RESEARCH AGENDA
POLAR REGIONS IN TRANSITION

Concept Paper of the MARE:N Advisory Board | Executive Summary

CONTENTS

1 INTRODUCTION		**4**
2 RESEARCH TOPICS		**6**
2.1	The polar amplification of climate change	6
2.2	The ice sheets: tipping points for the sea level	7
2.3	The Southern Ocean as a reservoir of heat and carbon	8
2.4	The future of permafrost ecosystems	9
2.5	Ecosystems in polar oceans under climate stress	10
2.6	Antarctic protection concepts	11
2.7	Science for sustainable development in the Arctic	12
2.8	The impact of human activities on Arctic ecosystems	13
3 CROSS-CUTTING TOPICS AND RESEARCH ENVIRONMENT		**14**
3.1	Model development	15
3.2	Future projections and forecasts	16
3.3	Instruments and observation systems	16
3.4	Promotion of young researchers	17
3.5	Knowledge transfer and communication	18
CONTRIBUTING AUTHORS		**20**

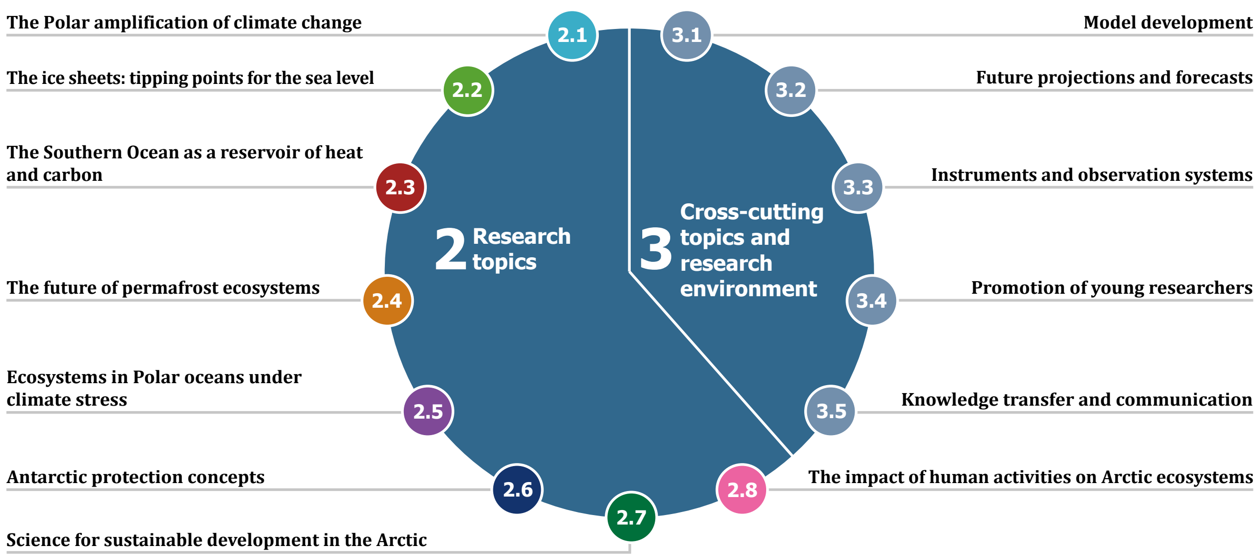
1 Introduction

Effective, internationally coordinated polar research is an indispensable prerequisite for a better understanding of the processes underlying change in the polar regions and for evaluating its local, regional and global consequences. Multiscale observations and progress in climate and Earth system models are needed to foster understanding of polar processes and to increase the reliability of projections up to the end of the 21st century and beyond. To achieve this, polar research needs to be internationally coordinated. The resulting findings should be used and communicated to develop options for the sustainable development of the polar regions together with key figures from politics, business and society and to support informed decision-making. In Arctic research, cooperation and dialogue with the local communities and Indigenous peoples are essential. At the same time, awareness in our society needs to be raised to preserve the uniqueness and beauty of the polar regions for future generations. Polar research is a joint task that relies on the interaction of all disciplines and in which researchers from many countries work together. However, research in the extreme polar regions can only be carried out with major logistical effort. Joining forces at international level facilitates building and operating complex and cost-intensive infrastructure.

German polar research is excellently integrated in international networks. Numerous delegates represent Germany, for example, in the Scientific Committee on Antarctic Research (SCAR), the International Arctic Science Committee (IASC), and the World Meteorological Organisation (WMO) committees with a polar focus. More precisely, SCAR develops and coordinates science programmes in Antarctica and the Southern Ocean, and as a non-governmental organisation advises the signatory states to the Antarctic Treaty and other organisations such as the Intergovernmental Panel on Climate Change (IPCC). The main tasks of the IASC are to promote international cooperation in Arctic research. The German Arctic Office at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research serves as an information and cooperation platform for German Arctic stakeholders from science, politics and business. It raises awareness of German involvement in the Arctic at national and international level.

The research programme of the Federal Government of Germany "MARE:N – Coastal, Marine and Polar Research for Sustainability" aims at the close integration of funding instruments and engagement of science, society, politics and business stakeholders. The resulting synergies will be used to meet the needs of forward-looking coastal, marine and polar research. MARE:N research activities are integrated in international programmes of the United Nations (UN) and the European Union. They contribute to the development of international strategies for the protection and sustainable development of coastal, marine and polar regions, and in turn support the implementation of both the European directives and the UN 2030 Agenda for Sustainable Development.

The Federal Ministry of Education and Research (BMBF) has commissioned a dedicated Advisory Board to develop a polar research concept paper. The scientific expert group identified eight research topics of high relevance to society. These topics are complemented by two cross-cutting topics and the required research environment (see illustration below).



The concept paper "Polar Regions in Transition" will enable the Federal Government to address the respective future scientific needs in pending political processes and national, European and international frameworks. The present executive summary offers an overview of the German polar research strategy and forms the basis for national and international research calls of the next decade. The BMBF announced additional investments of more than 20 million euros in polar research by 2025.

Arctic Council Ministerial, Reykjavík 2021

2 Research topics

2.1 THE POLAR AMPLIFICATION OF CLIMATE CHANGE

Guiding questions:

- What are the essential processes for polar amplification (local ↔ remote driven, dynamic ↔ thermodynamic, atmosphere ↔ ocean, sea ice and land, Arctic ↔ Antarctic)?
- How well can weather forecasting, climate and Earth system models represent the major processes and phenomena in the polar regions?
- What development paths are possible for polar amplification in the 21st century and beyond?
- What are the impacts of polar climate change on climate variability and extreme events in the polar regions and in mid-latitudes – today and in the future?
- What can we learn from climate variability today and in the past about current and future developments in the polar regions?

Societal relevance

As a result of the global warming caused by the increase in atmospheric CO_2 concentrations , dramatic climate changes are currently being observed in the Arctic: The near-surface air temperature has increased by 1.4°C over the past 30 years, which corresponds to an amplification of the global warming in the Arctic by a factor of 2.3 during this period. The summer sea ice cover of the Arctic Ocean fell by almost half between 1970 and 2020, while Greenland's ice sheet is melting drastically, forcing a further rise in the sea level.

In Antarctica, an increased warming has so far only been observed for the Antarctic Peninsula. In principle, similar amplification mechanisms are at work in the polar Southern Ocean as in the Arctic. Today, however, it is assumed that the amplification of climate-relevant processes in the Antarctic will mainly manifest itself as warming of the near-surface air layers with a time delay due to the heat absorption of the ocean. This rise in the temperature of the ocean, together with possible changes in the ocean circulation, may cause the water below the ice shelf to warm up considerably and thus contribute to a significant rise in the sea level.

The climate changes currently observed in the polar regions are already having a comprehensive and serious impact on ecosystems and the way of life of the population living there. Polar climate changes also create new opportunities for the commercial exploitation of the polar regions (for example, for shipping and tourism) and the associated risks (for example, oil disasters). Between 2013 and 2019, Arctic shipping rose by 75 percent. Along the Northeast Passage, a significant increase in shipping is expected between 2020 and 2030 due to resource extraction. For this reason, the five Arctic countries intend to minimise the environmental impact of shipping on the sensitive ecosystems of the North, while ensuring the safety of shipping activities (see also Chapter 2.8).

It can be assumed that climate changes in the polar regions (via so-called atmospheric and oceanic teleconnections) affect the weather and climate, as well as associated extreme events (for example, particularly warm or cold winters or heat and dry periods in summer) in Germany, Europe and other parts of the world. For this reason, the polar regions are a central focus of global climate research of outstanding societal relevance.

Reliable forecasting and projections, on time scales from days to centuries, with weather, climate, and Earth system models are urgently needed to provide evidence-based support for important societal decision-making processes. Reliable projections regarding the future development of the polar climate are highly dependent on realistic quantitative representation of the relevant polar amplification processes in models that form an essential basis for the development of effective and sustainable adaptation and action strategies for future economic and societal development.

The following research and development needs are identified:

- Improvement of process understanding of the causes and impacts of climate change in the polar regions on different time scales. This includes the quantification of Arctic ↔ Antarctic, regional ↔ large-scale, local ↔ remote, atmospheric ↔ oceanic/cryosphere, and dynamic ↔ thermodynamic drivers of polar amplification, as well as studies on possible changes in climate variability and extreme events in the polar regions.

- Investigation of the causes of the very different changes in sea ice coverage in the Arctic compared to the Antarctic (Antarctic sea ice paradox) and answering the question of whether the Antarctic sea ice is about to decline sharply.

- Establishment of scale-resolving, year-round measuring systems for determining energy fluxes and energy budgets in key regions of polar amplification (marginal ice zone, shelf regions, edge currents).

- Implementation of dedicated measurement campaigns and long-term observations for process and climate-oriented model evaluation, for the development of new or improvement of existing parametrisations, for the evaluation of a new generation of high-resolution models ("digital twins"), as well as for the evaluation of satellite remote sensing data.

- Investigation of the influence of polar amplification via atmospheric and oceanic processes on weather, climate, and extreme events in mid-latitudes, including answering the question of whether causality is misinterpreted from observation data and whether models underestimate the remote effects.

- Estimation of the possible future development pathways of polar amplification in the 21st century, including quantification of the uncertainties concerning the regional and global impacts.

- Classification of current polar climate change using data and models from the Earth's historical past, including systematic use of marine and terrestrial high-resolution time series of past warm periods. Environmental data from ice cores is of particular interest here.

2.2 THE ICE SHEETS: TIPPING POINTS FOR THE SEA LEVEL

Guiding questions:

- How high are the contributions of the melting polar cryosphere to the global and regional sea level rise – today and in the future?
- What is the risk of parts of the Antarctic ice and the ice sheet of Greenland becoming unstable or experiencing extreme mass loss, and have such events already occurred in the history of the Earth?
- How does the melting of the Greenland ice sheet affect ocean circulation and thus regional changes in the sea level?
- How can the interactions of ice sheets with the ocean and atmosphere be better understood, quantified, and modelled to improve forecasts for regional and global sea levels over the next 100 to 300 years?

Societal relevance

In 2050, about one billion people will live near the coast; today the figure is 680 million. Many of them are exposed to rising sea levels – by 23 centimetres globally since the beginning of the 20th century – and to intensified extreme events (such as storm surges). Initially, the expansion of the increasingly warmer ocean water was the main reason, but since 2006 the global sea level has risen about two and a half times faster than between 1900 and 1990. The main cause is the increased melting of the Greenland and Antarctic ice sheets as well as the glaciers. The West Antarctic ice sheet has lost mass unexpectedly quickly. The Special Report on the Ocean and Cryosphere (SROCC, 2019) of the Intergovernmental Panel on Climate Change (IPCC) subsequently raised the global sea-level rise ceiling to 1.10 metres by 2100 and considered the ice sheet to be less stable than in previous reports. By 2050, extreme water levels, which historically have been once-in-a-century events, will occur at least once a year at many coastal locations. All this has implications for living conditions on coasts and for the protection measures that must be implemented to protect people and their livelihoods. In the coming centuries, a further temperature rise due to climate change could mean that the tipping point is reached for parts of the Antarctic ice sheet – that is, the melting would be unstoppable, and the sea level could rise by several metres globally.

The following research and development needs are identified:

Society urgently needs reliable projections of polar contributions to global and regional sea levels over the next 100 to 300 years, resulting in the following research needs:

- Observation and simulation of the complex processes between the atmosphere, ocean, sea ice, glaciers and ice sheets as well as solid earth. Examples include the interaction between the hydrology of meltwater and glacier dynamics, the role of outlet glaciers and calving together with subglacial gliding and the properties of the ice surface. Vertical land movements are also required for the regional sea level, and on longer time scales the distribution of the geothermal heat flow is of great interest.

- Capturing all the components of the glacier or ice sheet mass balances: ice dynamics, elevation and mass changes of ice shelves, glaciers, and ice sheets, filling knowledge gaps in ice geometry (ice shelf caverns, fjords), grounding line movements, calving, thickness, and density distribution of the firn, and the hydrology of glaciers and ice sheets.

- Quantification of basal melt rates from ice shelves, distribution of meltwater in the ocean, influence on local, regional, and Atlantic-wide ocean circulation, and effects on the regional sea level.

- Investigation of the key regions for the rapid ice-sheet reaction in past warm periods through geological and geophysical observations and modelling of the relevant geological time periods.

2.3 THE SOUTHERN OCEAN AS A RESERVOIR OF HEAT AND CARBON

Guiding questions:

- How do climate change and the increasing atmospheric CO_2 concentration influence the uptake of heat and carbon and its distribution in the Southern Ocean?
- How do changes in ocean dynamics affect biogeochemical processes and element cycles and thus acidification, biological productivity and carbon storage?
- To what extent will expected changes in biological productivity and species composition affect carbon uptake in the Southern Ocean?
- What are the global consequences of changes in the Southern Ocean heat and carbon reservoirs?

Societal relevance

Continued CO_2 emissions from the use of fossil fuels and land-use change have led to a strong increase in atmospheric CO_2 levels. These anthropogenic emissions are rapidly changing the climate of our planet with multiple risks to society and the economy. The ocean significantly mitigates the warming of the atmosphere. It has absorbed more than 90 percent of the additional heat brought into the climate system by greenhouse gases, as well as more than 25 percent of the anthropogenic CO_2 emissions. The Southern Ocean extends around the Antarctic continent and occupies about 25 percent of the ocean surface area, but has absorbed a disproportionately large amount, namely around 50 percent, of the excess heat since 2005; for the period 1970–2017 this figure was around 40 percent. Also with respect to anthropogenic carbon uptake (40 percent), the Southern Ocean absorbs more than would be expected from its area alone.

The absorption and storage of heat and anthropogenic CO_2 is closely intertwined with ocean circulation. Much of the heat and CO_2 exchange takes place in the area of the Antarctic Circumpolar Current (ACC) – the main engine of global ocean circulation, which integrates, dampens or amplifies climate change and thus significantly influences the global climate. This physical pump will lose efficiency as the ocean is warming.

The anthropogenic CO_2 uptake takes place on top of the natural carbon cycle, which exchanges significantly larger amounts of CO_2 between the ocean and the atmosphere. The biological pump plays an important role here, transporting CO_2 bound by microalgae into the deep ocean, where it is isolated from exchange with the atmosphere. From past cold and warm periods, we know that a disturbance of this sensitive equilibrium due to climate and environmental changes (such as ocean acidification) can have a considerable impact on atmospheric CO_2 concentration and thus global warming.

The following research and development needs are identified:

- Compilation of heat and carbon budgets based on observations and simulations. Identification of long-term trends and variability caused by climate change.
- Identification and quantification of factors affecting horizontal and vertical circulation and associated heat and CO_2 uptake, including the role of vortices.
- Identification and understanding of the effects of changing circulation patterns in climate change (in particular intermediate and bottom water formation, polynyas, effects of meltwater fluxes, horizontal circulation) on heat and CO_2 uptake and transport as well as improved representation of these processes in future projections.
- Understanding and quantifying the influence of biological and biogeochemical processes on the CO_2 uptake and its alteration with changing environmental conditions and representation in Earth system models.
- Unlocking the global impacts of CO_2 and heat uptake in the Southern Ocean through the identification of connecting pathways and climate archives (sediment and ice cores).

2.4 THE FUTURE OF PERMAFROST ECOSYSTEMS

Guiding questions:

- What are the impacts of climate change on permafrost, the dynamics of permafrost landscapes and future greenhouse gas emissions?
- How do vegetation, biodiversity, permafrost and the climate interact, and what changes occur in ecosystem functions?
- What influence do rising sea temperatures have on the stability of submarine permafrost and the associated carbon storage?
- How do changes in permafrost ecosystems and Earth system feedbacks affect the achievement of UN sustainability goals?

Societal relevance

A major challenge for humanity over the next three decades is to keep global warming well below 2°C above pre-industrial levels (Paris Agreement) and end biodiversity loss (EU Biodiversity Strategy 2030 and EU Green Deal). One crucial scientific contribution to societal discussions regarding UN Sustainable Development Goals 13 and 15 ("Climate Action" and "Life on Land", respectively) is the estimation of corresponding emission scenarios: What amount of greenhouse gas can humans still emit, or how much additional carbon must be bound from the atmosphere (negative emissions)? The models underlying the answer to this question do not take into account the interactions of changing permafrost landscapes with the future climate. As climate change is accelerating in the high northern latitudes and permafrost ecosystems contain large amounts of frozen organic matter, there is a risk of high additional greenhouse gas emissions from thawing permafrost soils. Due to their particular vulnerability to climate change, the permafrost regions have now been recognised as one of the few large tipping elements in the Earth system. The major uncertainty regarding the stability and future development of permafrost ecosystems prevents the development of reliable strategies for reducing anthropogenic greenhouse gas emissions and makes it difficult to conserve biodiversity. At the same time, the uncertainties and risks of thawing permafrost and biodiversity loss pose major challenges for the local population. On the other hand, intelligent land use policies could potentially reduce permafrost degradation, greenhouse gas emissions and species loss, thereby facilitating the achievement of the Sustainable Development Goals (SDG).

The following research and development needs are identified:

Reliable projection of future changes in permafrost ecosystems and climate requires a deeper understanding of the coupled hydrologic, biogeochemical, and ecological processes and their feedbacks with the climate. This in turn calls for a greater integration of observations and models, in particular on the following topics:

- long-term monitoring of permafrost temperatures, soil properties and greenhouse gas emissions;
- hydrological and geomorphological changes in the landscape and consequences for permafrost ecosystem functions;
- influence of the coupling of biogeochemical and hydrological cycles, plant-soil-microorganism interactions and the stabilization of organic soil matter on the current and future net greenhouse gas balance;

- the influence of extreme weather events and climate variability on permafrost landscapes;
- interactions of vegetation dynamics, permafrost dynamics, biodiversity and fire;
- the introduction and conversion of organic matter, nutrients and pollutants into aquatic systems;
- temporal and spatial variability of the biodiversity, including micro-organisms in permafrost ecosystems;
- opportunities for genetic adaptation and the phenotypic response of key species;
- destabilization of submarine permafrost and resulting greenhouse gas emissions.

Using such extended Earth system models, it is possible to determine reliable scenarios concerning necessary future anthropogenic (negative) CO_2 emissions. There is also the question of the extent to which land management can be adapted to stabilise permafrost ecosystems.

2.5 ECOSYSTEMS IN POLAR OCEANS UNDER CLIMATE STRESS

Guiding questions:

- How and where does climate change threaten polar marine ecosystems with their special organisms, communities, functions, and goods and services useful to humans? Are there tipping points with irreversible consequences for these ecosystems?
- How does climate change affect food webs in the polar oceans, their productivity and role in the global carbon cycle?
- Which species and ecosystem functions are suitable as indicators for the “health status” of the ecosystems in polar oceans?
- How well can polar marine organisms adapt to the sometimes rapid environmental changes? Which processes are decisive here?
- How can robust future scenarios be developed from research findings using modelling approaches?

Societal relevance

The Arctic and Antarctic Oceans have high ecological, cultural and aesthetic value for humanity. The threat to existence of iconic creatures such as polar bears and penguins has contributed significantly to raising public awareness of the consequences and risks of global climate change. At the same time, both polar oceans contain important biological resources that can be used, i.a. for human nutrition. They thus provide globally important ecosystem services from which regional populations (Arctic), but also Europe and the world can benefit (see EU Blue Growth Strategy, UN Decade of Ocean Science for Sustainable Development 2021–2030.

The large capacity of polar oceans to absorb carbon dioxide compared to other regions reduces the global concentrations of greenhouse gases in the atmosphere and thus buffers their negative effects worldwide (see Research topic 3). Microalgae (phytoplankton) play a central role in CO_2 uptake, since they absorb CO_2 for photosynthesis (and thereby produce oxygen). With the sinking of algal biomass, part of this fixed carbon is transported to great water depths and thus withdrawn from the global cycle in the long term. However, the efficiency of this biological carbon pump depends crucially on predator-prey relationships and remineralisation processes in the water column and also on the sea floor, which have so far only partially been quantified (see Research topic 3).

In addition to their contributions to global biogeochemical cycles and globally relevant ecosystem services, polar regions represent a huge field laboratory for studies to increase our fundamental understanding of marine ecosystem functions as well as for research into the physiological and ecological life strategies of polar organisms. Many of these specially adapted, highly sensitive organisms exist only in the Antarctic or Arctic Ocean, underlining the need to protect these vulnerable habitats (see Research topic 6). So far, it has been challenging to predict what consequences current and future climate-related environmental changes will have for polar ocean ecosystems and their benefits for the indigenous, regional and global population.

The following research and development needs are identified:

- Long-term studies (if possible year-round) at representative sites for the census of populations and documentation of spatial and temporal changes (phenology) in the communities and food webs of the polar oceans (including the accompanying environmental conditions).
- Identification and use of indicator species to determine the impact of climate change on ecosystem functions and services.

- Experimental and field studies on the tolerance and adaptability of important species to (multiple) stressors at different levels (e. g. phenotypic plasticity, gene regulation, microevolution).

- Modelling the changes of communities, food webs and energy flows in response to climate change. Integration of essential ecological processes in polar oceans into global models.

- Investigations into connectivity and exchange processes between polar ecosystems and lower latitudes as well as into land-ocean interactions for an overall conceptual understanding.

2.6 ANTARCTIC PROTECTION CONCEPTS

Guiding questions:

- Which groups of organisms and habitats are of great importance for the Antarctic and global biosphere, but are sensitive to human impact and, thus, in particular need of protection?
- How can the effectiveness of protected areas and area-independent protection measures be optimised under the specific Antarctic conditions?
- What influence do pollution, non-native species and introduced diseases have on the well-being of organisms in an Antarctic largely isolated from the rest of the world?
- How can the "human footprint", especially of fisheries and tourism, on the sensitive Antarctic biosphere and its environment be reduced?
- How can an efficient network of protected areas be established from an ecological-strategic point of view?

Societal relevance

Life in Antarctica contributes significantly to global biodiversity and ecosystem services. Good knowledge of the communities is therefore indispensable when preparing global reports with policy advice, for example within the framework of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Decade of Ocean Science as well as the United Nations' Global Ocean Assessment. An understanding of ecological processes is also important for Antarctic-specific recommendations for action under the Antarctic Treaty System with its Protocol on Environmental Protection and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

Antarctica is regarded as an ecosystem of great scientific and aesthetic value that is predominantly unaffected by humans and has recently been increasingly exposed to anthropogenic – i. e. human-induced – changes. There is therefore a broad consensus that additional efforts are needed to keep the "human footprint" as small as possible.

Safeguard measures must be scientifically justified to the furthest extent possible. They aim to preserve the biodiversity and ecosystem services, the atmosphere and the terrestrial, freshwater, glacier and marine environments of the Southern Polar Region from adverse anthropogenic influences and interventions. This results in particular from the uniqueness and high sensitivity of many organisms to environmental changes. Direct threats are mainly based on increasing exploitation by fisheries and tourism, which can lead to the destruction of habitats, pollution and the introduction of non-native species, including pathogens.

Among the globally relevant ecosystem services, oxygen production, carbon dioxide uptake, nutrient recycling and food production are of particular importance for worldwide migratory whale and bird species. For these reasons, areas with high biological activity and biodiversity should be given special attention in the scientific validation of existing and new protection concepts. Natural resources such as krill and toothfish are used directly for human consumption only to a limited extent. They are otherwise used for animal feed production and in the production of health-related lifestyle products. There are only a few examples of the usability of genetic resources, for example in connection with cold resistance or in the pharmaceutical-medical field.

Against this background, the internationally agreed goal of protecting 30 percent of the world's oceans by 2030 is also to be implemented in the Antarctic. This has so far only been achieved for less than a third of the Southern Ocean. Nonetheless, the species conservation decided upon after the depletion of some Antarctic mammalian stocks serves as a model for regulations in other oceans. With regard to the atmosphere, the first successes of research into the ozone layer in Antarctica and the 1987 Convention for its protection are emerging.

The following research and development needs are identified:

- The success of international regulations for the protection of the Antarctic environment and biosphere can only be assessed with an increased understanding of the ecological system. As a basis for this, long-term observations must ensure an analysis of human impact and interference on key organisms and ecological functions.

- The designation of new protected areas and the review of existing protected areas require a constant improvement in the knowledge of geographical priorities in terms of biodiversity, specific environmental conditions, ecosystem services and the occurrence of rare communities.

- In addition to general studies on biodiversity, the scientific relevance and effectiveness of various protective measures can be demonstrated and verified through the development of future scenarios in ecological and physical modelling approaches.

- Socio-scientific research could increase the acceptance of science-based policy decisions to protect Antarctica.

2.7 SCIENCE FOR SUSTAINABLE DEVELOPMENT IN THE ARCTIC

Guiding questions:

- What are the major opportunities and barriers to sustainable development (social and cultural equity, economic development and environmental protection)?
- How can science contribute to the strengthening of governance structures for sustainable development and address existing gaps?
- How do sustainable development in the Arctic and global change processes affect each other and what can science contribute in this context?
- How can the natural, social and human sciences contribute in appropriate ways to sustainable development in an Arctic marked by significant change and diversity? Howe can researchers work with stakeholders and Indigenous rights holders to co-produce research results that have societal relevance for the present and the future?

Societal relevance

The Arctic is characterized by rapid and profound socio-cultural, political, economic and ecological change. Changes in the Arctic environment, in particular, have global impacts, but create especially complex and overlapping challenges for the people living in the Arctic. These challenges require close cooperation between the local population, researchers, politicians, NGOs and businesses. Indigenous peoples' participation and self-determination play a particularly important role in this regard. A number of international conventions, instruments and guidelines reaffirm the right of indigenous peoples to give or deny consent to projects that affect their lands, waters and ways of life. This includes research projects in the natural and social sciences and humanities. Germany's Arctic Policy Guidelines also highlight the right of Indigenous peoples in the Arctic to self-determination. Close cooperation and co-creative research approaches can improve scientific output and build trust. To enable mutual knowledge exchange and to ensure that research projects have societal relevance, collaboration between researchers, Indigenous rights holders and the local population should extend throughout the lifecycle of research projects, beginning with the definition of research questions and methods. This chapter presents research needs based on existing needs analyses, which were developed in cooperation with stakeholders and Indigenous rights holders or by Indigenous organisations (in particular EU-PolarNet 2020 [EPRP], ICARP III, Saami Arctic Strategy, SDWG Strategic Framework), as well as contributions from various experts.

The following research and development needs are identified:

- Analyses of the interactions of socio-ecological systems as well as the cumulative, socio-cultural effects of climate change and other transformations; research for the protection and sustainable use of Arctic ecosystems with a focus on Indigenous-led and community-based management and the co-creative development of monitoring, mitigation and adaptation strategies.

- Analyses of the socio-cultural impacts of different transformation processes, taking into account social dimensions such as age, gender or Indigeneity; research into the causes of and changes in social and cultural inequalities; research into histories, cultures and languages and research to promote Indigenous and local knowledge, arts and crafts and the preservation of cultural heritage (SDWG Strategic Framework, p. 10); transdisciplinary research into desirable developments in the Arctic; research into the health and education needs of Indigenous and local communities; research into Indigenous rights, legal systems and legal pluralism.

- Analyses of economic developments, including in subsistence economies and emerging sectors; research on sustainable investments in infrastructure (SDWG Strategic Framework, p. 10); research on the impacts of commercial resource exploitation and sustainable use of resources (see also ICARP III); research into strengthening economic activities, including in remote parts of the Arctic; research on linkages between subsistence and economic activities (see also AHDR-II, EPRP p. 49, Saami Arctic Strategy)

- Analyses of the stakeholders and rights holders involved in the various on-going developments and their interests, and "the potential mismatch between emerging interests and activities and the international agreements, national laws and regulations in the specific regions" (EPRP, p. 62); research on governance systems; on the "relationship between improved well-being and quality of life and increased self-determination and Indigenous participation in regional and local governance" (EPRP, p. 46); research on the role of institutions and business enterprises (see also AHDR-II, EPRP, p. 6, ICARP III, Saami Arctic Strategy); research on Indigenous governance methods.

- Analyses of local, regional and international interdependencies; research on the impacts of the growing global interest in the Arctic (AHDR-II, p. 496); research on Arctic innovations and their transfer (AHDR-II, p. 496).

- Research on transdisciplinary and transformative research in the Arctic; research on the development, implementation and evaluation of co-creative and collaborative research projects between Indigenous and non-Indigenous partners (see also EPRP), taking into account different concepts of ethics; research on colonial continuities in science.

2.8 THE IMPACT OF HUMAN ACTIVITIES ON ARCTIC ECOSYSTEMS

Guiding questions:

- Which Arctic organisms and ecosystems are of particular importance to the region and globally and are at particular risk and thus in need of special protection?
- How can science contribute to better quantify the impact of human activities on Arctic ecosystems?
- How can science contribute to permanently prevent future negative effects on the Arctic and permanently reduce existing effects or achieve positive effects?
- How can a stronger link between scientific, social and humanities research and cooperation with the indigenous and local population (transdisciplinarity) contribute to answering these questions?

Societal relevance

The Arctic provides the livelihood for unique marine and terrestrial ecosystems that are highly adapted to the extreme living conditions, such as the very low temperatures and long darkness in the Arctic winter. The sea ice in the Arctic Ocean also creates a special habitat. The unique living conditions in the Arctic contribute to biodiversity and globally relevant ecosystem services.

In addition to the climate changes affecting the Arctic Ocean and land areas (sub-chapters 2.1 and 2.5), a variety of other human activities outside and within the region also have impacts on ecosystems: Air and sea currents, as well as rivers, introduce pollutants, such as chemicals and plastic particles, which are deposited in the permafrost soil, in the sea ice and on the sea floor. Human activities such as shipping, fishing, tourism (especially cruise ships) and the extraction and transport of mineral and energy resources increase the pressure on ecosystems. Furthermore, there are waste and waste water from cities and settlements in the Arctic, which additionally increase this pressure. In addition to environmental changes, people in the Arctic can also be threatened by pollutants in the food chain. Research projects must respect the rights of the indigenous population to free, prior and informed consent. This requires an exchange of ideas during the planning phase, so that the research questions are developed together with the local stakeholders (see sub-chapter 2.7).

The following research and development needs are identified:

- Interactions of multiple stressors and their effects on Arctic ecosystems should be investigated to identify particularly vulnerable species and areas.

- More regionally differentiated studies are needed to identify the concrete local impacts and to develop appropriate approaches in order to avoid and minimise these impacts. This requires observations beyond seasonal surveys, and multi-year data series.

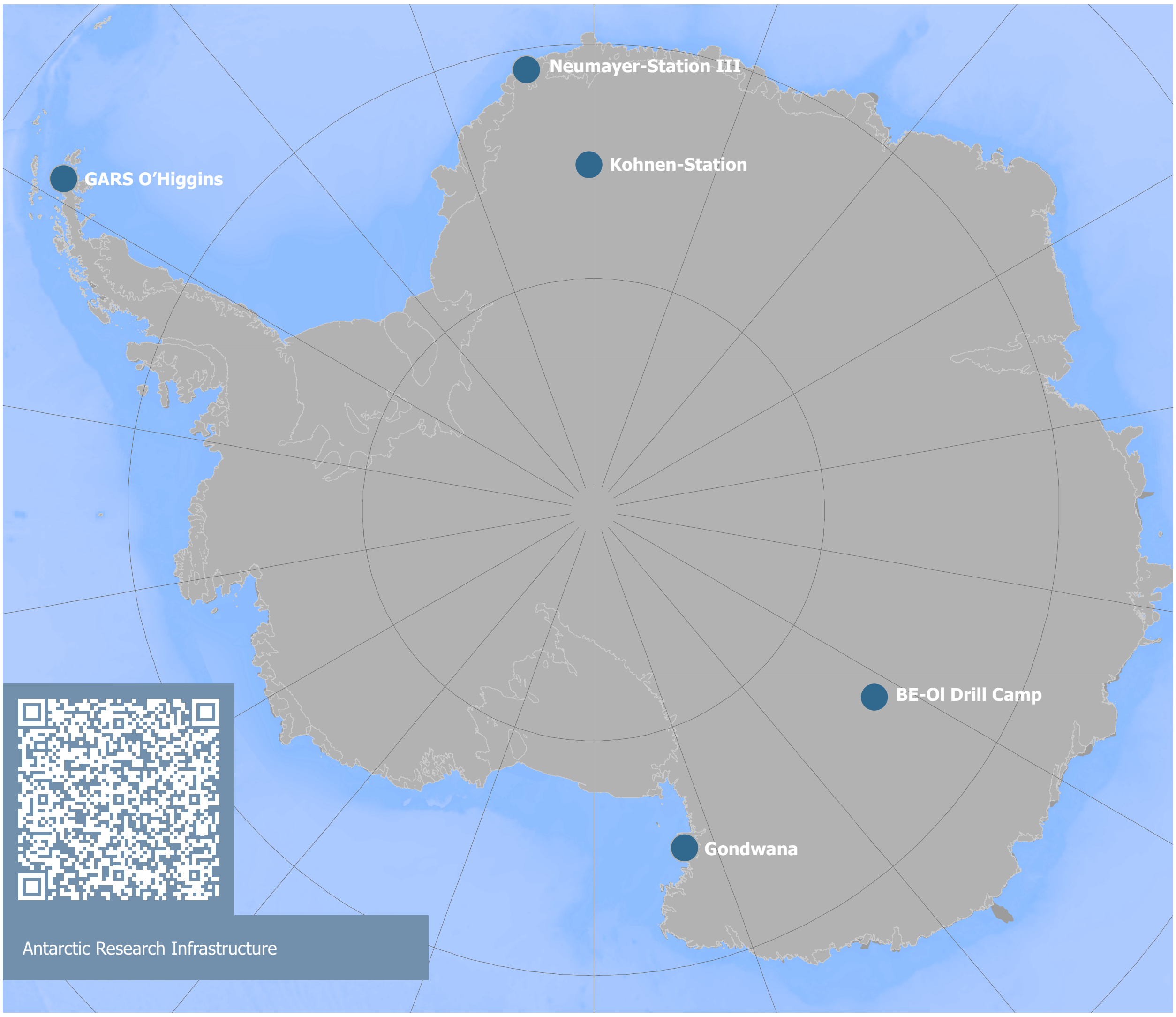
- Existing data and studies, which already show clear trends, must be used as a basis for scientifically based protection measures in order to avoid negative impacts on the Arctic ecosystems.

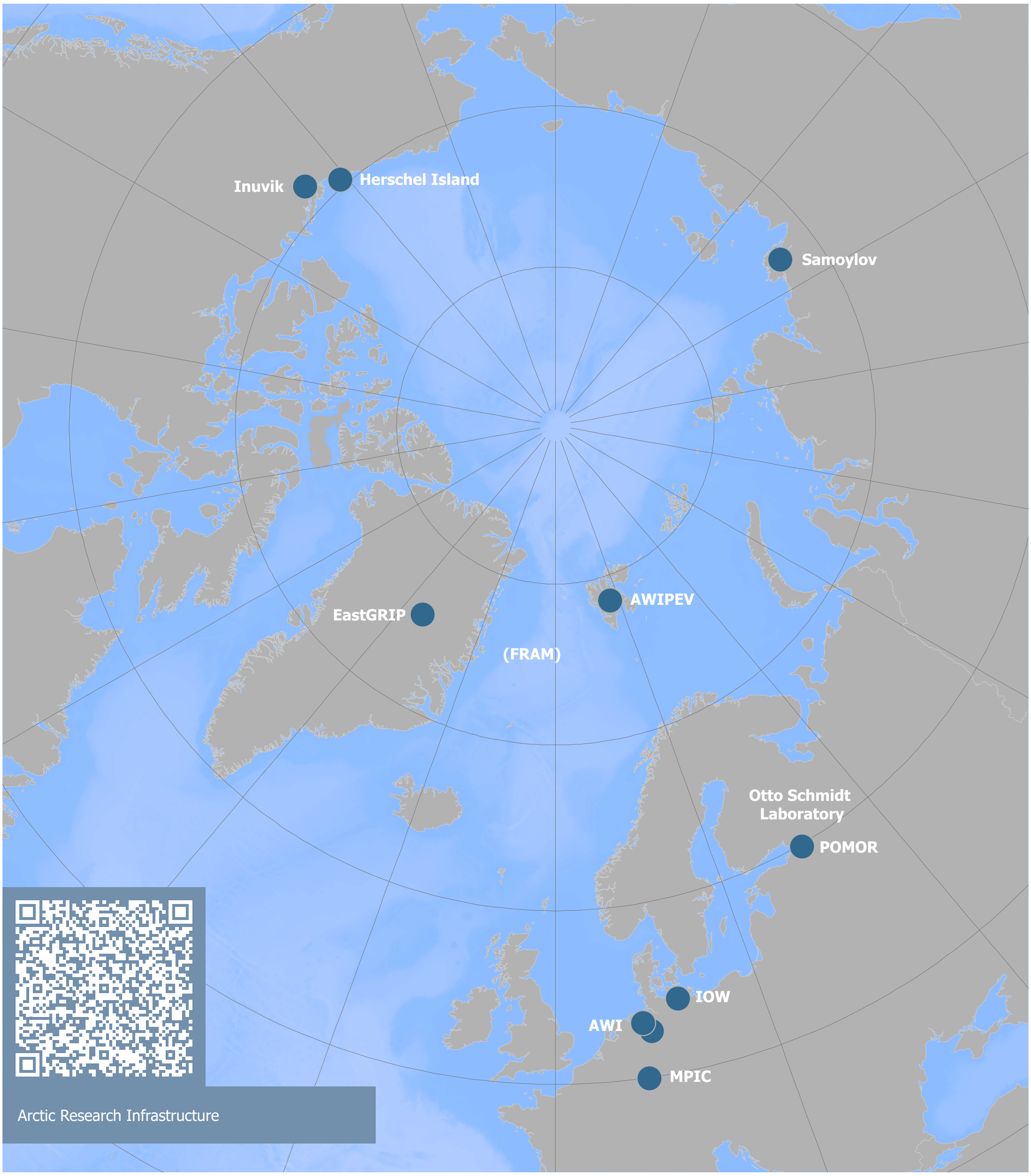
- The definition of research questions and methods, as well as the development, management, and dissemination of knowledge and results on the impacts of human activities on Arctic ecosystems must be done with the consent of, or in collaboration with, indigenous and local communities.

3 Cross-cutting topics and research environment

The cross-cutting topics and research environment of polar research depends on considerable funds to operate the national infrastructure in the coming years. The existing research infrastructures needs continuous maintenance and renewal to meet future challenges. For access to and consequently research on the high latitudes, powerful instruments and tools are necessary, meeting specific needs and modern standards. These include ice-breaking research ships, year-round stations as logistical bases, specialized aircraft and numerous vehicles for polar missions on land, water and in the air. In this context, satellite missions with German participation are indispensable to develop information and communication facilities as well as high-performance data networks. Modelling requires additional resources in the area of high-performance computing and the storage of large data sets. The constant availability of such infrastructure facilities is a prerequisite for the implementation of necessary long-term programs in the difficult-to-access polar regions. Large research institutions in particular have built up such infrastructures and continuously adapt them to emerging requirements.

An overview of the infrastructures operated by German institutions, or maintained with their support, is pictured in the following two maps. Scanning the QR code forwards to the respective homepage, where further information is available.




Inuvik
Herschel Island
Samoylov
EastGRIP
AWIPEV
(FRAM)
Otto Schmidt
Laboratory
POMOR
IOW
AWI
MPIC
Arctic Research Infrastructure

CROSS-CUTTING TOPICS AND RESEARCH ENVIRONMENT

3.1 MODEL DEVELOPMENT

Guiding questions:

- How can weather, climate and Earth system models be decisively improved in their representation of central processes in the polar regions?
- How can models and observations in the polar regions be optimally combined using data assimilation and inversion techniques?
- How can we objectively measure the quality of models in polar regions (metrics) and efficiently diagnose the origin of model errors?
- How can we future-proof the models and associated workflows for a new generation of computers of the highest performance class (exascale) with highly heterogeneous computer architectures?
- How can we further develop data analysis capabilities so that even large and complex data sets can be efficiently analysed and visualised in the future?

Societal relevance

Numerical models and data assimilation are nowadays the basis for operational weather and climate forecasts (from hours and days to months and years). These forecasts are used daily by numerous users (for example, business, government, and the public) to make decisions, some of which are important, including warning of extreme events.

Numerical models also provide the basis for climate projections, which are used to estimate the impact of human activities on the climate. Models are thus of central importance to stakeholders (for example, policymakers, business, and the general public) in terms of developing concrete evidence-based adaptation and mitigation strategies. Uncertainties in the projections concern the reliability of statements on the carbon storage capacity of the polar oceans, the living conditions for polar ecosystems, global and regional sea levels, the risk of climate extremes, and the danger of abrupt climate transitions in the polar regions.

Data assimilation allows models to optimally combine observations and satellite data. Thus, the states of the climate system and its changes can be efficiently monitored. So-called analyses and reanalyses are widely used today to quantify past climate changes (for example, insurance industry and renewable energy business models).

Finally, models (numerical "laboratories") can be used to gain a deeper understanding of how the climate and Earth system works and how it changes from geological time scales (for example, ice ages) to future developments. Next-generation high-resolution models (digital twins) in particular have the potential to illustrate different climate states and thus also to make them more tangible for the layperson. Models therefore also contribute to an improved understanding of the world and its changes.

The following research and development needs are identified:

- Further development of the representation of Earth system processes in the polar regions for weather, climate and Earth system models and their evaluation using observations and climate reconstructions.

- Development of Earth system models that can represent critical feedbacks and tipping points at high latitudes, including ice sheets and their interaction with the lithosphere, icebergs, ice shelf-ocean interactions, and permafrost.

- Development of models with high spatial resolution (down to kilometre scale) in the polar regions (digital twin), with the help of which central processes (for example ocean eddies and land and sea ice deformation) can be simulated by physical laws instead of parametrisations. This includes better representation of bathymetry and topography (for example, ocean straits and ice shelf caverns in ocean models).

- Development of Earth system models with a realistic representation of biogeochemical processes and marine and terrestrial ecosystems. New approaches should also be taken into account that greatly minimise the computational effort and thus allow integration into very high-resolution simulations.

- Development of data assimilation and inversion procedures for component models (for example, atmosphere, land ice, biogeochemistry, permafrost) and fully coupled climate and Earth system models.

- Development of diagnostic capabilities to determine the origin of model errors at the process level and thus prioritise model developments. This includes the development of appropriate metrics to quantify model quality in polar regions and the use of data assimilation capabilities.

- Development of scalable high-resolution model systems and associated workflows (for example, ESM-Tools, data analysis, virtual field campaigns) that can be effectively used on next-generation supercomputers with heterogeneous computing architectures. The focus should be on removing existing bottlenecks (for example, scalability, performance portability, use of graphics processors and other methods of scientific computing).

3.2 FUTURE PROJECTIONS AND FORECASTS

Guiding questions:

- How can we provide decision makers and society with the best possible future projections to 2100 and beyond, taking into account key processes, feedbacks, and tipping points in the polar regions?
- How can we ensure that processes in the polar regions do not contribute to "climate surprises", i. e. that the actual development of the future climate is outside what is expected according to current knowledge?
- How predictable is the climate system in the polar regions on time scales ranging from days to years, and how reliable are predictions today?
- How can we most effectively improve predictive capacity based on user needs?
- How can we best communicate future projections and predictions and their uncertainties?

Societal relevance

Climate change in the polar regions is causing widespread transformation. Prominent examples include the rapid decline of sea ice in the Arctic, severe erosion of Arctic coasts, thawing of permafrost, and melting of ice sheets in the Arctic and Antarctic. These changes are leading to significant challenges for humanity – in the polar regions and beyond (for example, sea-level rise and extreme events in mid-latitudes). The availability of reliable future projections – taking into account critical processes, feedbacks, and tipping points in polar regions – thus has a central role to play in making evidence-based adaptation and mitigation decisions.

Climate change in the polar regions is expected to lead to a strong increase in commercial activities (for example, shipping and tourism). To minimise the associated risks, reliable forecasts of weather, climate and environmental conditions are essential. In addition, improvements in forecast quality in the polar regions through long-range teleconnections have also been shown to potentially improve the quality and thus utility of midlatitude forecasts, especially for weather situations with strong interactions between the polar regions and midlatitudes (meandering jet stream).

The following research and development needs are identified:

- Combination of different research methods to quantify and target the robustness of climate projections in polar regions. This requires open-method calls that allow researchers to combine, for example, existing simulations, projections of high-resolution climate models, Earth system models with improved representation of critical interactions, model hierarchies, emulators, AI methods, emergent constraints, and paleo knowledge. The goal would also be to quantify model and scenario uncertainty as well as internal variability.

- Understanding potential "climate surprises" where future developments fall outside current projections. This includes quantifying the appropriate thresholds or tipping points in ice, ocean, atmosphere, carbon cycle, and ecosystems, as well as estimating long-term changes and so-called commitments, and worst-case scenarios (for example, under what conditions a sea level rise of 1.5 metres could occur by 2100).

- Implementation and analysis of so-called storyline scenarios (for example by nudging the jet stream) in order to quantify the influence of climate change on current extreme events in the polar regions (attribution) and to estimate possible developments of analogous extreme events in a 1.5°C, 2°C and 4°C warmer world (adaptation).

- Improvement of the communication of projected climate changes and their uncertainties using a strong visualisation component – "pictures of the future" (for example, virtual satellite images, digital twins, storyline scenarios) – and the use of established and new communication formats (for example, #FactoryWisskomm).

- Determination of the limits of predictability of weather, climate, and environment in polar regions and evaluation of the development of actual forecast quality using appropriate (including newly developed) polar-specific verification methods.

- Improvement of the central components of prediction systems taking into account user needs (dialogical). This includes, for example, the development of coupled data assimilation methods, the optimisation of observation systems, and the further development of models (for example, sea ice deformation including press ice ridges).

3.3 INSTRUMENTS AND OBSERVATION SYSTEMS

Guiding questions:

- Which instruments and observing systems do scientists need in the polar regions?
- Which instruments and observing systems are scientists currently lacking?
- Which future scientific application fields can already be clearly identified?

Research and development needs

Gaps in synoptic and long-term observing systems need to be addressed to detect and understand the impacts of climate change on ecosystem services, communities, and their conservation. Current local and regional data coverage is insufficient to study all polar systems at high temporal resolution. To reduce uncertainties in marine carbon uptake and storage, the physical and biological pumps in the polar ocean need to be better captured with continuously operated observations of ocean dynamics and biogeochemical changes. This is particularly important for the Arctic Ocean, the subpolar North Atlantic, and the Atlantic sector of the Southern Ocean. One challenge is to further develop biogeochemical (BGC) sensors to include applications on deep drifters and other polar platforms, such as AUVs, ROVs, bottom landers, and benthic crawlers, which will need to be equipped with more advanced high-resolution imaging techniques. In most cases, only project funds are available for the development of BGC sensors – and the urgently needed progress and widespread use is uncertain due to the associated lack of long-term perspective. Sensors that can be scaled down even further, including cameras fitted to marine mammals and seabirds, will not only provide valuable ecological information on animal behaviour and climate change, but also physical and chemical data from areas that are difficult to access. The development of procedures for the operational linkage of continuous optical measurements is necessary to generate high quality observational data sets on key BGC parameters (primary production, particle flux, etc.) with optimal spatial and temporal coverage.

Observations on the glaciers and ice sheets are logistically extremely challenging and ship measurements should be supplemented with measurements from autonomous measuring stations. In order to perform process studies, additional measurements from aircraft and drone systems are needed, as this improves the spatial and temporal resolution. For permafrost applications it makes sense to develop new sensor combinations, for example for the spectral range of the Short-Wave Infrared (SWIR). As a reference for satellite data in ice-covered areas, laser altimeters are important for depth measurements of melt-water lakes, in coastal areas, and for sea ice. In addition, there are, for example, measurements of snow accumulation, snow and firn structure, and reference stations for positioning with the available satellite navigation signals. To better verify spatial variations against satellite-based estimates, installations and systematic measurements are needed. Satellite measurements in particular are subject to uncertainties in microwave signal penetration, spatial interpolation, volume-to-mass conversions, accounting for glacial-isostatic compensation in gravity field measurements, and, for sea ice, snow accumulation and freeboard for ice thickness conversion.

Access to sedimentary archives deep below the seabed is needed for the necessary paleoclimate research. In the future, it will be important to further develop drilling rigs that can be flexibly deployed on multipurpose research vessels and which can extract sediment cores from drilling depths of several hundred metres.

Drone systems have made significant progress in recent years. In addition to current commercial systems, consideration should be given to the development and operation of systems with larger carrying capacity for scientific instrumentation as well as greater range in polar regions (HALE: High Altitude Long Endurance). Systems for detecting the atmosphere at 80–100 kilometres above the ground need to be augmented with infrared cameras, wind measurements and tomography. The measurement of turbulence, for example through the use of Distributed Temperature Sensing (DTS) techniques, is also desirable. In addition, the installation of such a measurement package (spectrometer, camera and wind measurement system) on polar research stations or ships could mean better forecasting of the weather in the mid-latitudes as well in the future.

Future satellite developments should further increase the temporal and spatial sampling rates and the accuracy of the data products, but also allow the evaluation of new, additional variables. The potential instability of the West Antarctic Ice Sheet and the detection of extreme changes in outlet glaciers in Greenland and Antarctica require rapid response to events and rapid deployment of additional sensors. To this end, the concept for a national TanDEM-L mission can make a significant contribution, also enabling tomographic studies for the first time. Initial continuity in national X-band radar sensing is provided by the HRWS MirrorSAR follow-on mission. HRWS MirrorSAR's multistatic imaging concept enables significant quality improvements, especially for the edge regions of Antarctica with high reliefs, where satellite altimetry measurements are limited, but on the other hand mass changes occur. In addition, innovative concepts for deriving new geophysical parameters, such as snow thickness, should be implemented. There is also an emerging gap in data collection from altimetry missions starting in 2025. Airborne missions with Ku- and Ka-band SAR systems need to be established until ESA's CRISTAL mission is operational. For all satellite data, lower-cost access to highest-resolution satellite data should be made available in addition to the regular acquisitions of the European missions.

Laboratory analytics that can be continuously upgraded and used in the laboratory and, if possible, on research vessels and stations are essential. These laboratory analytics – also with a view to so-called lab-on-a-chip technologies – are partly located at universities with polar research, which should be provided with more possibilities for the further development and modernisation of their analytics in the future.

To make the national contribution visible not only in science, but also in the provision and further development of sophisticated technologies for polar research in Europe, additional resources as well as increased coordination among stakeholders are necessary. The many active university research groups will also depend on the provision of these technologies. Field measurement efficiency and logistics are only possible through a coordinated approach and the cooperation of partners and should be strengthened in the future. Henceforth when choosing observation sites, the requirements from the point of view of the models that use the observation data as input should also be taken into account. In addition, dataset analysis would benefit from Big Data infrastructure and AI algorithms.

3.4 PROMOTION OF YOUNG RESEARCHERS

Germany offers young polar researchers its own national funding structures (e. g. graduate schools) on the one hand, and access to participation in international structures on the other.

Coordinated programmes and flagship projects

The German national committee of APECS (founded in July 2016) represents Master and PhD students, postdocs, newly appointed lecturers and others with an interest in polar regions in the Association of Polar Early Career Scientists (APECS). The goals of APECS Germany are to provide networking and support to young polar researchers, education and outreach on polar issues to young people and the general public, and to disseminate information via newsletters, social media and the website (https://apecsgermany. wixsite.com/apecsde). To this end, APECS Germany organises career development events for young scientists as well as educational and outreach activities to excite and inspire young people into studying the polar regions.

Since 1981, there has been coordinated funding of Antarctic research in Germany by the German Research Foundation (DFG), which focuses also in particular on promoting young researchers, such as the training of PhD students. The DFG Priority Programme 1158 "Antarctic Research with Comparative Studies in Arctic Ice Regions" (https:// www.spp-antarktisforschung.de/) primarily supports university research groups in using the logistics required for research work and thus in getting young academics in Germany interested in the polar regions and training future generations of polar researchers. The coordination meetings and topic workshops within the priority programme also serve to network young and experienced polar researchers.

In cooperation with universities, the Helmholtz Association's Helmholtz Young Investigator Groups help young scientists become scientifically independent with programme-oriented funding, thus offering them sound career prospects. Likewise, the DFG's programmes for young researchers (e. g. the Walter Benjamin Programme, the Emmy Noether Programme, the Heisenberg Programme) offer the opportunity to develop an independent research profile.

The Universities of Hamburg (UHH) and Saint Petersburg (SPbU) jointly offer the German-Russian master's programme in Polar and Marine Sciences POMOR (https://pomor.spbu.ru/en). The course has been conducted since 2002 in close cooperation with the Universities of Bremen, Kiel and Potsdam, the Technical University of Hamburg, AWI, GEOMAR, the Leibniz Institute for Baltic Sea Research Warnemünde and the Otto Schmidt Laboratory for Polar and Marine Research in St. Petersburg (OSL). POMOR is an English-language, research-oriented master's programme. The first and second semesters take place at SPbU and OSL, and the third at one of the German partner universities. A field internship integrated into German-Russian research projects is obligatory. The teaching and supervision of the master's theses are carried out jointly by German and Russian lecturers. Students of the MSc POMOR, internationally accredited until 2025, graduate with a dual degree at UHH and SPbU. Various other universities offer master's programmes with a polar connection (for example, in the context of theses), but this is usually not explicitly part of the curricula.

The Polar Teachers Working Group in the German Society for Polar Research (https://www.polarforschung.de/arbeitskreise/ak-polarlehrer/) is a nationwide network of teachers of geography, biology, physics, chemistry and social studies from all grades and school types. Its members engage in teaching with special attention paid to the implementation of polar themes.

Other programmes and facilities

Other programmes include graduate schools, such as POLMAR (https://polmar.awi.de) and ArcTrain (https://arctrain.de) and international programmes with German participation, such as the University of the Arctic (https://www.uarctic.org), the Fellowship Programmes of SCAR (https://scar.org/awards/fellowships) and IASC (https://iasc.info/capacity-building/fellowship), the CORELIS - Cold Region Landscapes Integrated Sciences (https://corelis.spbu. ru/en/) international master programme and the Permafrost Young Researchers Network (https://pyrn.arcticportal.org/national-representatives).

Future demand

An important and sustainable pillar for the implementation of the research and cross-cutting topics is the training of students, doctoral candidates, postdocs and young scientists. In addition to the continuation of the currently existing key programmes, the promotion of young researchers must therefore be given high priority in new programmes in order to promote young researchers and give them access to participation in international structures. To this end, the establishment and expansion of international summer schools, master's programmes and graduate schools, as well as a tenure-track programme are planned. These support programmes could have a sustainable impact by building and strengthening alumni networks. In the long term, the next generation of scientists will be able to build bridges in international polar research. The aim is also to improve the networking of young researchers between universities and non-university research institutions.

3.5 KNOWLEDGE TRANSFER AND COMMUNICATION

Guiding questions:

- How can knowledge transfer and communication in polar research be significantly advanced?
- What success stories are based on the contribution of polar research?
- How are societally relevant topics defined that are suitable for knowledge transfer?
- Which measures are suitable for reaching the respective target group?
- How can knowledge transfer and communication be anchored in future research projects?
- What kind of knowledge transfer and communication do we need in the future with regard to climate and environmental protection, adaptation strategies and sustainable development?

Development needs

With respect to the overall goal of advancing knowledge transfer and communication in polar research, there is a need for development in the following areas:

- **Knowledge transfer as an integral part of research activities:** In order to anchor knowledge transfer in polar research, it is necessary that BMBF-funded research projects include an integrated transfer and communication strategy in which goals, target groups and knowledge transfer measures are discussed. This should be worked out from the outset together with the research design by appropriate specialist personnel, if necessary together with local partners, and realistically backed up with resources. It should also be ensured that results from the stakeholder dialogue are fed back into the research process on a continuous and ongoing basis. In addition to scientific quality, the transfer and communication strategy should be taken into account when reviewing research proposals, and review panels should be staffed with appropriate experts, possibly from outside the scientific community. Training and continuing education programmes would help to better qualify scientists for knowledge transfer and communication activities. At the same time, care should be taken to ensure that, in addition to scientific expertise, transfer and communication expertise appropriate to the project context and objectives is available within the project team's staffing structure and provided for in the project budget. This overarching need corresponds to the BMBF’s goal of establishing science communication as an integral component of BMBF funding.

- **Develop and use new knowledge transfer formats to incorporate skills transfer into existing communications in addition to knowledge transfer:** In addition to the established measures of knowledge transfer, new formats of interdisciplinary and transdisciplinary cooperation and culturally appropriate and context-specific forms of communication must be developed. Digital, interactive formats and visualisations, such as augmented and virtual reality, Massive Open Online Course (MOOC), e-learning, etc. offer considerable potential for communicating content to different groups according to their needs, entering into a dialogue with them, and thus creating experiential spaces for the target group. The opened experiential space thus provides an opportunity to create a deep understanding of new research findings and acceptance of related measures. However, this interaction with “learners” also offers the opportunity to incorporate feedback into the further development of research and provides a far-reaching gain in knowledge for science. In this way mutual understanding can be strengthened and a change of perspective made possible in the sense of a transdisciplinary research approach.

- **Transfer activities as a further criterion for the quality of the scientific performance:** One obstacle to knowledge transfer is that scientific performance is evaluated almost exclusively by output in the form of scientific publications. In order to strengthen the importance of knowledge transfer, a recognition of transfer and communication achievements is necessary that goes beyond the traditional evaluation of scientific performance. This calls for a special set of indicators for transfer services that enables evaluation and impact measurement, but which can also be carried out via narratives. The further assessment of the effects in society can only be made possible by appropriate accompanying research, for which additional means must be explicitly provided.

- **Antarctic-specific communication – raising awareness in society:** According to the Antarctic Treaty, Antarctica and the Southern Ocean surrounding it are an area in which the ecological balance is to be maintained, in which territorial claims are dormant, in which there are no military operations and no extraction of mineral resources, and which is dedicated to peaceful research and international cooperation. These favourable and unique conditions mean that, with the appropriate social and political will, the importance of Antarctica for life in other continents and also in the northern hemisphere can be studied, especially with regard to climate change, biodiversity and ecosystem services, and Antarctica can serve as an example region for conservation measures. Transfer and communication measures that help to improve this understanding among the population and decision-makers should be strengthened.

- **Arctic-specific communication – dialogue with the local and indigenous population:** In addition to target groups within German and international society, Arctic research transfer and communication activities should particularly consider the diverse social groups in the Arctic. Where appropriate, communication and transfer activities should be developed in dialogue with the indigenous and local population and their political, administrative, and economic representatives, especially when research is conducted on indigenous lands. Such activities support the implementation of the German Arctic Guidelines, promote the inclusion of local and indigenous knowledge as an equal form of knowledge, and enable transdisciplinary research approaches.

In view of the rapid changes in the polar regions, the transfer of knowledge and the communication of research results to society are becoming increasingly important. Knowledge-based decisions on climate and environmental protection, adaptation strategies and sustainable development require an intensive dialogue between science and society and thus also innovative knowledge transfer and communication measures.

Contributing authors

MARE:N Polar Research Scientific Advisory Board

- Christian Beer (University of Hamburg)
- Nicole Biebow (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Matthias Braun (University of Erlangen-Nuremberg)
- Nina Döring (IASS Potsdam – Institute for Advanced Sustainability Studies e. V.)
- Christoph Gaedicke (Federal Institute for Geosciences and Natural Resources – BGR)
- Julian Gutt (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Wilhelm Hagen (University of Bremen)
- Judith Hauck (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Günther Heinemann (University of Trier)
- Heike Herata (Federal Environment Agency – UBA)
- Jürgen Holfort (Federal Maritime and Hydrographic Agency – BSH)
- Thomas Jung (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Heidi Kassens (GEOMAR Helmholtz Centre for Ocean Research Kiel)
- Sybille Klenzendorf (WWF)
- Andreas Läufer (Federal Institute for Geosciences and Natural Resources – BGR)
- Gerrit Lohmann (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Uwe Nixdorf (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Simon Plass (German Aerospace Center – DLR)
- Petra Quillfeldt (University of Giessen)
- Monika Rhein (IUP/MARUM, University of Bremen, Chair NK SCAR/IASC)
- Volker Rachold (German Arctic Office at the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research – AWI)
- Arne Riedel (Ecologic Institute)
- Torsten Sachs (Helmholtz Centre Potsdam German Research Centre for Geosciences – GFZ)
- Manfred Wendisch (University of Leipzig)

With chapter contributions by:

- Holger Auel (University of Bremen)
- Kai Bischof (University of Bremen)
- Michael Bittner (German Aerospace Center – DLR)
- Angelika Brandt (Senckenberg Research Institute and Natural History Museum)
- Antje Boetius (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Victor Brovkin (Max Planck Institute for Meteorology Hamburg)
- Erhard Diedrich (German Aerospace Center – DLR)
- Andreas Dietz (German Aerospace Center – DLR)
- Stephan Dudeck (University of Lapland)
- Olaf Eisen (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Hauke Flores (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Stephan Frickenhaus (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Michael Fritz (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Johannes Fürst (University of Erlangen-Nuremberg)
- Helge Goessling (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Klaus Grosfeld (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Guido Grosse (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Georg Guggenberger (University of Hanover)
- Stefan Hain (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Martin Heimann (Max Planck Institute for Biogeochemistry Jena)
- Andreas Herber (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Helena Herr (University of Hamburg)
- Thora Herrmann (Helmholtz Centre for Environmental Research – UFZ)
- Ulrike Herzschuh (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Mario Hoppema (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Martin Howarth (Technische Universität Dresden)
- Angelika Humbert (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Torsten Kanzow (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Michael Karcher (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Ulf Karsten (University of Rostock)
- Frank Kauker (OASYS GmbH)
- Peter Köhler (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Lisa Küchelbacher (German Aerospace Center – DLR)
- Frank Lamy (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Moritz Langer (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)

- Gisela Lannig (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Hugues Lantuit (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Lester Lembke-Jene (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Susanne Liebner (Helmholtz Centre Potsdam German Research Centre for Geosciences – GFZ)
- Heike Link (University of Rostock)
- Martina Löbl (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Cornelia Lüdecke (Munich)
- Andreas Macke (Leibniz Institute for Tropospheric Research)
- Felix Mark (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Dirk Mengedoht (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Bettina Meyer (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Heinrich Miller (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Anne Morgenstern (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Juliane Müller (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Bettina Münch-Epple (WWF)
- Marcel Nicolaus (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Eva-Maria Nöthing (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Dirk Notz (University of Hamburg)
- Elle Merete Omma (Saami Council)
- Mustafa Osama (ThINK – Thuringian Institute for Sustainability and Climate Protection)
- Lavinia Patara (GEOMAR Helmholtz-Center for Ocean Research Kiel)
- Dieter Piepenburg (GEOMAR Helmholtz Centre for Ocean Research Kiel)
- Hans-Otto Pörtner (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Christian Printzen (Senckenberg Research Institute and Natural History Museum)
- Johannes Quaas (University of Leipzig)
- Thomas Rackow (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Lutz Reinhardt (Federal Institute for Geosciences and Natural Resources – BGR)
- Annette Rinke (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Ralf Röchert (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Gertrude Saxinger (Austrian Polar Research Institute)
- Barbara Schellhammer (Munich School of Philosophy)
- Ingo Schewe (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Ralf Schiebel (Max Planck Institute for Chemistry Mainz)
- Daniel Scholz (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Thomas Soltwedel (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Gunnar Spreen (University of Bremen)
- Rüdiger Stein (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Daniel Steinhage (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Lars Stemmler (Bremenports)
- Katharina Teschke (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Ralf Tiedemann (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Vilena Valeeva (IASS Potsdam
- Institute for Advanced Sustainability Studies e. V.)
- Christine Wesche (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Ilka Weikusat (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Martin Werner (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Thomas Westerhold (MARUM – Center for Marine Environmental Sciences, University of Bremen)
- Nicole Wienrich (IASS Potsdam – Institute for Advanced Sustainability Studies e. V.)
- Ricarda Winckelmann (Potsdam Institute for Climate Impact Research – PIK)
- Karsten Wurr (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)
- Sabine Wüst (German Aerospace Center – DLR)
- Ying Ye (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research – AWI)

Projektträger Jülich has actively supported the work of the advisory board, in particular Lydia Gustavs and Susanne Fretzdorff. The creation of this document was enabled by the following process:

- June 2020 – Consultation processes within the framework of the Arctic Dialogue and SCAR/IASC Annual Meeting
- August 2020 – Appointment of the chairpersons and selection of the Scientific Advisory Board.
- September 2020 – Constituent meeting of the Scientific Advisory Board
- December 2020, January, February, March and April 2021 – Working meetings of the Scientific Advisory Board
- May 2021 – Handover of the concept paper to the BMBF

Bibliography

Imprint

Publisher:
MARE:N “Research Agenda Polar Regions in Transition” Scientific Advisory Board

Typesetting and layout:
Project Management Jülich, Forschungszentrum Jülich GmbH

Print:
WEISS-Druck GmbH & Co. KG, Monschau

Translation:
GlobalSprachTeam | https://sprachteam.com

Image credits:
Title: Stefanie Arndt (AWI) | p. 4: Projektträger Jülich | p. 5: Arctic Council Secretariat/ Jessica Cook | p. 6: Michael Fischer (AWI) | S. 14: @Alfred-Wegener-Institut/Christine Wesche, Projektträger Jülich | p. 62: © DLR (CC-BY 3.0) | p. 66: Josefine Lenz (AWI)

Date:
October 2021