators (RN 2) of the changing climate and related ECVs by autonomous, *in situ* data collection systems, new sensor technologies (including biosensors and omic-based technologies – RN 3) based on renewable energy solutions with low energy consumption (e.g. new generation of batteries) as well as complex observational units (e.g. drilling rigs for paleo-reconstruc-

Photo: Ronald JW Visser

tions) all suited for harsh environmental conditions,
- Support international effort for implementing intensive observational surveys in both time and space (e.g. MOSAiC, YOPP, SAS) to establish baselines of the current status of the Polar Regions, to improve climate and forecast models and to consolidate satellite products,
- Enhance and pursue efforts to observe from space and groundtruth the retrieved information,
- Improve the temporal and spatial coverage of key parameters in atmosphere, terrestrial, cryosphere and ocean observational systems, including the measurement-capability during the polar night and to make this data available and accessible in a timely manner to relevant stakeholders and users,
- Introduce new technologies for modelling and data assimilation (including data quality control) to increase the spatial-temporal coverage of processes and to achieve a new level of forecast and climate projections,
- Improve Earth System Models (ESM), for both weather and climate modelling thus predicting the behaviour of the climate system and its components more accurately,
- Improve ecosystem models to test hypotheses, design experiments and to inform conservation management,
- Enhance the use of ICT techniques (e.g. machine and deep learning) that could significantly improve modelling efforts and the processing and analysis of an increasing number of data, and
- Develop the integration of observational systems into observational networks that operate at different levels of system complexity and are able to homogenise data across areas of differing temporal and spatial variability (e.g. complex terrestrial landscapes, highly structured coastal areas vs deep sea systems), and that incorporate marine, terrestrial, atmospheric and social science data.

Besides the acquisition of data other requirements are:
- Real-time transmission and communication at fair costs as a primary requirement for many applications in the Polar Regions. It is essential to promote ICT research supporting real time access to data and information from heterogeneous sources, addressing current limitations in data collection, integration, processing and communication of information (e.g., new communication networks, data management approaches, cloud-computing and information visualisation) (Siegert, et al. 2019), and
- Better and more integrated platforms for high-performance computing (HPC) – so called exascale systems – to handle the rapidly growing Big Data requirements that are needed. Such computing capabilities underpin modelling (e.g. ESMs), experimental designs, automated data and image analysis, and bioinformatics. A coordinated effort is required to ensure these HPC platforms are accessible and beneficial for the scientific communities.

Key Question 6.2.
Co-production of knowledge as a benefit to societal stakeholders

Modern societies and economies are modifying due to climate and environmental change, globalisation and technological progress resulting in a focus on new economic activities, transportation routes and use of natural resources in the Polar Regions. In addition, northern communities might face unprecedented new challenges due to complex inter-linkages between climate-related hazards and societal factors. These perspectives increase the demand for science-based knowledge, gathered jointly with stakeholders, to find sustainable solutions for both new economic activities and traditional livelihoods for people who live in the region[17]. Research questions no longer emerge from science alone but in interaction with civil society, governments, and other stakeholders (Mauser, et al. 2013). This has been acknowledged already worldwide (Díaz, et al. 2015) but is currently implemented in European Polar research as well. In the Arctic, policymakers and the research community have highlighted the importance of including Indigenous knowledge and Peoples in the research conducted on, or affecting their culture and lands[18].

[17] White paper on status of stakeholder engagement in Polar research
[18] See for example, statements published by Arctic Council and the Arctic Science Ministerial, 2018

Research Need 6.1. Co-production of knowledge

INDIGENOUS AND LOCAL KNOWLEDGE SYSTEMS

Indigenous and local knowledge systems are defined as "a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Díaz, et al. 2015). Like Western science, local and Indigenous knowledge is not static – it is dynamic and holistic. Western science, Indigenous and local knowledge are separate but complementary knowledge systems.

KNOWLEDGE CO-PRODUCTION

Knowledge co-production combines science with local and traditional knowledge to solve problems in which neither science nor local knowledge is sufficient by itself. It is "the collaborative process of bringing a plurality of knowledge sources and types together to address a defined problem and build an integrated or systems-oriented understanding of that problem" (Armitage, et al. 2011).

Often though, efforts to include Indigenous and local knowledge only consider those aspects that can easily be integrated with Western thought; therefore, there is a need to shift away from focusing on integration and move towards knowledge co-production (Nalau, et al. 2018).

Photo: Peter Prokosch

When designing research projects in the Polar Regions, it is indispensable to:

- Raise awareness of researchers – especially within natural sciences – about the benefits of including stakeholders – and in the Arctic local and Indigenous knowledge-holders- in research projects,
- Involve stakeholders from the very beginning (co-design) to identify research objectives and methodologies that address the needs of both the stake- and right-holders and the project, and
- Get a better understanding of different methods for co-producing, documenting, analysing, and sharing knowledge (Tengö, et al. 2014), as well as to share experiences using these methods.

Specific recommendations to Arctic research designers must include to:

- Use participatory methods in the co-designing of research objectives with local and Indigenous Peoples,
- Understand that the inclusion of Indigenous knowledge and traditional knowledge requires adequate resources and capacity to address the unique needs and circumstances of the cultures, languages, communities, religions, governance processes, and knowledge systems of the indigenous community,
- Accept that the legacy of research projects should benefit the local and Indigenous participants (in their diversity) – thus, the ownership and long-term outcome of the project should be enhanced through capacity building activities which address local needs (KQ 6.4),
- Acknowledge that the co-production of knowledge requires creative and culturally appropriate methodologies and technologies[19]. Adequate ethical standards for mode of local participation, ownership of data, and how data and results are shared and archived might differ from community to community, depending on the local context. They should be agreed through a dialogue, while the principle of openness in data sharing has to be explained and shared, in particular for those obtained via public support. This must be considered in drafting guidelines for making contextualised ethical research standards, and
- Develop research that can assist in the co-determination of desired futures envisioned by stake-and right-holders for both the Arctic and Antarctic (Sköld, et al. 2019).

Key Question 6.3. FAIR data management principles for polar data collections

Individual scientists, communities and disciplines have different mechanisms for documenting and sharing data and knowledge. Efforts are required to improve understanding of data and information across communities, while acknowledging the nature and scientific content of different disciplines. This is an enormous task, but technology can help if data documentation and data-interfaces are standardised and machine-readable. There is need to define a limited set of standards enabling efficient data and information sharing across different communities, stakeholders, regions/countries, and disciplines. Cost efficient approaches are required to establish a sustainable system.

For Antarctica, data must be open and public[20], while in the Arctic, the concept of ethically open data is important: not all data and information can be openly available for protection of privacy rights of individuals, endangered species, natural resources, etc., but the underlying principle is to ensure free and open access to data[21]. In particular, Indigenous knowledge and data from Indigenous communities are considered to belong to the knowledge holders and Indigenous informants, also due to the special conditions of colonial history of data exploitation[22] by researchers and governments. For this reason, special protocols for the use and storage of Indigenous data must be developed with the Indigenous Peoples. (KQ 6.2). For such data, aggregation levels need to be identified at which analysed data can be made free and openly available as well as combined with other data.

[19] Arctic Council Permanent Participants. (2015 [updated 2018]). Ottawa traditional knowledge principles.

[20] Antarctic Treaty, 1959.

[21] Statement of Principles and Practices for Arctic Data, IASC.

[22] Exploitation can be defined as the use of results in research activities, in developing, creating, and marketing a product or process, in creating and providing a service, or in standardisation activities. Exploitation can be commercial, societal, political, or for improving public knowledge and action. European Commission H2020 Common Support Centre.

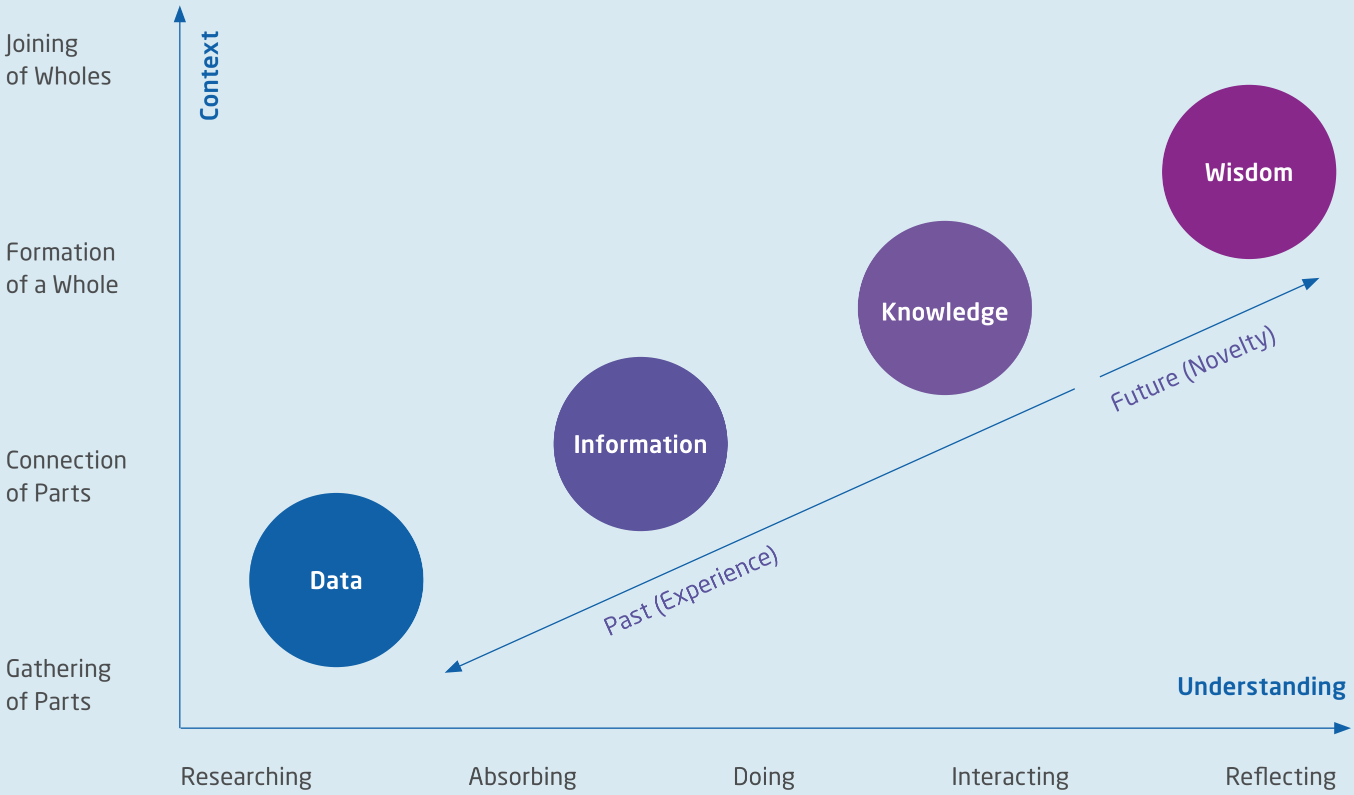

Figure 10. Illustration is based on the publication by Ackoff (1989).

From the Public Sector Information (PSI) Directive to the Open Data Directive: improving data availability by bringing new types of public data and publicly funded (including research) data into scope and improving access to data and in particular statistics, geospatial and dynamic data[23].

The FAIR (Findable, Accessible, Interoperable, Reusable) guiding principles are addressing the ability to access and use data across communities and disciplines[24]. Application of the FAIR principles puts data in context and enables information filtering and extraction. In general, polar data management should follow the principles "as open as possible, as closed as necessary" under consideration of ethical principles and of decolonised Polar research contexts. While information ages rapidly, knowledge has a longer lifespan. The understanding may prevalence, but it is wisdom that is considered permanent in the true sense (Figure 10).

[23] From the Public Sector Information (PSI) Directive to the Open Data Directive. EU Commission.
[24] GO FAIR Initiative.

The nature of data that need to be handled and combined in a consistent manner include quantitative (numerical) and qualitative (textual/non-numerical) data from natural and social sciences. The different types of data pose different opportunities and challenges:

- Quantitative social and health data can be anonymised and contextualised on large and small spatial scales, thereby simplifying integration with other data and re-use, and
- Qualitative social data, like interviews, oral history, and Indigenous knowledge, information from focus groups and observation protocols, are fully dependent on the context of data production: e.g. the researchers, the knowledge holders and the interaction of the two in the data production process.

Independently from the nature of data, the ability to link information across domains, e.g. on instrumentation, observations protocols, observations facilities, data, software, all the way through to decisions, is vital for the interpretation and understanding of the data - in particular for activities focusing on monitoring changes. This requires:

- A consolidated effort on the identification of resources, traceability of data, processes and decisions made based on scientific data,
- Coordinated efforts to address semantic annotation of data and the web services providing these, documentation structures preserving features of the data (e.g. imagery, dynamic processes in the nature), how to document quality and provenance, etc., and
- Improved dialogue within different communities and disciplines to establish a common understanding of data and information content. This includes an improved ability to translate terminologies from different communities.

These issues are not only valid for Polar Regions but also need to be well connected with other activities being developed at the global scale.

Key Question 6.4.
Ensuring knowledge access and capacity building in Polar Regions

Polar research has tremendously increased its output over the last decade, especially in the fields of understanding climate and social changes due to changing environments, industrialisation, or colonial legacies.

To improve the access of knowledge:

- Polar knowledge needs to be provided through a variety of channels and knowledge brokers. Policy advice and educational information should be released at different levels of complexity – e.g. in local and/or non-scientific language – in order to address the society at large, including local residents and Indigenous Peoples (KQ 6.2), and to directly benefit from use of research results in decision-making, and
- Effective and interoperable data sharing in Polar research needs to be promoted as it is important to create synergies with education, capacity building and policy, as well as to aim at an improved international scientific collaborative community (KQ 6.3).

Access to knowledge and knowledge transfer should lead to awareness creation among industrial and other economic stakeholders, as well as among policy-makers inside and outside the Polar Regions, about the social, economic, cultural, ethnic, ecological and climate specifics in the Polar Regions, and about the fact that processes occurring in polar areas have a significant impact on the rest of the world, including Europe.

More awareness can be created by the:

- Exploration and evaluation of new and known communication tools/channels to facilitate knowledge transfer. Gamification can also be useful for facilitating stakeholder uptake of knowledge. Improving education and capacity building through: (i) Systematic understanding of how to tap scientific and knowledge resources for societal benefit and to build capacity among individuals and stakeholders to facilitate adaptation, sustainable development, social equity, and justice, as well as mitigation of risks from environmental changes; (ii) enhanced cross-border cooperation for higher education to facilitate knowledge transfer.; and (iii) understanding and valuing the needs of the stakeholders (stakeholder engagement). A two-way learning regime can facilitate co-development processes with stakeholders, knowledge holders and decision makers and enhance user uptake of scientific results (KQs 6.2 and 6.5),
- Development of the understanding of the natural and cultural roles of the Polar Regions to society which includes their global environmental significance and their differences and similarities. This could lead to more public awareness of their role in the global climate system and for the development and preservation of lived cultural heritage, and
- Improvement of education on all levels, including training and outreach to the wider public. This requires constant development, utilising new and innovative technologies and interactive platforms that can support the demand for new skills, such as collaborative scenario development, entrepreneurship, and strategic planning.

Figure 11. Participatory mapping workshop between reindeer herders and researchers to better understand the complexities of land use and land use change. *Photo: Levi Westerveld.*

Key Question 6.5. Exploiting knowledge to inform decision making for the Polar Regions

The interests in Polar Regions are multiplying quickly and the number of actors directly or indirectly participating in these activities is also growing. To adapt to the present and future challenges of climate change in Polar Regions, these different stakeholders can benefit from having access to the best up-to-date knowledge tailored to their needs (KQ 6.4).

The types of knowledge required by different stakeholders will depend on the purpose of the decision to be made and the way it will be incorporated into strategic planning and decision-making. Whereas some stakeholders may be more interested in the dissemination of knowledge to contribute to developing their agendas (e.g. NGOs for preserving biodiversity), policy-makers may require access to relevant and evidence-based knowledge, ready to be integrated into actionable regulations and policies. On the other hand, industry and businesses are often looking for new products that, making use of the latest scientific knowledge and innovations, target problem-solving and support decision-making. Indigenous and local communities could be more concerned about finding sustainable solutions to their day-to-day challenges, due to increased global impacts on their livelihoods (Figure 11). The conversation between Indigenous knowledge and science is crucial in that respect (KQ 6.2).

The urgency implied by research findings related to climate change in Polar Regions seems to be disconnected sometimes from the political reaction. However, actual integration of knowledge into polar decision-making has already been reported to benefit planning and decision-making in various socio-economic sectors, including but not limited to shipping, search and rescue, fishing, or the prediction of the risk of avalanches[25].

A more generalised and sustained exploitation of available knowledge to address challenges in Polar Regions would benefit from the:

- Development of equitable platforms to help local and Indigenous communities to make informed decisions. Such platforms should integrate stories and knowledge assembled through community participatory mapping and knowledge sharing, and combine them with other existing cutting-edge services, such as satellite imagery, weather and climate information or tide reports (KQ 6.3),
- Use of participatory techniques such as scenario analysis (Carson, et al. 2019) to improve understanding and illustrate the added value of using evidence-based knowledge for decision-making,
- Development of prototypes or proofs of concept for user-relevant products or services illustrating the potential of available knowledge. Such tools can incentivise the uptake of knowledge by stakeholders and pave the way towards a possible operational use,
- Development of Decision Support Tools (DSTs). Key challenges for their implementation include, among others, the logistics of operating and maintaining the continuous delivery of information in Polar Regions, and
- Establishment of effective methods to improve policy understanding (e.g. regular policy briefings).

[25] Blog Polar Prediction Matters

Photo: Andrea Spolaor

4. Resource Requirements

Inclusive creation, access and usage of knowledge require:

- Coordinated calls to improve the technological capabilities to operate in and observe inaccessible areas year round, to transport, maintain and rapidly analyse samples, and to support the establishment of a sustained network of long-term observatories (super-sites) and collaborative networks, devoted to perform a well-integrated multidisciplinary observing programme and to validate remote sensing products. This requires:
  - Improving technologies for data collection, including autonomous systems,
  - Development of autonomous platforms capable of enlarging the spatial coverage in air, ground, and water,
  - Improving High Performance Computing, and
  - Improving capabilities for exploration within the ocean, ice and solid earth.
- Low-cost, low-energy and clean communication systems for (near) real-time transmission of observational data from Polar Regions (e.g. in cooperation with EUMETSAT, Copernicus, ESA, WMO, SCAR). A scoping study on operational informatics for the Polar Regions, including communication systems and standards, improving links between observations and models and enabling interaction and interoperability of measurements, could be a first step,
- Resources for the coordination and standardisation of observation protocols, especially for the design and implementation of standardised data management to ensure interoperability and to make the best use of existing and accumulating data sets,
- Research that addresses the identification of interdisciplinary observations (e.g. observations that are useful and necessary across domains/activities),
- Resources to better understand the added value of co-production of knowledge and to develop guidelines on how this can be best done, in particular:
  - Investments to understand how co-production of knowledge is best designed and practiced. It is important to understand what practices and processes should be used, and which knowledge producers play what roles and what kind of products (e.g. knowledge, people, and socio-ecological arrangements) emerge as a result (Miller and Wyborn, 2018).
  - Funding is required to increase the ways of meaningful interaction between research groups, local and Indigenous communities, and other stakeholders when designing research projects and management plans for future human activities. A mix of joint pilot and feasibility studies could be a way forward. However, it should be noted that long-term involvement, beyond the 3-5 years of the normal lifespan of research projects, is needed to ensure that there is a possibility to build trust amongst all the parties (EU-PolarNet Deliverable 4.15).
- Research that uses participatory methods and tests possible future scenarios and could make an important contribution to developing and maintaining the capacity for effective and sustainable management and informed decision-making in rapidly changing Polar Regions (Carson, et al. 2019).

VI. References

ACIA. 2005. Arctic Climate Impact Assessment. ACIA Overview report. Cambridge University Press. 1020 pp.

Ackoff RL. 1989. From data to wisdom: Presidential address to ISGSR, June 1988. Journal of Applied Systems Analysis, 16, 3-9.

AHDR, 2004. Arctic Human Development Report. Stefansson Arctic Institute, Akureyri, Iceland.

Arctic Council. 2009. Arctic Marine Shipping Assessment 2009 Report.

Arctic Council. 2016. Arctic resilience report. (Ed. M Carson and G Peterson). Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm, Sweden.

Armitage D, Berkes F, Dale A, et al. 2011. Co-management and the co-production of knowledge: Learning to adapt in Canada's Arctic. Global Environmental Change, 21(3), 995-1004.

Avango D, Nilsson AE, and Roberts P. 2013. Assessing Arctic Futures: Voices, Resources and Governance. The Polar Journal 3(2):431-446.

Baer K, Latola K, Scheepstra A. 2019. Tell us how to engage you! Asking polar stakeholders about their engagement preferences. Polar Record, 55(4), 245-250. DOI: 10.1017/S0032247419000354

Beaton MC, Hirshberg DB, Maxwell GR, and Spratt J. 2019. Including the North: A Comparative Study of the Policies on Inclusion and Equity in the Circumpolar North. Rovaniemi, FI: University of Lapland.

Bennett JR, Shaw JD, Terauds A, et al. 2015. Polar lessons learned: long-term management based on shared threats in Arctic and Antarctic environments. Frontiers in Ecology and the Environment 13:316-324.

Carson M, Hughes KA (authors). Barr S, Hansen AM, Meyer B, Saxinger G, Thinghuus M, Nolan J, Baer K (lead contributors). 2019. EU-PolarNet White Paper No. 3: Managing human impacts, resource use and conservation of the Polar Regions. www.eu-polarnet.eu

Chan FT, Stanislawczyk K, Sneekes AC, et al. 2019. Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. Global change biology 25:25-38.

Csonka Y, and Schweitzer P. 2004. Societies and Cultures: Change and Persistence. In Arctic Human Development Report. Akureyri: Stefansson Arctic Institute: 45-68.

Dessai S, Bhave A, Birch C, et al. 2018. Building narratives to characterise uncertainty in regional climate change through expert elicitation. Environmental Research Letters 13(7): 074005. DOI: 10.1088/1748-9326/aabcdd

Díaz S, Demissew S, Carabias J, et al. 2015. The IPBES conceptual framework — connecting nature and people. Current Opinion in Environmental Sustainability, 14, 1-16. DOI: 10.1016/j.cosust.2014.11.002

Fuentes V, Alurralde G, Meyer B, et al. 2016. Glacial melting: an overlooked threat to Antarctic krill. Scientific reports 6:27234.

Hacquebord L, Avango D. 2009. Settlements in an Arctic Resource Frontier Region. Arctic Anthropology 46(1-2):25-39.

Heleniak T, Turunen E, and Wang S. 2020. Demographic Change in the Arctic. In Ken Coates and Carin Holroyd (Eds.). Palgrave Handbook on Arctic Policy Palgrave Macmillan.

Heleniak T. 2015. Arctic Populations and Migration. Arctic Human Development Report, pp. 53-104, Copenhagen: Nordic Council of Ministers

Heleniak T. 2020. The Future of the Arctic Populations. Polar Geography, DOI: 10.1080/1088937X.2019.1707316

Hirshberg D. and Petrov AN. 2015. Education and Human Capital. In: Arctic Human Development Report: Regional Processes and Global Linkages. Larson, J and Fondahl, G. (Eds.). Copenhagen: Nordic Council of Ministers.

Hovelsrud GK, Amundsen H, Dannevig H, et al. 2017. Adaptation options. In: AMAP. Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area. Arctic Monitoring and Assessment Programme (AMAP), Oslo, p. 219–252.

Hughes KA, Pescott OL, Peyton J, et al. 2020. Invasive non-native species likely to threaten biodiversity and ecosystems in the Antarctic Peninsula region. Global change biology.

IPCC, 2019. Summary for Policy-makers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Jungsberg L, Turunen E, Heleniak T, et al. 2019. Atlas of population, society and economy in the Arctic, Nordregio Working Paper 2019:3, DOI: doi.org/10.30689/WP2019:3.1403-2511.

Larsen JN and Fondahl, G. (Eds.). 2014. Arctic Human Development Report. Regional Processes and Global Linkages, II. ed. Nordic Council of Ministers, Copenhagen.

Larsen JN, Schweitzer P, Petrov A. 2014. Arctic Social Indicators II: Implementation. TemaNord 2014:568. Copenhagen: Nordic Council of Ministers. DOI: 10.6027/TN2014-568

Larsen, JN, Schweitzer P, Fondahl G, (Eds.). 2010. Arctic Social Indicators. TemaNord 2010:519. Copenhagen: Nordic Council of Ministers. DOI: 10.6027/TN2014-567

Mauser W, Klepper G, Rice M, et al. 2013. Transdisciplinary global change research: the co-creation of knowledge for sustainability. Current Opinion in Environmental Sustainability, 5(3), 420-431. DOI: 10.1016/j.cosust.2013.07.001

McCarthy AH, Peck LS, Hughes KA, Aldridge DC. 2019. Antarctica: The final frontier for marine biological invasions. Global change biology 25:2221-2241.

Miller CA, Wyborn C. 2018. Co-production in global sustainability: Histories and theories. Environmental Science & Policy. DOI: 10.1016/j.envsci.2018.01.016

Nalau J, Becken S, Schliephack J, et al. 2018. The role of Indigenous and traditional knowledge in ecosystem-based adaptation: a review of the literature and case studies from the Pacific Islands. Weather, Climate, and Society, 10(4), 851-865.

Pershing AJ, Record NR, Franklin BS, et al. 2019. Challenges to natural and human communities from surprising ocean temperatures. Proceedings of the National Academy of Sciences 116:18378-18383.

Rogers A, Frinault B, Barnes D, et al. 2019. Antarctic futures: an assessment of climate-driven changes in ecosystem structure, function, and service provisioning in the Southern Ocean. Annual review of marine science 12.

Schweitzer P, Povoroznyuk O, and Schiesser S. 2017. Beyond Wilderness: Towards an Anthropology of Infrastructure and the Built Environment in the Russian North. The Polar Journal 7(1):58-85.

Schweitzer P, Povoroznyuk, O. 2019. A Right to Remoteness? A Missing Bridge and Articulations of Indigeneity along an East Siberian Railroad. Social Anthropology 27(2):236-252.

Schweitzer P, Sköld P, and UlturgashevaO. 2014. Cultures and Identities. In: Arctic Human Development Report II: Regional Processes and Global Linkages. JN. Larsen, G. Fondahl, H. Rasmussen (Eds). Copenhagen: Nordic Council of Ministers: 105-150.

Siegert M, Løset S (authors). Carlson D, Dañobeitia J, Fleming A, Gunnarsson B, Johnsen NA, Ørbæk J B, Biebow N (lead contributors). 2019. EU-PolarNet White Paper No. 5: Advancing operational informatics for Polar Regions. www.eu-polarnet.eu

Sköld P, Liggett D (authors). Smieszek M, Evengård B, Staffansson J, Bastmeijer K, Muir M, Latola K, Scheepstra A (lead contributors). 2019. EU-PolarNet White Paper No.4. The road to the desired states of social-ecological systems in the Polar Regions. www.eu-polarnet.eu.

Sørensen LL, De Santis L (authors). Hagen JO, Holm LK, Huybrechts P, Orsi A, Stroeve J, Vieira G, van den Broeke M, Barbante C, Houssais MN (lead contributors). 2019. EU-PolarNet White Paper No. 1: The coupled polar climate system: Global context, predictability and regional impacts. www.eu-polarnet.eu

Statistics Norway. 2015. The Economy of the North. Statistics Norway, Kongsvinger.

Stepien A, Koivurov, T, Kankaanpää P. (Eds.). 2014. The Strategic Assessment of Development of the Arctic: An assessment conducted for the European Union. Report. Arctic Centre, Rovaniemi.

Tengö M, Brondizio ES, Elmqvist T, et al. 2014. Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach. Ambio, 43(5), 579–591. DOI: 10.1007/s13280-014-0501-3

VII. Acronyms

AC	Arctic Council
AHDR	Arctic Human Development Report
ATCM	Antarctic Treaty Consultative Meetings
ATS	Antarctic Treaty System
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCAS	Convention for the Conservation of Antarctic Seals
CEP	Antarctic Treaty Consultative Meeting´s Committee for Environmental Protection
COP21	21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC)
CRAMRA	Convention on the Regulation of Antarctic Mineral Resource Activities
DST	Decision Support Tool
ECV	Essential Climate Variable
EEZ	Exclusive Economic Zone
EPRP	Integrated European Polar Research Programme
ESA	European Space Agency
ESM	Earth System Model
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAIR	Findable, Accessible, Interoperable, Reusable
GCOS	Global Climate Observing System
HPC	High-Performance Computing
IA	Impact Assessment
IASC	International Arctic Science Committee
ICT	Information and Communications Technology
IMO	International Maritime Organization
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel for Climate Change
IPR	Intellectual Property Rights
IWC	International Whaling Commission
KQ	Key Question
MOOC	Massive Open Online Course
NGO	Non-governmental organisation
NNMS	Non-Native Marine Species
NNS	Non-Native Species
NWP	Numerical Weather Prediction
OH	One Health
OPEC	Organization of the Petroleum Exporting Countries
PSI	Public Sector Information
R&D	Research and Development
R2O	Research-to-Operations
RN	Research Need
SAON	Sustaining Arctic Observing Networks
SAR	Search and Rescue
SAS	Synoptic Arctic Survey
SCAR	Scientific Committee on Antarctic Research
SDG	Sustainable Development Goal
SES	Socio-Ecological Systems
SLO	Social License to Operate
SOOS	Southern Ocean Observing System
UN	United Nations
UN-SDGs	United Nations Sustainable Development Goals
WAP	West Antarctic Peninsula
WCRP	World Climate Research Program
WMO	World Meteorological Organization

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Photo: Ronald JW Visser

APPENDIX I. Input material to the EPRP and drafting process

I. EU-PolarNet Deliverables of relevance to the EPRP

WORK PACKAGE 1. International Integration and Policy Guidance:

D1.4: Minutes of workshop with international partners & stakeholders, at IASC/SCAR Meeting.
D1.8. Minutes of a workshop with international partners and stakeholders at ASSW.
D1.9: Minutes of workshop with international partners & stakeholders at SCAR Open Science Conference, Kuala Lumpur, Malaysia, 24 August 2016.
D1.12: Minutes of workshop with international partners & stakeholders at a relevant Arctic Conference.
D1.15: Minutes of AMAP/EU-PolarNet Stakeholder Workshop on Research Needs on Climate-related Effects on the Arctic Cryosphere and Adaptation Options.
D1.19: Minutes of workshop with international partners & stakeholders, at a relevant Arctic Conference.

WORK PACKAGE 2. Polar Research for Science and Society:

D2.1: Report on prioritised objectives in Polar research.
D2.3: Inventory of existing monitoring and modelling programmes.
D2.4: First progress report on science -stakeholder Interaction.
D2.5: Strategic analysis of monitoring and modelling programmes.
D2.6: Roadmap for optimisation of monitoring and modelling programmes.
D2.7: Second progress report on science -stakeholder Interaction.
D2.8: Set of white papers addressing priority questions in polar research and targeting funding agencies and policy makers.

WORK PACKAGE 3. Infrastructures, Facilities and Data:

D3.1: Survey of the existing Polar Research data systems and infrastructures, including their architectures, standard/good practice baselines, policies and scopes.
D3.2: European Polar Infrastructure Catalogue.
D3.3: Survey of existing use of space assets by European polar operators, including recommendations for improved coordination.
D3.4: Survey of polar commercial infrastructure.
D3.5: Data management recommendations for polar research data systems and infrastructures in Europe.
D3.6: Gap analysis highlighting the technical and operational requirements of the European Polar Research Programme for satellite applications.
D3.8: White paper on European polar data accessibility.

WORK PACKAGE 4. Interaction with Stakeholders:

D4.5: A stakeholder map.
D4.9: Minutes of stakeholder dialogue at an Arctic Conference.
D4.11: Minutes of stakeholder dialogue at Arctic Frontiers Conference.
D4.13: Minutes of stakeholder dialogue at Arctic Frontiers Conference.
D4.14: Completed stakeholder consultations: report on the needs, gaps and opportunities produced.
D4.15: White paper on status of stakeholder engagement in polar research.

II. Desk study on European Polar research priorities: input documents

The desk study consisted of a comprehensive analysis which was conducted based on the information extracted from more than 150 national and international Polar research strategy documents (see the list). The information was further organised along twelve broad, overarching topics. Relevant societal challenges were connected to each of these overarching topics in order to ensure that research priorities are fitted to societal needs. The results of the study contributed to a synthesis document: "Report on prioritised objectives in Polar research"; which was published as Deliverable 2.1 on the EU-PolarNet website.

III. Public online consultations

The different EU-PolarNet surveys were published online on the EU-PolarNet website, but also announced through newsletters and targeted emails. These were sent out to a list of recipients established from a preliminary stakeholder mapping exercise.

III. 1. Consultation within the international scientific community (February 16 - March 9, 2016)

The survey reached out to the research community to collect its view on the previous desk study. The synthesis report, based on 236 replies from 23 countries, can be found in EU-PolarNet public Deliverable D2.1: Report on prioritised objectives in Polar Research.

Questions:

- Are your national priorities for Polar research reflected in our summary?
  - (Well, Fair, Poor)
- Do you feel there is a societal challenge that has not been addressed in our document?
  - (Yes, No) If yes, please indicate, which societal challenge is missing.
- What are the most important topics for European Polar research that should be the subject of strategic discussions with stakeholders, in order to develop future funding priorities?
  - Sustainable and safe management of the Polar Regions with major concern to the Arctic Population well-being;
  - Climatic connection between high and middle latitudes
- Have we missed looking at any important document?
  - (Yes, No) If yes, please indicate which document(s) is/are missing and the web link to access it/them or a full reference.
- Any further comments

III. 2. Stakeholder engagement questionnaire, published online (April - November, 2017)

The questionnaire aimed at determining which potential barriers stakeholders have experienced or are expecting to encounter when engaging in Polar research projects. The specific objectives of the different questions were to identify individuals and organisations with an interest in engaging in Polar research projects, to find out what motivates stakeholders to engage in polar projects, and to learn about the way they would like to get involved.

Questions:

- Which of the following stakeholder groups do you associate with?
- On which level do you generally operate? (local, national, regional, international)
- Which polar topic(s) is/are of interest to you?
- What would your motivation be to get engaged in research projects in the Polar Regions?
- At what stage of a research project would you be most interested to get involved?
- How would you best be involved in a research project?
- Which barriers do you think you might encounter if you engaged in a scientific project?

Results based on 302 replies were analysed in a research note: Tell us how to engage you! Asking polar stakeholders about their engagement preferences by Baer et al., 2019 and provided input to a White paper on status of stakeholder engagement in Polar research as EU-PolarNet public deliverable D4.15.

III. 3. Stakeholder consultation on research priorities (April 19 - June 2, 2017)

The survey featured one single key question: What are the most important topics in relation to your work and/or everyday life (either locally, nationally, or internationally) in the Polar Regions that should be solved by future research?

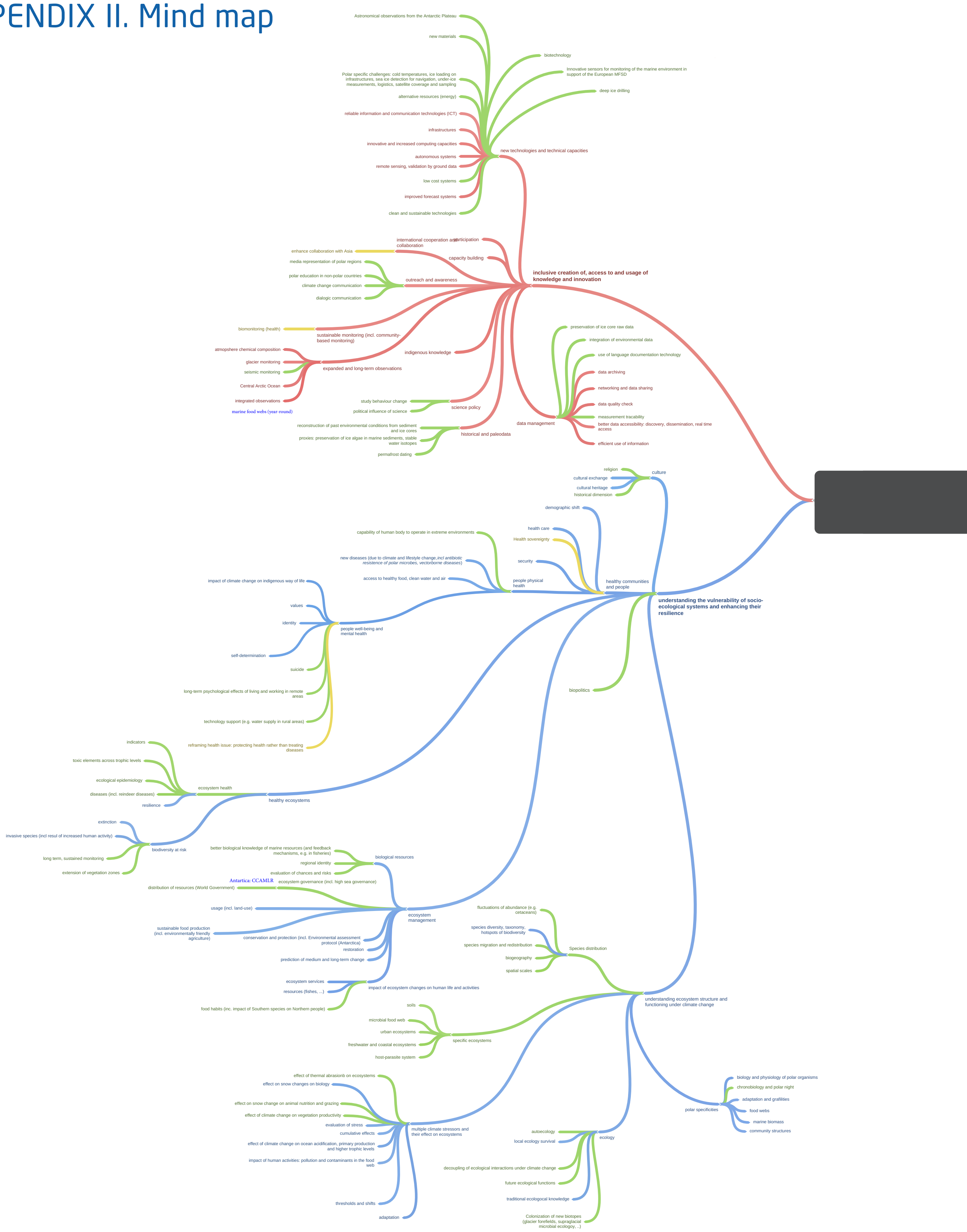
Respondents were asked to indicate up to three priorities and to categorise their topics under one of five predefined overarching themes: People and societal issues; Climate and cryosphere; Sustainable resources and human impact; Polar biology, ecology and biodiversity; and New technology. These overarching themes were the result of the previous prioritisation exercise that was conducted together with the research community. The synthesis report, based on more than 500 replies from 36 countries, can be found on the EU-PolarNet website.

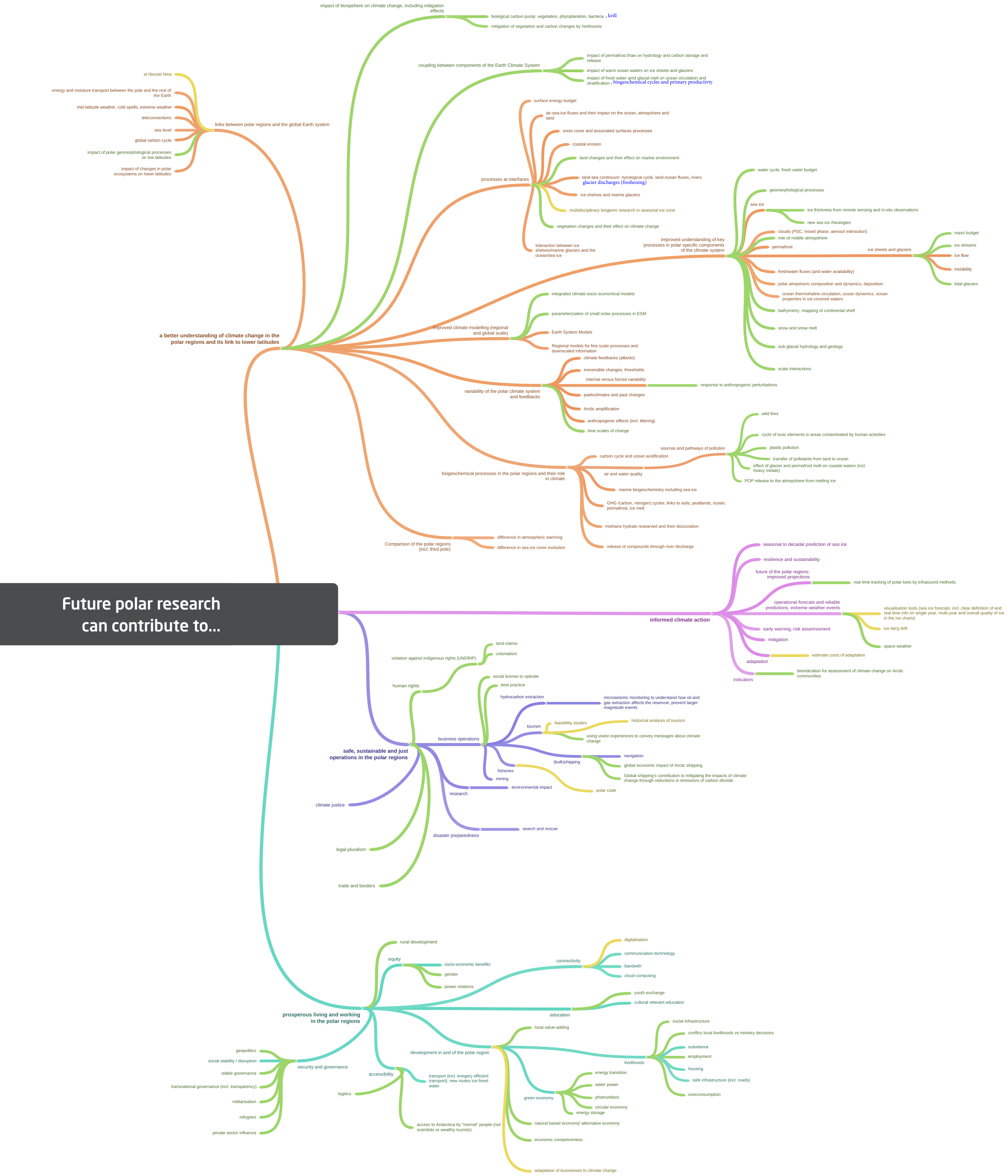
IV. EPRP drafting and review process

Preliminary drafts of the EPRP chapters were produced by each chapter expert group during the summer 2019. These drafts were discussed together for overlaps and missing issues during an EPRP drafting workshop in September 2019 in Sandbjerg Manor (Denmark). Following this meeting, a first draft of the six chapters was crafted.

First-order chapter drafts were then reviewed by the EPRP Working Group and comments were sent to the lead/co-lead authors for chapter revision. At the same time, the general sections of the EPRP document were being drafted so that a full EPRP draft could be issued for external review together. Within the project, the EU-PolarNet consortium (list of members available on the EU-PolarNet website) and Executive Board have been involved in the review process. Outside the project, the review was undertaken by the EU-PolarNet Stakeholder Panel, the EU-PolarNet External Expert Advisory Board and several external reviewers selected for their high-level expertise in Polar questions.

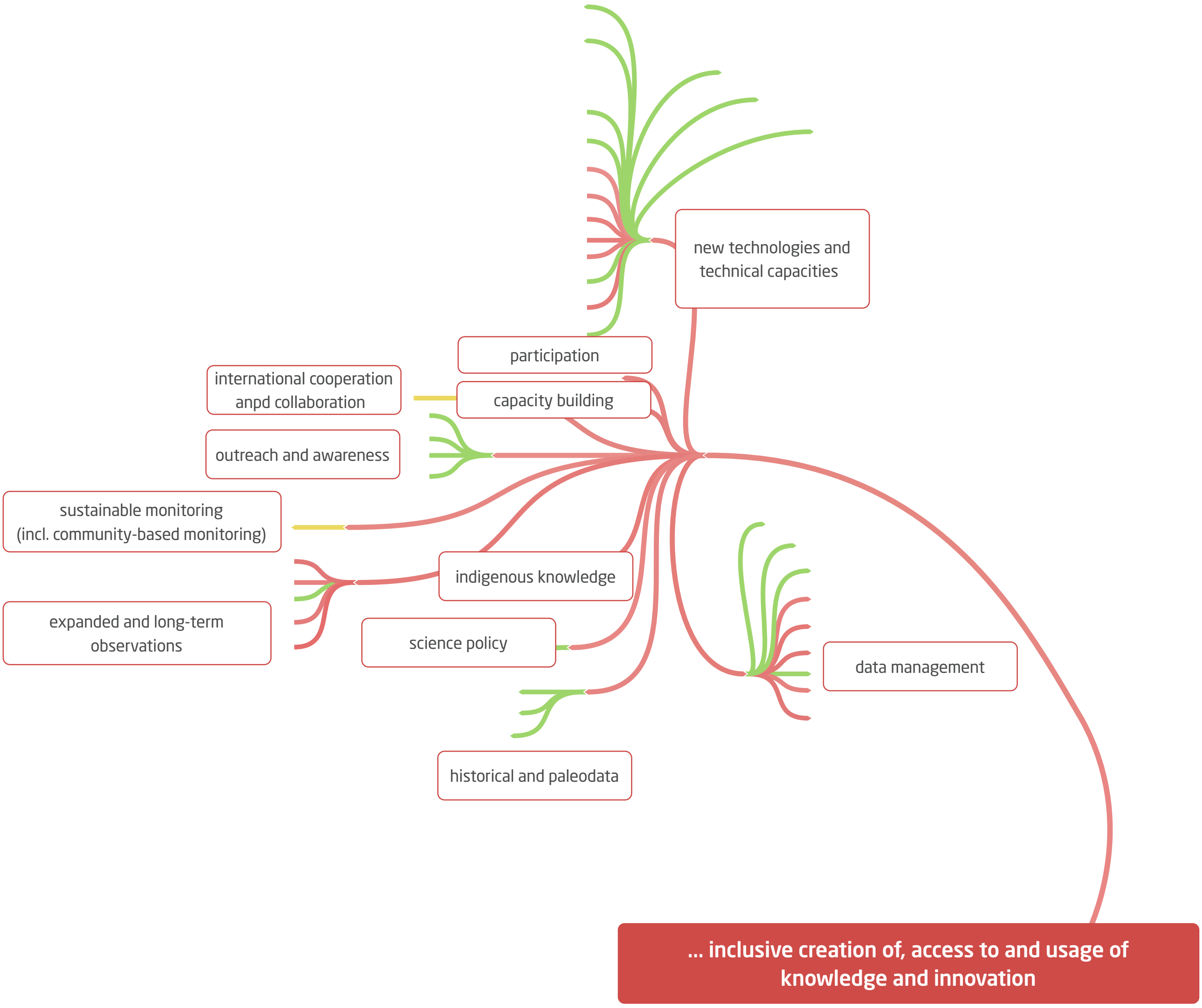
APPENDIX II. Mind map



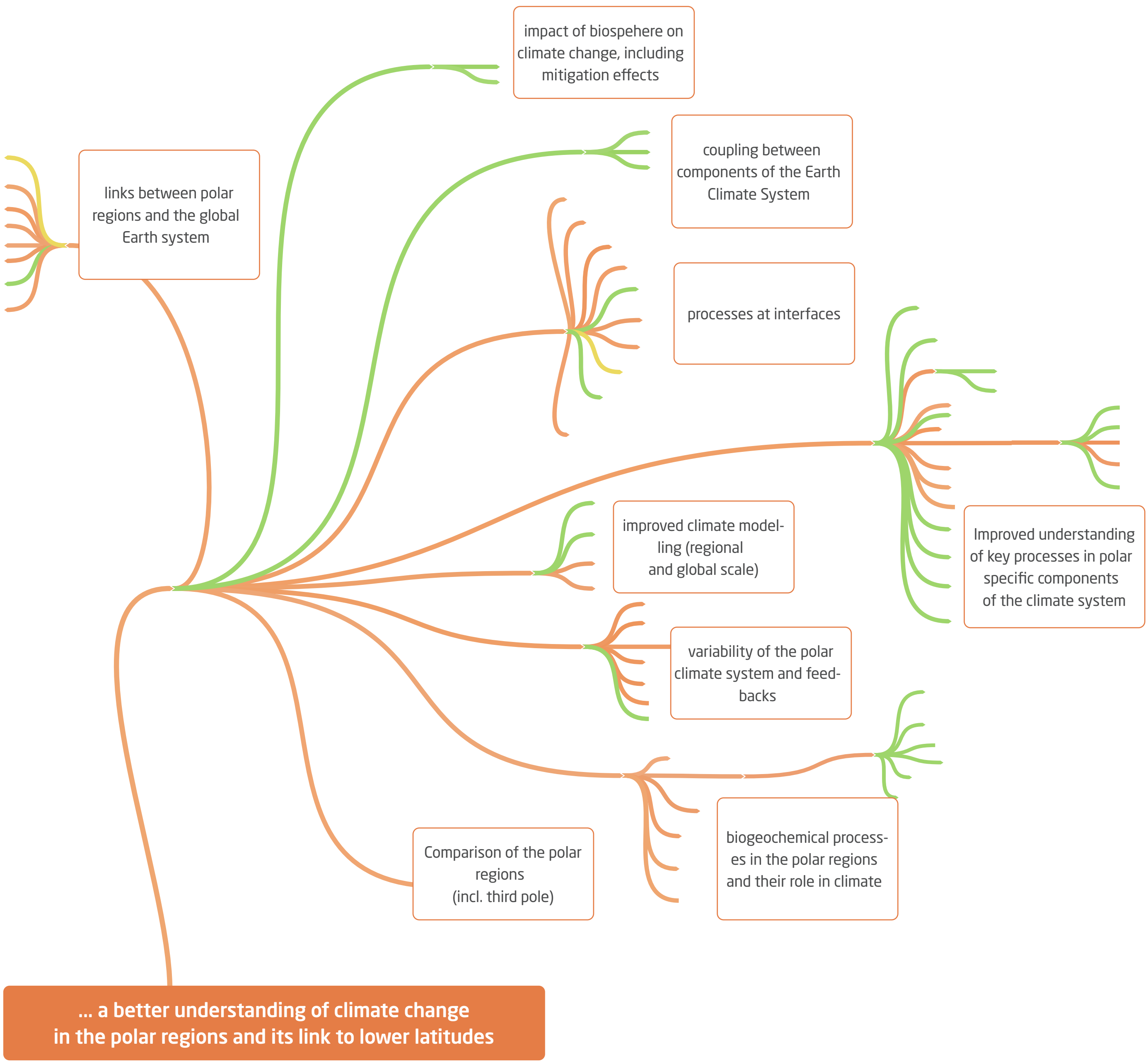


Future polar research can contribute to...
a better understanding of climate change in the polar regions and its link to lower latitudes
links between polar regions and the global Earth system
el Nino/el Nina
energy and moisture transport between the pole and the rest of the Earth
mid-latitude weather, cold spells, extreme weather
teleconnections
sea level
global carbon cycle
impact of polar geomorphological processes on low latitudes
impact of changes in polar ecosystems on lower latitudes
impact of biospehere on climate change, including mitigation effects
biological carbon pump: vegetation, phytoplankton, bacteria
krill
mitigation of vegetation and carbon changes by herbivores
coupling between components of the Earth Climate System
impact of permafrost thaw on hydrology and carbon storage and release
impact of warm ocean waters on ice sheets and glaciers
impact of fresh water amd glacial melt on ocean circulation and stratification
biogeochemical cycles and primary productivity
processes at interfaces
surface energy budget
air-sea-ice fluxes and their impact on the ocean, atmosphere and land
snow cover and associated surfaces processes
coastal erosion
land changes and their effect on marine environment
land-sea continuum: hyrological cycle, land-ocean fluxes, rivers
glacier discharges (freshening)
ice shelves and marine glaciers
multidisciplinary longterm research in seasonal ice zone
vegetation changes and their effect on climate change
Interaction between ice shelves/marine glaciers and the ocean/sea ice
Improved understanding of key processes in polar specific components of the climate system
water cycle, fresh water budget
geomorphological processes
sea ice
ice thickness from remote sensing and in-situ observations
new sea ice rheologies
clouds (PSC, mixed phase, aerosol interaction)
role of middle atmosphere
permafrost
ice sheets and glaciers
mass budget
ice streams
ice flow
instability
tidal glaciers
freshwater fluxes (and water availability)
polar atmpsheric composition and dynamics, deposition
ocean thermohaline circulation, ocean dynamics, ocean properties in ice-covered waters
bathymetry, mapping of continental shelf
snow and snow melt
sub-glacial hydrology and geology
scale interactions
improved climate modelling (regional and global scale)
integrated climate-socio economical models
parameterization of small sclae processes in ESM
Earth System Models
Regional models for fine scale processes and downscaled information
variability of the polar climate system and feedbacks
climate feedbacks (albedo)
irreversible changes, thresholds
internal versus forced variability
response to anthropogenic perturbations
paelocllmates and past changes
Arctic amplification
anthropogenic effects (incl. littering)
time scales of change
biogeochemical processes in the polar regions and their role in climate
carbon cycle and ocean acidification
sources and pathways of pollution
wild fires
cycle of toxic elements in areas contaminated by human activites
plastic pollution
transfer of pollutants from land to ocean
effect of glacier and permafrost melt on coastal waters (incl. heavy metals)
POP release to the atmosphere from melting ice
air and water quality
marine biogeochemistry including sea ice
GHG (carbon, nitrogen) cycles, links to soils, peatlands, ocean, permafrost, ice melt
methane hydrate researved and their dissociation
release of compounds through river discharge
Comparison of the polar regions (incl. third pole)
difference in atmospheric warming
difference in sea ice cover evolution
informed climate action
seasonal to decadal prediction of sea ice
resilience and sustainability
future of the polar regions: improved projections
real time tracking of polar lows by infrasound methods
operational forecasts and reliable predictions, extreme weather events
visualisation tools (sea ice forecast, incl. clear definition of and real time info on single year, multi-year and overall quality of ice in the ice charts)
ice berg drift
space weather
early warning, risk assemssment
mitigation
adaptation
estimate costs of adaptation
indicators
bioindication for assessment of climate change on Arctic communities
safe, sustainable and just operations in the polar regions
human rights
violation against indigenous rights (UNDRIP)
land-claims
colonialism
business operations
social license to operate
best practice
hydrocarbon extraction
microseismic monitoring to understand how oil and gas extraction affects the reservoir, prevent larger magnitude events
tourism
feasibility studies
historical analysis of tourism
using visitor experiences to convey messages about climate change
(bulk)shipping
navigation
global economic impact of Arctic shipping
Global shipping's contribution to mitigating the impacts of climate change through reductions in emissions of carbon dioxide
fisheries
mining
polar code
research
environmental impact
climate justice
disaster preparedness
search and rescue
legal pluralism
trade and borders
prosperous living and working in the polar regions
equity
rural development
socio-economic benefits
gender
power relations
connectivity
digitalisation
communication technology
bandwith
cloud-computing
education
youth exchange
cultural relevant education
development in and of the polar region
local value-adding
livelihoods
social infrastructure
conflics local livelihoods vs ministry decisions
substance
employment
housing
safe infrastructure (incl. roads)
overconsumption
green economy
energy transition
water power
photovoltaic
circular economy
energy storage
natural based economy/ alternative economy
economic competiveness
adaptation of businesses to climate change
security and governance
geopolitics
social stability / disruption
stable governance
transnational governance (incl. transparency)
militarisation
refugees
private sector influence
accessibility
logitics
transport (incl. enegery efficient transport), new routes ice-freed water
access to Antarctica by "normal" people (nor scientists or wealthy tourists)

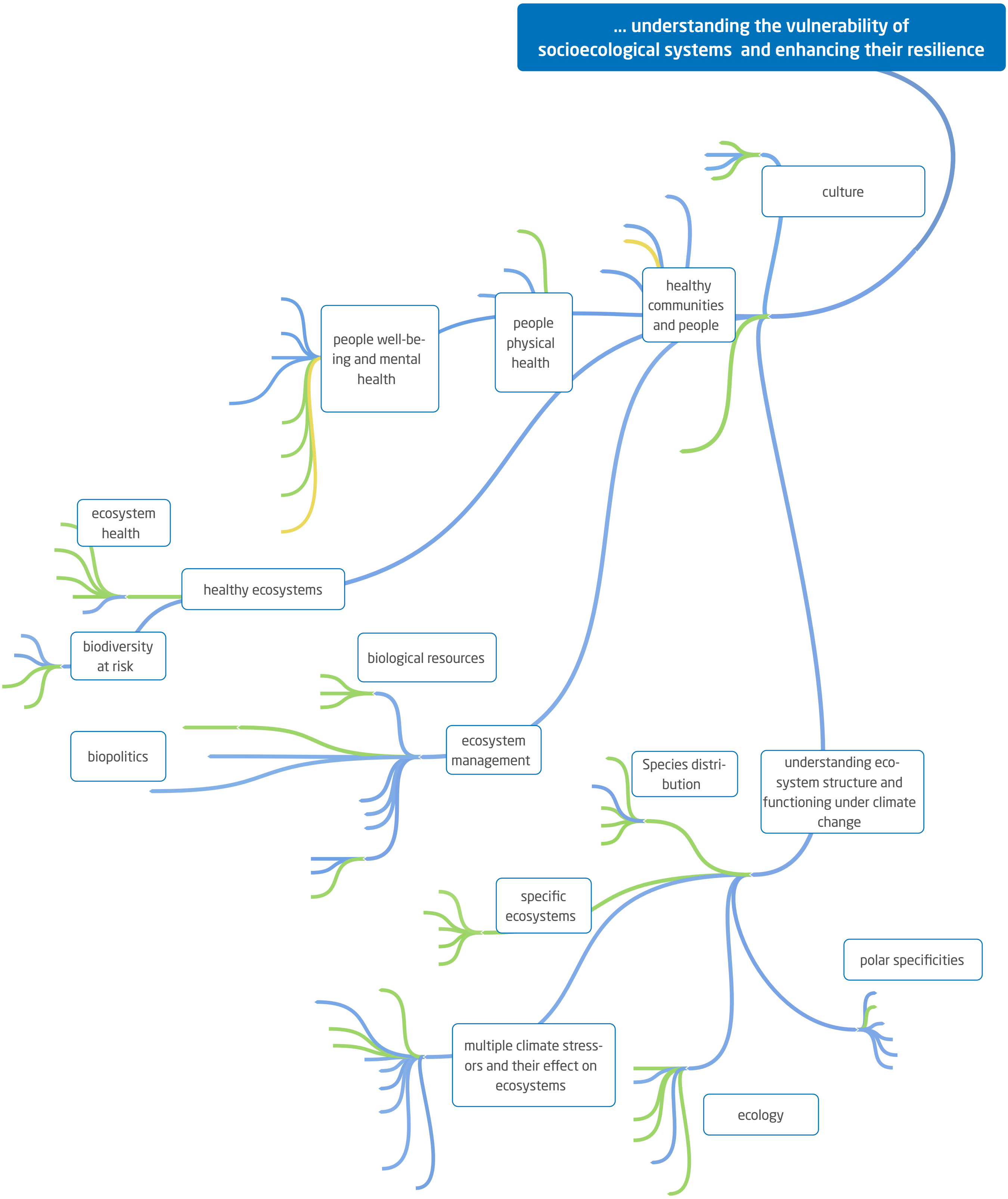
Future polar research can contribute to...



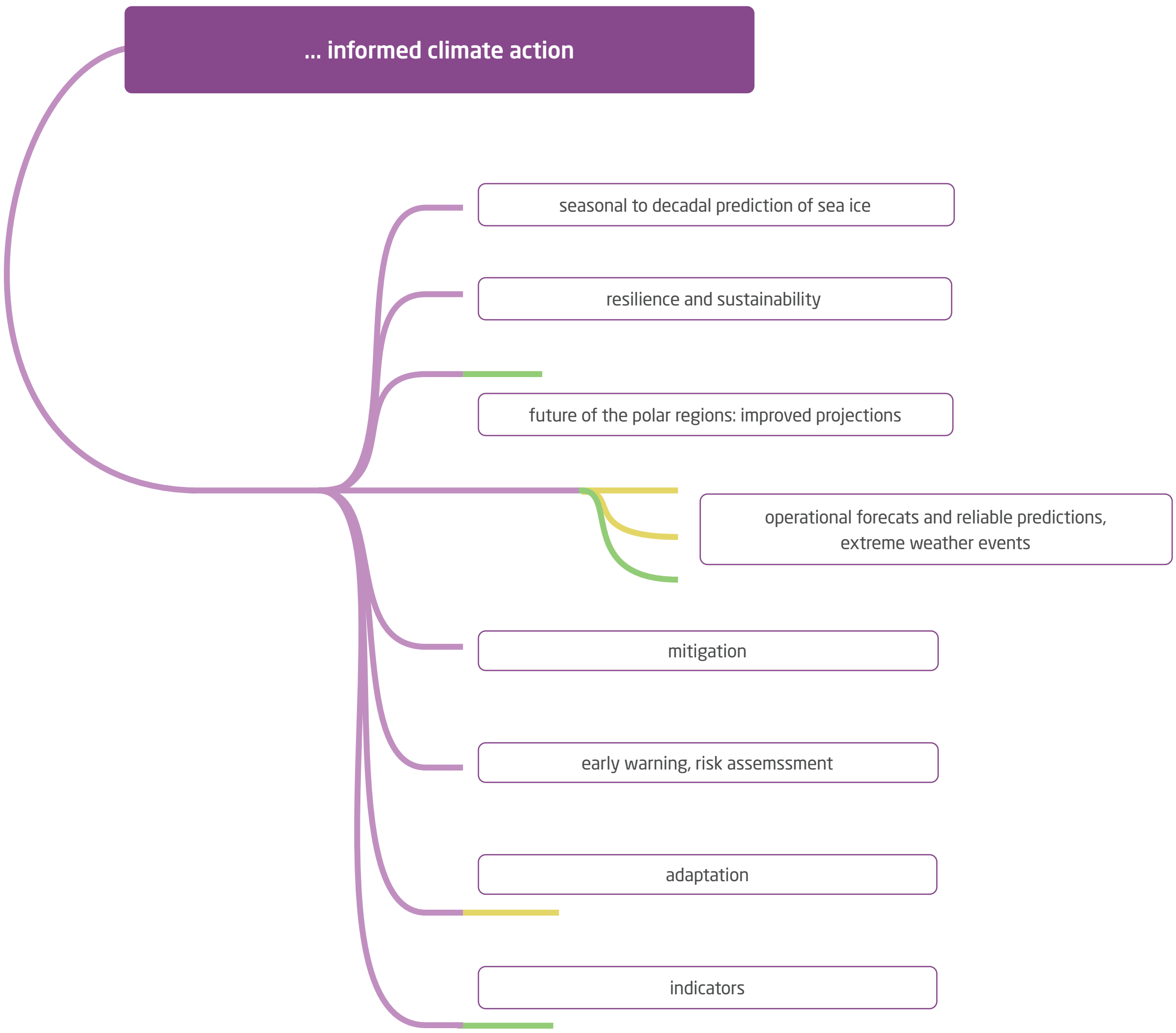
Future polar research can contribute to...

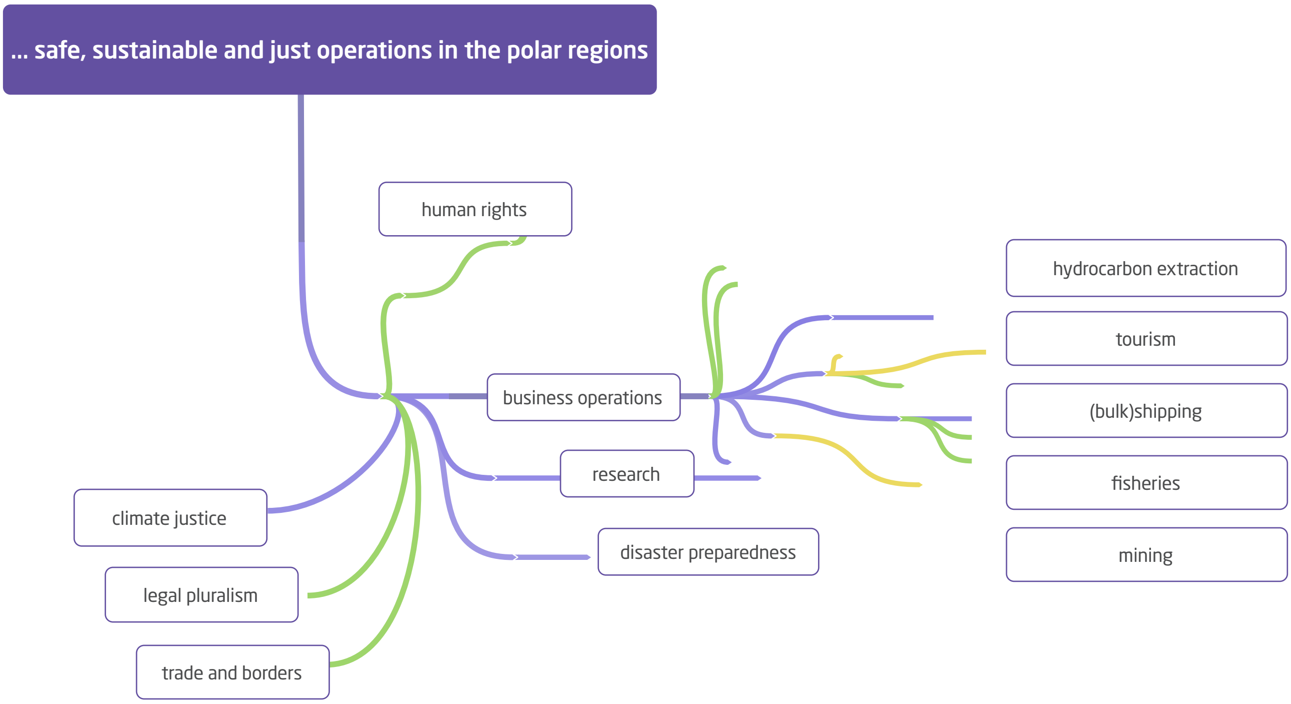


Future polar research can contribute to...

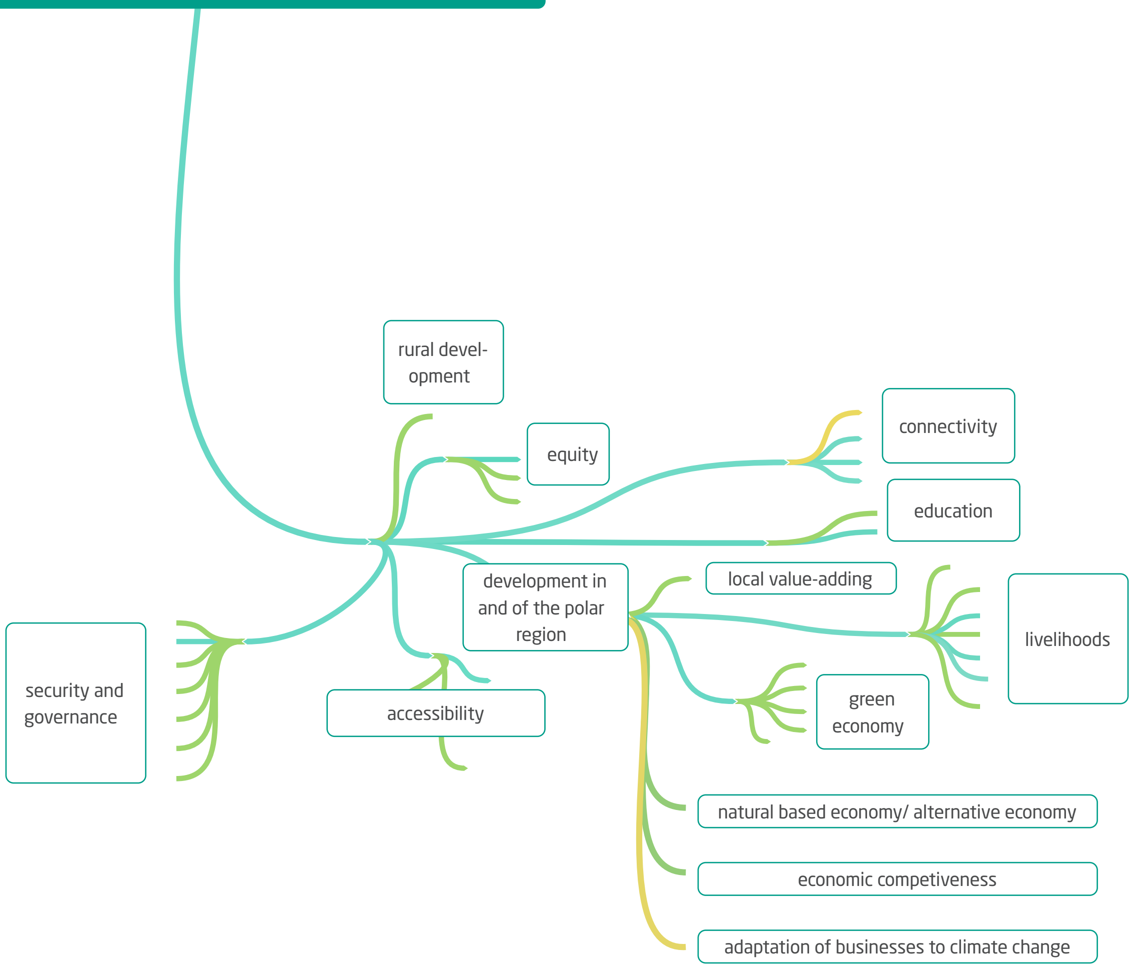


Future polar research can contribute to...




… safe, sustainable and just operations in the polar regions
human rights
business operations
research
disaster preparedness
climate justice
legal pluralism
trade and borders
hydrocarbon extraction
tourism
(bulk)shipping
fisheries
mining

... prosperous living and working in the polar regions



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Research Need 3. Resilient socio-ecological systems

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This document is based on the outcomes of the EU funded project EU-PolarNet (Grant Agreement No.: 652641). Sincere thanks to the Alfred Wegener Institute (Germany), the EU-PolarNet External Experts Advisory Board, and the whole EU-PolarNet Consortium.

Citation: EU-PolarNet (2020) Integrated European Polar Research Programme (Eds. Velázquez D, Houssais MN, Biebow N). 91 pp. Bremerhaven: Alfred Wegener Institute.

Imprint

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Tel.: +49 (0)471/4831-1011
Design: www.glinsmann-design.de
Cover Photo: Ronald JW Visser
Funding: EU-PolarNet has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 652641.

Photo: Annette JM Scheepstra

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EU-PolarNet has received funding from the
European Union's Horizon 2020 research and innovation
programme under grant agreement No 652641.