EU-PolarNet
connecting science with society

The EU-PolarNet White Papers

Preamble by the EU-PolarNet coordinator

The Polar Regions are unique realms of planet Earth, they fascinate us with their remoteness, harsh and beautiful landscapes, and their highly adapted wildlife. They are essential for our climate and the weather patterns we are used to. They are sentinels of climate change, human expansion and the hunt for new resources, but also for peaceful international cooperation in Earth system research and nature protection. Since the advent of the Framework Programme in the 1980s, EU researchers have made tremendous strides in polar research, such as:

- improving understanding of polar climate processes and developing techniques to provide robust projections of change at the poles and across the global climate system;
- understanding the structure and function of polar ecosystems and how life has adapted to survive in extreme environments; and
- mapping the transport and accumulation of pollutants in e.g. food webs, and helping communities plan for the future.

Today, EU members operate world-class research infrastructures in both the Arctic and Antarctic, they have prominent leadership roles in many fields of polar research, and comprise an integrated and effective research community.
In coming years, there is need and potential to deliver even more facts and information by developing co-designed research programmes using interdisciplinary methodologies that encourage real-world problem-oriented approaches enhancing societal impacts.
In the recent Joint Communication to the European Parliament and the Council 'An integrated European Union policy for the Arctic ', the European Commission and the High Representative noted that the EU is committed to the Arctic and will engage with the region in three priority areas, as follows:

- climate change and safeguarding the Arctic environment;
- promoting sustainable development of the region; and
- supporting international cooperation on Arctic issues.

They also indicated that, under Horizon2020, the EU expects to maintain funding to Arctic research, which has amounted to around 200 million Euro over the last decade.

Antje Boetius, Director of the Alfred Wegener Institute *(Photo: Kerstin Rolfes)*

The five white papers introduced here are a product of the EU-PolarNet; a project funded under H2020 for five years, involving a consortium covering a vast range of European expertise in both Antarctic and Arctic Research. EU-PolarNet includes natural and social scientists, providers of polar logistics and infrastructures, and key stakeholders. EU-PolarNet works with the European Commission on many aspects related to the Polar Regions, identifying and developing, most often jointly with stakeholders, the research needs and opportunities that are of high societal relevance to Europe. These activities will contribute to the development of an Integrated Polar Research Programme, which will be presented to the European Commission in 2020.

The white papers represent an important step towards developing this programme. In them we identify research topics of most relevance to society and timeliness for their delivery, for further consideration in the appropriate panels and boards.

Prof Dr Antje Boetius
Director of the Alfred Wegener Institute
Helmholtz Centre for Polar and Marine Research

Foreword by the chairs

With rapid environmental change in recent decades, nowhere is climate change more evident and far reaching than in the Polar Regions. With communities and ecosystems subject to multiple environmental, climatic, cultural and economic stresses, the Polar Regions truly represent the sentinel of climate change. Already now, changes in the Polar Regions are changing the lives of polar residents, and are affecting the well-being of many polar communities. Furthermore, the state of the polar systems has far reaching effects on atmosphere, ocean and land including the change of weather pattern in Europe.

At both poles dramatic physical changes, such as the loss of ice cover and opening of ice-free areas on both land and sea, are well-documented and have become emblems of climate change. However, other subtle changes are also becoming apparent that may disrupt established (infra)structures, patterns and practices in ecosystems, communities and economic sectors. These recently identified changes may lead to major modifications in global ecosystem functioning and services. Across the Arctic, many diverse human communities will need to respond in order to navigate the profound changes in the ecosystem services on which they currently rely. Lives and livelihoods will undoubtedly be affected. In both Polar Regions, our ability to draw benefits safely and sustainably from natural resources, and to preserve and conserve the natural capital, their unique biodiversity and wilderness are at stake.

The changes occurring in the Polar Regions are, however, not just regional in impact. From north and south, changes near the poles exert a far wider influence on the global system. European weather is influenced by Arctic sea ice, and recent patterns of unusual weather, and occasional extreme events, have their genesis in a changing Arctic and Antarctic. Ice lost from Antarctica and Greenland contributes to rising global sea-levels that are being felt on coastlines around the world, increasing the risk to European coastal communities, assets and natural systems. Furthermore, the influence of the Polar Regions is not limited to physical and biological systems. Historically, the impact of competition for polar resources has had wide geo-strategic and socio-economic impacts, and may lead to significant political challenges in coming decades

David Vaughan, Director of Science, British Antarctic Survey

Antonio Quesada, Executive secretary of the Spanish Polar Committee

European researchers contribute significantly to understanding the consequences of climate change in the Polar Regions, and help developing specific strategies to mitigate and adapt to these changes. In its Arctic policy[1] the EU states that a safe, stable, sustainable and prosperous Arctic is important not just for the region itself, but for the European Union (EU) and the world.

The EU-PolarNet white papers will give the EU and national research agencies guidance, which research themes are of high importance to advance in the understanding of the ongoing change not only in the Arctic but in both Polar Regions.

Prof David Vaughan
Director of Science, British Antarctic Survey

Prof Antonio Quesada
Executive secretary of the Spanish Polar Committee

[1]https://eeas.europa.eu/arctic-policy/eu-arctic-policy_en

The EU-PolarNet White Papers

The following white papers were developed by a specially selected team of EU and overseas experts from diverse areas of polar research. These experts were challenged to identify polar research topics with a clear societal relevance and a specific importance for Europe that could make them suitable for future EU support. These topics will, if adopted, further enhance EU research excellence, increase efficient use of European resources and expertise, and lead to a step change in data availability, access and interoperability. They will further increase the scale of polar research cooperation in Europe and, by including non-EU partners, will improve global cooperation. Each of the topics employs a strongly interdisciplinary approach to deliver benefits in the complex and multi-faceted real-world of policy issues. Some of the white papers describe approaches that step outside traditional disciplinary boundaries, offering a transformational or even 'post-disciplinary' approach. Each is designed to deliver tangible benefits to problems that arise in the Polar Regions from the complex interactions of a changing physical environment, stressed ecosystems, complex issues of sovereignty and governance, and layered cultural and social structures.

White Paper development

The EU-PolarNet white papers presented here were developed after preparatory work conducted in two stages.
First, an assessment of existing prioritised objectives, as expressed in published documents describing international, national and institutional policies and strategies of polar research identified ten priority as follows:

1. Polar climate system
2. Cryosphere
3. Palaeoclimate and palaeoenvironment
4. Polar biology, ecology and biodiversity
5. Human impacts
6. Solid Earth and its interactions
7. Sustainable management of resources
8. People, society and culture
9. Human health and wellbeing
10. Astronomy, astrophysics and space

Second, an online survey in 2017 allowed the identification of a public perspective on key polar research priorities. In this process, over 550 responses were obtained, representing institutions, companies, communities and individuals. The answers were categorised and sorted, and provided the basic foundations upon which the white papers were built.

In September 2017, armed with the results of these two preparatory exercises, EU-PolarNet convened a team of 50 experts from 16 countries to identify key needs, and debate and draft the white papers presented here. This team drew participants from many areas of polar research, including:

- Climate, atmospheric, oceanographic, cryospheric and geological sciences;
- Social, historical and cultural research;
- International policy development, environmental regulation, resource management and governance;
- Behavioural, ecosystem and evolutionary biology; and
- Satellite, communications, instrument and autonomous technologies.

These researchers were complemented by representatives from business and Arctic communities. Following a specially prepared methodology, involving several stages of refinement, the teams identified the topics and began the preparation of what has become the EU-PolarNet white papers. Interactions between experts from different knowledge areas were facilitated, promoting cross-fertilisation and co-creation from the beginning. As a consequence, the white papers presented here are the result of an interdisciplinary effort aimed at finding synergies focused on societal challenges.

The EU-PolarNet Consortium wishes to gratefully acknowledge this team of invited experts, whose generous contribution of their time and expertise was essential for the success of the workshop and its outcomes.

The breadth of expertise available within the workshop team, the retreat-style approach and the 'safe-house' method for debate, allowed topics identified in the white papers to benefit from a truly interdisciplinary collaboration. The topics themselves are issue-focused, and their implementation could prove to be transformational in polar research.

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The Arctic and Antarctic: Similar, not identical

The Polar Regions share many real and apparent similarities. Both are cold, icy, and sparsely populated (if at all); and both are considered remote, except perhaps by the people who live there! However, the Polar Regions are also profoundly different geographically, politically and biologically. It is important to acknowledge and understand these differences.

Geographic connectivity

While there is connectivity between the Arctic areas and northern latitudes via both land and sea, a strong Antarctic Circumpolar Current system impedes the exchange between the Antarctic and the Southern Ocean with the rest of the world. Despite their differences, both Polar Regions act as sentinels of climate change, and represent natural laboratories capable of providing extremely valuable insights into physical, biological and ecological processes at lower latitudes. For example, the relative simplicity of polar ecosystem structures, and rapidity of the changes to which they are being exposed, make them ideal places to investigate the fundamentals of ecosystem vulnerability and resilience.

Governance and human presence

While the Arctic Ocean is itself an international area, the lands that encircle it are the territory of eight Arctic Countries that cooperate under the auspices of the Arctic Council (AC). The Arctic regions are home to indigenous populations whose presence dates back thousands of years. The Antarctic is a continent under international governance through the Antarctic Treaty System (ATS). Parts of Antarctica have been subject to transient human presence for almost 200 years, but only in the past 65 years has human presence been substantial.

Protection and conservation

In the Arctic, it is important to build development pathways that protect ecosystems while optimising the sustainable use of resources (especially those that are renewable) for the benefit of local communities and humanity in general. In the Antarctic, the imperative lies primarily in protection and conservation in accordance with the ATS, which among other things supports peaceful use of the area for science; other forms of international cooperation through commercial activities like tourism and fishing may occur.

Given these differences, a question arises as to whether benefits will arise from a fully 'Integrated' Polar Research Programme. To this question our expert teams have responded positively, citing key areas where north-south divergence of research communities and programmes has led to incomplete exploitation of potential north-south synergies and efficiencies. For example:

- There is a strong likelihood that, with atmospheric and ocean warming altering glaciological conditions, key parts of Antarctica over the coming century will resemble Greenland as it is today. Process studies undertaken in Greenland could thus improve projections of ice-loss from Antarctica and consequently of global sea-level rise.

- The ecosystem approach enshrined in the international agreements that manage Southern Ocean fisheries may provide a sustainable and equitable framework for the protection of the Arctic Ocean as sea ice retreats and new fishing grounds become available.

- Tourism is now a global phenomenon and is well established in the Polar Regions. The management and conservation issues that the remote and wild places on our planet face and the benefits that tourism brings are universal and apply equally to both Polar Regions.

Our White Papers seek to maximise synergies and cooperation between Arctic and Antarctic research communities by identifying research topics which are important to investigate in both Polar Regions.

EU-PolarNet
White Paper No. 1

The coupled polar climate system:
Global context, predictability and regional impacts

Glacier front, Alpefjord, Northeast Greenland National Park *(Photo: Peter Prokosch)*

Motivation and background

Polar Regions are the fastest warming areas on Earth. Local and indigenous communities and operators in the Polar Regions are the most directly affected. Nevertheless, the natural physical processes that take place in the Polar Regions have also a strong global impact on climate conditions and therefore affect lives and livelihoods across the world. Further future changes in climate mean that many of these processes may be altered in intensity and their effects may induce changes across the Planet with largely still unknown impacts on local and global societies.

The Earth's current climate is changing more rapidly than has been predicted in most scientific forecasts. In the last decade progress has been made in many fields of polar climate research. In particular, numerical development of individual model components of polar systems (e.g., atmosphere, ocean and ice) has largely improved. However, what is lacking in these models and has been underestimated so far is how the different natural physical processes interact. For instance, increased rain implies more influx of freshwater from rivers to the oceans, locally influencing the salinity, which in turn can have an influence on the extent and thickness of sea-ice cover. These complex interfaces are poorly understood, but are of great importance for a better understanding of our global climate system.

To improve the understanding of the Polar climate system, further studies about the interactions between its various components are needed and development of advanced observational and modelling techniques is required. Only in a fully coupled model and truly interactively observational setting can climate feedbacks be properly identified and predictability horizons be determined. An important step is the use of an interdisciplinary approach with innovative observation and modelling techniques. This is also needed to downscale climate parameters from the global to the regional setting, to assess local impacts and devise adaptation strategies.

Thus, this white paper outlines the state of the art and actions required to significantly advance the knowledge of the polar climate system in both hemispheres. The paper gives recommendations to develop a research programme addressing the following objectives:

- Enhance the understanding from data acquisition and long-term observation of processes controlling, and feedbacks (Box 1) resulting from, the interactions between the polar climate system components.
- Identify key interaction and feedback processes and improve the description of these processes in coupled earth system models and in coupled regional models.
- Advance the settings of observation systems and fully coupled climate models in order to improve assessments of regional climate change impacts.
- Identify risks and vulnerability in the Polar Regions in order to define adaptation and mitigation actions in response to climate changes.

Tackling these objectives will guide the science in white paper No. 2 (Footprints on Changing Polar Ecosystems: Processes, Threats, Responses and Opportunities for Future Generations), No. 5 (Advancing operational informatics for Polar Regions) and No. 4 (The Road to the Desired States of Social-ecological Systems in the Polar Regions). However, the research based on this present white paper will also benefit from outcomes from white paper Nos. 4 and 5.

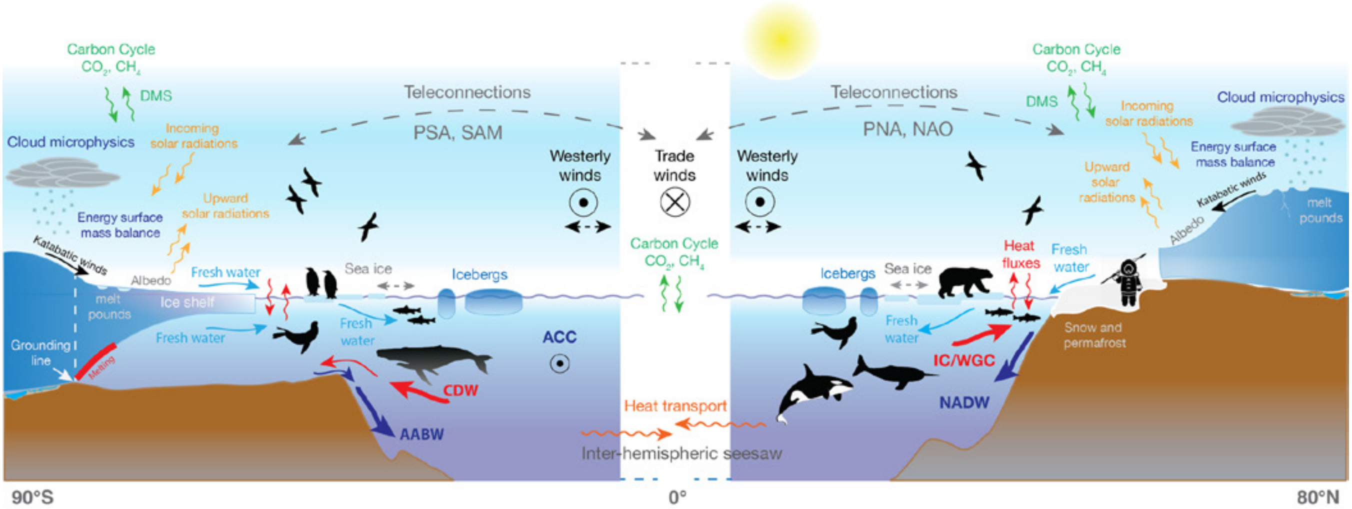


Fig 1. Components of the Polar System and their interactions (non exhaustive). Most of those processes and feedbacks are still poorly understood or quantified and require further observations. Pacific South/North American pattern (PSA, PNA), North Atlantic Oscillation (NAO), South Annular Mode (SAM), Dimethylsulfide (DMS), Carbon dioxide (CO_2), Methane (CH_4); Ocean: Antarctic Circumpolar Current (ACC), Antarctic Bottom Water (AABW), Circumpolar Deep Water (CDW), North Atlantic Deep Water (NADW), Irminger Current (IC), West Greenland Current (WGC). Modified after Colleoni et al., 2018[1].

Societal Relevance

Indigenous peoples, residents and operators in the Polar Regions are those most directly affected by climate change. However, natural physical processes occurring in the Polar Regions regulate environmental conditions across the globe. 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 coupled climate models in a global context will benefit the people, environmental policy, ecosystem management, and businesses well beyond the Polar Regions. Thus, a better understanding of the coupled Polar climate system is important to address the following societally relevant effects of climate change.

Reduction in sea ice

Arctic sea ice has declined strongly in the past two decades, extending the open water season, with direct impacts on economic activities (e.g. shipping, extractive industries, tourism and fisheries). Thus this decline has relevant consequences for society but also for the biodiversity and for the climate system:

Expanding open water areas in summer have altered the usual energy balance of the Arctic, as the dark surface of open waters absorbs energy, whereas sea ice reflects it. This further amplifies warming in the Arctic with the potential to impact on large-scale atmospheric and oceanic circulation. This is directly related to extreme weather events, including pathways and frequency of occurrences of polar lows. The sea ice decline in the Arctic and also, although still locally, in Antarctica strongly affects the production of bottom water that ventilates the oceans and triggers the Meridional Overturning Circulation (Box 2). The decline of the sea ice in the Polar Regions strongly affects also the marine and terrestrial ecosystems since it plays an important role for marine biogeochemistry and as a platform for foraging (wildlife feeding).

On one hand, the reduction of sea ice has physical effects on the coasts since the increased fetch will put coastal communities at risk from large waves during storms and increase coastal erosion, especially in permafrost coasts. Furthermore, the local

Box 1: Feedbacks occur when outputs of a system are routed back as inputs as part of a chain of cause-and-effect that forms a circuit or loop. The system can then be said to feed back into itself. An interaction mechanism between processes in the climate system is called a climate feedback, when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

Box 2: The Meridional Overturning Circulation is a system of surface and deep currents encompassing all ocean basins. It transports large amounts of water around the globe, and connects the surface ocean and atmosphere with the huge reservoir of the deep sea. As such, it is of critical importance to the global climate system. It regulates part of the inter-hemispheric heat transport.

[1]Colleoni, F., De Santis, L., Siddoway, C. S., Bergamasco, A., Golledge, N. R., Lohmann, G., & Siegert, M. J. (2018). Spatio-temporal variability of processes across Antarctic ice-bed-ocean interfaces. Nature communications, 9(1), 2289

communities use the sea ice as infrastructure for transport and for hunting. Thus, not only reduction but also thinning of the sea ice has consequences for the local communities.

On the other hand, sea ice retreat also opens new routes for ocean transportation and facilitates exploitation of resources.

Global sea level rise

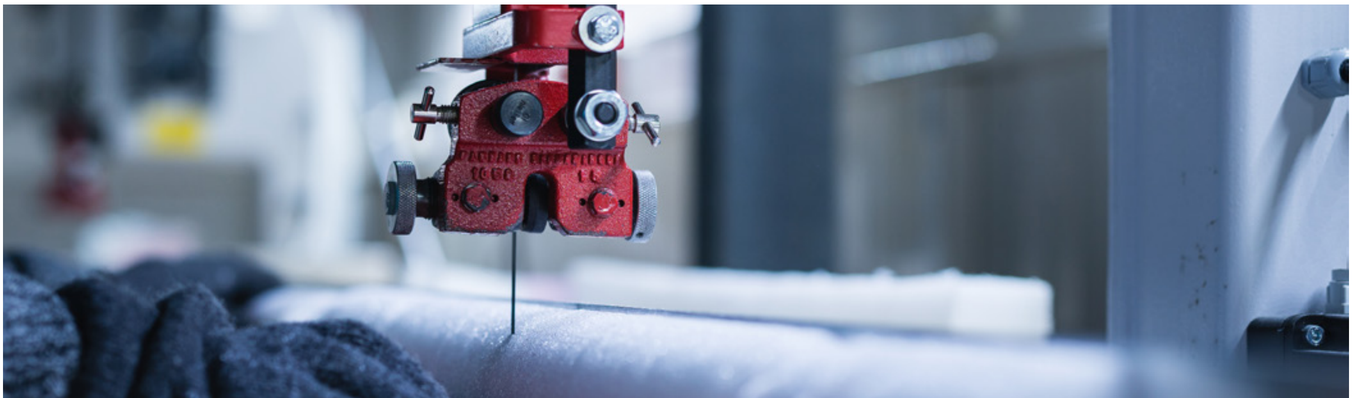
The Antarctic and Greenland ice sheets and the small glaciers across the Arctic, the Antarctic Peninsula and Sub-Antarctic Islands and at lower latitudes hold sufficient water to significantly raise global sea-level over coming decades and centuries. The uncertain stability of these glacial systems, many of which are affected by rapid transformations, makes them uniquely vulnerable to atmospheric warming, hydrological cycle variations and changes in ocean temperature and circulation. Paleoclimate studies (Box 3) confirmed that ice retreat and discharge from Antarctica contributed several meters to sea level during past warm climate periods.

Improving our understanding and ability to predict changes in the glacier systems poses particular challenges to science, but is essential in order to manage the risks to coastal communities, precious coastal ecosystems and major capital assets across the globe. Thus, it is urgent to better know how polar ice sheets will react to the warming, how much and how fast the global sea level will rise and how the global circulation (and consequently the latitudinal heat transfer and precipitation) will change. Action must be taken right now to plan good mitigation policies. Under the Paris Agreement, an IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) is under preparation, for release in late 2019.

Changes in freshwater flow impacting marine waters

Future changes in Arctic precipitation and temperature patterns are expected to influence the snow cover in the northern hemisphere. Here, snow cover shows large declines in springtime, impacting the length of snow melt season, river discharge and amount of freshwater input to the Arctic Ocean.

Increased freshwater fluxes from melting glaciers and ice sheets as well as an enhanced hydrological cycle and river discharge of e.g. nutrients and suspended particulate matter will have potentially severe impacts on coastal marine and terrestrial ecosystems, will increase natural hazards from proglacial lakes and river flooding, and will influence hydropower potential and river services. These problems should be addressed in close consultation with local communities. Shifts in the distribution of marine species due to ocean warming and increased inflow of freshwater, which for example changes the salinity of sea water, will have consequences for fishery activities and natural ocean resources. At the global scale, stronger ocean stratification as a result of meltwater runoff may potentially impact the ocean Meridional Overturning Circulation, with consequences for the ocean ventilation and heat transport to the Polar Regions, but it may also impact carbon exchanges between the atmosphere and the oceans, with potential consequences on atmospheric CO_2 evolution.



Box 3: Paleoclimate information

Paleoclimate information is extracted from ice and sediment strata in which several proxies (like the composition of air bubbles and dust trapped into ice layers, or of the fossils and minerals contained in sediments) reflect warm (interglacial) or cold (glacial) environmental conditions at the times of sediment deposition. Proxies tell about changes in precipitation/accumulation rates, sea ice covered or open waters, ventilated or stagnant circulation, etc. For example open water conditions in the Ross Sea and in the Wilkes Land margins during the warm Pliocene (ca. 3 Million years) constrained simulation of Antarctic marine sectors collapse (equivalent to +11.3 m of mean global sea level rise, DeConto and Pollard, 2016[1]), when the atmospheric CO_2 concentration was 350-400ppm, the global average air temperature was +3°C, and the global mean Surface Sea Temperature was + 2°C SST (+3-5°C in Antarctica, Ross Sea).

[1] DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), 591-597.

Photo: Alfred Wegener Institute / J. V. Kleine

Spring melting at Kongsfjorden *(Photo: Alfred Wegener Institute / René Bürgi)*

Changes in permafrost and terrestrial habitats

Terrestrial and sub-sea permafrost are extremely sensitive to climate change and key to the carbon cycle, with significant impacts on carbon dioxide and methane release into the atmosphere. Permafrost degradation results in changes in the landscape and ecosystems, with hazard implications such as damage to infrastructures, increased coastal erosion, contaminant release, health issues and modifications concerning mobility of humans and animals. The scientific community (experimental and modellers) must work together to improve the integration and coupling of permafrost (including sub-sea permafrost) models in ESM, as the permafrost areas are essential components of the climate system. Governments, businesses and individuals need to collaborate more with the climate scientific community to base investment in and management of permafrost regions on informed decisions.

Cloud formation and atmospheric composition

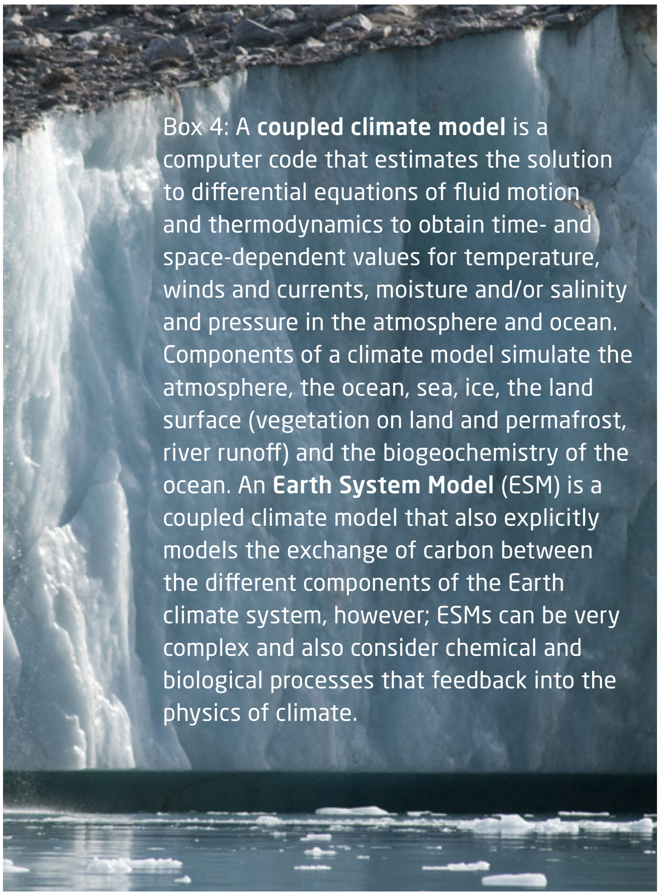
Changes in terrestrial as well as at marine surfaces including the retreat of sea ice will affect not only greenhouse gas exchange between the surface and the atmosphere but also the surface-atmosphere exchange of particles and trace gases, which can form new particles in the atmosphere. This influences atmospheric chemical processes such as particle and cloud formation and alters the atmospheric composition and oxidation processes. These changes will have an effect on precipitation, air quality, radiative balance and subsequently on climate change. Changes in patterns of the atmospheric circulation will also affect the transport mechanisms of pollutant emitted outside the Polar Regions, and this can additionally influence the atmospheric composition in Polar Regions and thus on the regional climate.

Fog rolling over the Lena River while the first summer sun bathes the last remnants of the winter ice *(Photo: Alfred Wegener Institute / Torsten Sachs)*

The vertical and horizontal distribution of clouds and the interactions with the climate system are one of the most difficult components to model, especially in the Polar Regions, due to difficulties in obtaining good measurements. This leads to a lag in the understanding of key processes and has consequences for the accuracy of climate change projections.

Research Needs

This white paper identifies three urgent actions that will initiate crucial research leading to a better understanding of the Polar Regions' environment, and to its proper representation in regional and fully-coupled Earth System Models (Box 4). Only with an accurate representation of the coupling between the different components of the polar climate system can the sensitivity of these regions to climate change be properly addressed. The actions are based on **understanding the true coupled Earth Climate System** (subtopic 1), **understanding the limits of predictability of coupled Earth System Models** (subtopic 2), and **developing the techniques that will allow downscaling from global to regional scale** (subtopic 3) to provide stakeholders with the projections that they will require for making informed choices.



Box 4: A **coupled climate model** is a computer code that estimates the solution to differential equations of fluid motion and thermodynamics to obtain time- and space-dependent values for temperature, winds and currents, moisture and/or salinity and pressure in the atmosphere and ocean. Components of a climate model simulate the atmosphere, the ocean, sea, ice, the land surface (vegetation on land and permafrost, river runoff) and the biogeochemistry of the ocean. An **Earth System Model** (ESM) is a coupled climate model that also explicitly models the exchange of carbon between the different components of the Earth climate system, however; ESMs can be very complex and also consider chemical and biological processes that feedback into the physics of climate.

Photo: Peter Prokosch

Subtopic 1: The coupled polar climate system in a global context

Recent years have seen the development of several first generation Earth System Models (ESMs), and these are currently the best available tools to study the coupled climate system. However, these have been heavily tuned and developed for the mid-latitudes where most people live, and their representation of polar processes is incomplete. In particular, important polar components (e.g., ice-sheets, glaciers, permafrost, snow, sea-ice, seasonally-frozen rivers and lakes) are either poorly represented or are passive rather than interactive (coupled) components. This means that the associated feedbacks are also poorly represented, and this negatively impacts the quality of projections produced.

We propose research to improve the understanding of the interactions between the polar components and ensure that these currently passive polar components become active (fully-coupled) components in future regional and ESMs. Requirements to make these components active and fully coupled are 1) improved knowledge of currently poorly represented processes and their interaction or coupling through intensive field studies and enhanced data utilization, 2) explicit representation rather than parameterization of these processes in ESMs, and 3) increased observational coverage and technological capacity, including baseline characterization and long term observation, to evaluate and calibrate these components.

Table 1: Time scales for dynamic processes in the earth system.

Time scale	Processes	Components
< 1sec	atmospheric turbulence	atmosphere
< 1 day	ocean turbulence, atmospheric transport, cloud formation	atmosphere, hydrosphere (oceans, lakes and rivers)
1 day – 1 year	weather systems, cloud formation, pollutant transport, thaw propagation, sea ice and snow cover	atmosphere, hydrosphere, cryosphere (snow, ice and permafrost), biosphere
1 year – 100 years	ice shelves, ocean ventilation and circulation, permafrost degradation and active layer thickening, carbon cycle.	hydrosphere, cryosphere, biosphere, lithosphere
100 years <	ice sheet dynamics and isostatic adjustment	cryosphere, lithosphere (soils and rocks)


Penguins observing a measurement tower in Antarctica *(Photo: Alfred Wegener Institute / Stefan Hendricks)*

A fundamental problem with the proposed coupled approach of observing polar climate processes and modelling is the wide variety of time-scales involved (Table 1).

This variety of time-scales ranging from sub-second to millennial poses a huge challenge for running computationally expensive ESMs over sufficiently long periods; overcoming this requires smart solutions for initializing the slow components such as the oceans and ice sheets, and innovative integration techniques such as variable temporal and spatial model resolutions. The wide range of time scales also poses challenges for observational capacity and innovation to constrain and evaluate model outcomes, such as lengthening existing time series, merging in situ with remote sensing observations, data assimilation and use of palaeoclimate and palaeoenvironmental records. Addressing these problems requires intimate knowledge of the processes involved.

This subtopic would need stronger collaboration between field researchers and modellers. It requires field and laboratory studies of processes coupling the atmosphere, ocean and cryosphere, which are still not fully understood, taking advantage of the enhanced network of observation platforms in the Arctic and Antarctic. Furthermore, this subtopic requires participation of modellers from the many, currently rather isolated, discipline-based modelling communities, in order to integrate key model components and build tools that would allow routine coupling of model components.

Although progress on multiple-coupled models must be the end goal, we can identify several areas where an improved understanding of the interaction or coupling is urgently required to fully explore the two-way feedbacks that are known to be important in shaping polar change:

- Ocean circulation and heat content vs. ice-sheet/glaciers (polar)
- Atmosphere vs. sea/ice/ocean/permafrost (carbon cycling, cloud formation, transport of short-lived climate forcers (e.g. Black carbon))
- Ice-sheet/glacier vs. subglacial hydrological and sediment conditions
- Changes in hydrology vs. snow cover and precipitation

Subtopic impacts

Research on this subtopic would provide societal benefits in many areas where improved projections of environmental changes are required; for example:
- better sea level rise predictions
- more detailed risk maps of storm surges
- improved representation of feedback processes
- better understanding of greenhouse gas climate sensitivity (how easy and how fast the climate and ice sheets react to greenhouse gas variations), climate forcing (black carbon, etc.), through better inclusion of interactions between atmosphere, ocean, cryosphere and biogeochemical cycles.
- better forecasting/projections/predictability of extreme events

Subtopic 2: Predictability of the polar climate system

This topic is aimed at understanding and expanding the limits to which we can robustly predict future changes in the Polar Regions. Especially, how rapid the changes will be and whether these changes will be gradual or sudden (e.g., involving 'tipping points'). Progress on this subtopic will increase understanding by a wide range of stakeholders about the limits of predictability, or inherent uncertainty, in projections of change, allowing a better choice of adaptation pathways.

Society requires reliable predictions in order to meet the challenges communities and ecosystems will face under a warming world with significantly less snow and ice. Improving predictability of climate change and its effects, including both risks and opportunities, in the Polar Regions will not only help local inhabitants, but through teleconnections via atmospheric and oceanic circulation, it will also improve predictability at lower latitudes.

Many aspects of the polar climate system are experiencing profound changes, though the pace and magnitude of changes vary among the different components of the Polar Regions (see Table 1). Therefore, predictability and adaptation pathways need to take into account the different rate and magnitude of future changes. Several physical factors affects and inhibit the predictability in the polar climate system. For example on seasonal time scales these include sea ice extent and thickness, snow depth, permafrost active layer depth and sea surface temperature. On decadal time scales the factors or processes inhibiting predictability include ice shelf collapse and ice stream speed flow acceleration, sea ice thickness, permafrost degradation, and heat and salinity of subsurface water masses. There is also decadal predictability associated with greenhouse gas-induced warming, most notably in the Arctic and in the marine sectors of the Antarctic ice sheet. While some impacts of polar changes are more immediate (i.e. sea ice loss, coastal erosion, shifts in ecosystems), other components, such as ice sheet contribution to sea level rise, are generally more gradual, though may contain larger uncertainties that are difficult to assess, especially with sparse data coverage. This poses added complexity and challenges in providing useful and reliable forecasts relevant for society.

Accurate characterization of the current state of the different components of the polar system, and how these are coupled, is required in order to make significant improvements in polar predictability. Shortcomings in current coupling and feedbacks of cryospheric components in climate models limit our predictability, but this can be addressed by improving the models and their coupling.

Further, predictability of the polar climate system relevant for society should be tested by hindcasting (retrospective prediction tested against observations) over the last 30 years, which have the most reliable observations, especially since the launch of satellites, and the establishment of Polar monitoring sites, including indigenous observations back in time. In many cases, the lack of direct observational data should be addressed by gathering data using paleoclimate proxies.

Predictions on seasonal time-scales, essential for community and industry planning, will require (1) improved observation networks for model initialization and guidance; (2) improved assimilation schemes for initiating the models; (3) improved models coupling the polar climate components: atmosphere, ocean, sea ice, land ice; (4) encouraging and taking advantage of new satellite data (more satellites, better resolution, better coverage, new sensors) and improved observations, and (5) considering the indigenous/residents' knowledge

Inherent in this effort, is a focus on potential threshold of changes or even irreversible change within the polar systems, some of which will be possibly reached within the next few decades. Threshold and Irreversible changes include:

- The **ice surface lowering instability**, which may lead to irreversible loss of the Greenland ice sheet as a result of 21st century warming.
- **Small ice-cap instability** will lead to irreversible decay for many Arctic ice caps in the coming decades
- As the warm ocean waters intrude below the West Antarctic ice shelves, the **grounding line retreats** and increases the risk of ice shelf collapse.
- **Marine ice cliff instability and marine ice sheet instability,** which may be most significant in West Antarctica, but could also trigger mass loss from marine sectors of East Antarctic ice sheet.
- **Disappearance of the Arctic summer sea ice.**
- **Freshening of the Southern Ocean waters and slowdown of the global thermohaline circulation** in the Southern Ocean and in the North Atlantic Ocean, which strongly influence the European Atlantic climate.
- **Permafrost thawing** especially in ice-rich terrains resulting in wetland formation is an irreversible process in future climate scenarios. As the so called active layer,

Polar bear *(Ursus maritimus)* with two cups North of Svalbard *(Photo: Ronald J. W. Visser)*

Sea-Ice research in the Arctic *(Photo: Alfred Wegener Institute: Stefan Hendricks)*

the part of the permafrost that thaws and refreezes over the course of the seasons, thickens, increasing amounts of organic matter start to decompose. This leads to increasing greenhouse gas (methane and carbon dioxide) release, and release of contaminants, including the possibility for disease spreading.
- **Changes in snow cover:** Arctic snow cover is decreasing rapidly, particularly due to earlier spring melt and later onset of snow cover leading to a reduction in snow cover duration. These changes have an impact on ecosystems with a prolonged vegetation growing season and consequences on fauna and population, increases the potential for winter thaws and permafrost, shift rain-on-snow events posing a risk for water resources management, modifying the surface albedo having a feedback on climate.

Each of these thresholds of changes, if exceeded, would have irreversible effects on biodiversity at local/regional scale, and on local communities and sectors.

The most pressing of these effects, which could arise within the next few decades, are:
- **Arctic summer sea ice disappearance.** This will feed back on atmospheric temperatures, moisture content, cloud cover, atmospheric-oceanic interactions, coastal communities (increased fetch), increased maritime activity (shipping, resource extraction), marine food webs, carbon cycle and have large impact on the atmospheric transport patterns in Arctic.
- **Widespread surficial thaw of permafrost and active layer thickening**, which will feed back into the global climate system mainly through changes in the carbon cycle, surface hydrology and land cover.
- **Greenland ice surface mass balance turning negative** crossing threshold of stability of the ice sheet, initiating potentially irreversible decay on century to millennial time scales.
- **Small ice cap instability and loss** for (Arctic) ice caps.
- **Antarctic ice sheet (AIS) marine ice sheet instability** (mainly, but not only, in the western sector of the Antarctic ice sheet) from reduced mechanical constraints from the surrounding ice shelves whose grounding line lays on a retrograde slope bed. The sensitivity of the AIS ice streams to perturbations in heat fluxes occurs at interannual and decadal time-scales.

Subtopic impacts

Research on this subtopic would benefit many areas for which improved projections of environmental change are required, including the forecasting of extreme weather events, better understanding of climate-cryosphere interactions, and providing robust information for designing adaptation strategies and a better management of resources.

- Identification of thresholds or abrupt or irreversible changes
- Improved forecasting of extreme weather events within and beyond Polar Regions
- Improved predictability skills through better understanding of climate-cryosphere interactions and feedbacks
- Better management of resources
- Informed strategies for adaptation and priorities at different time-scales
- Improved risk assessments

Subtopic 3: Regional impacts and adaptation pathways in response to polar climate change

This subtopic aims at identifying regional environmental sensitivity, risk and vulnerability in the Polar Regions and beyond. The research community will provide information to communities and sectors in Polar Regions that will allow them to prepare for and adapt to new challenges and opportunities they will face.

Current Earth System Models (ESMs) offer projections of many climate parameters but on very broad scales, typically ranging from 50-100 km. These are not suitable to properly resolve regional and local impacts or inform local adaptation plans.

There are strong indications that the environmental changes we may see in the coming decades may be much larger than those seen in recent past and historical time scales. For instance, sea level rise, permafrost thawing, sea ice retreat, and melting of Arctic ice caps all have been more rapid than predicted (in the previous IPCC reports).

Local communities must lead in defining their requirements to inform their adaptation plans. They may require information on storm occurrences, sea-ice thinning, fast ice retreat, glacier retreat, snow melt season, river flooding, permafrost thaw, vegetation (browning, drought), ecosystem health at scales affecting people's lives and activities. To respond to the needs of decision makers and local communities to plan adaptation strategies at a local scale, climate-change-risk-assessment tools are required.

The main tools used to project the impacts of future emissions in global climate models provide information at scales that are too coarse for impact assessment and planning for most local decision makers. Numerous techniques have been developed to provide climate change information at scales more relevant to decision makers based on the assumption that local climate is a combination of large-scale atmospheric characteristics and local-scale features.

Multiple techniques can be used to "downscale" global models to regional and local scales. Downscaling techniques can be divided into two broad categories: dynamical and statistical. Dynamical downscaling refers to the use of high-resolution regional simulations to dynamically extrapolate the effects of large-scale climate processes to regional or local scale. Statistical downscaling encompasses the use of various statistics-based techniques to determine relationships between large-scale climate patterns resolved by global climate models and observed local climate responses.

Downscaling is, however, not a trivial exercise, and requires new approaches that could fulfil local demands. This, in turn, may need new understanding of key processes that may emerge from scientific investigations and Indigenous and local knowledge. It will also require new techniques for linking models across scales.

Inuit hunter traveling by snow scooter on melting sea ice, Pond Inlet, Canada
(Photo: Peter Prokosch)

The early attempts at regional climate modelling were based on uncoupled atmospheric models or stand-alone ocean models, an approach that is still maintained as the most common on the regional scale. However, this approach has some fundamental limitations, since regional feedbacks into the global climate system are neglected. To overcome these limitations, regional climate modelling is currently in a transition from uncoupled regional models into coupled atmosphere-ocean models, leading to fully integrated earth system models.

To transfer physical model results into policy tools, new methods have to be developed, by integrating socio-economic variables and community-based knowledge, such as hazard and risk assessment and mapping at regional and local scales applied in different key geographical settings.

An integrated program is needed that supports community-based decision-making building on the best possible evidence/understanding of the coupled climate system, and understanding processes that link global and local scales.

Subtopic impact

Research on this subtopic will not only improve the engagement of climate change research in polar communities and among policy-makers, but will also improve the understanding of the requirements of these communities in the scientific community, paving the way for a much stronger dialogue, and more informed decision-making.

Communities outside the Polar Regions are also affected by changes in weather patterns thus the tools developed can also be employed in other regions benefitting the European society in general.

Relevant Cooperation Partners

Stakeholders

In the generation of these programmes a large number of actors will be involved, under a co-design perspective. Moreover, the outputs obtained from the research will address the public and private sectors as well as local communities in several regions. Table 2 summarises the most important stakeholders.

International Partners

Both bilateral, national and international funding initiatives will be required for the research emanating from this white paper. Thus, the research needed could benefit from co-designed programs.

The basics of these co-designed programs reside in the international cooperation, in coordination of measurements strategies and monitoring stations, in sharing data acquisition programs and in the built-in interoperability of databases and sharing supercomputing resources. There are already several international long-term initiatives that could be utilized to enhance the cooperation principles. Underneath some of these initiatives are listed, however, this is not a complete list.

The International Ocean Discovery Program (IODP) is an international marine research collaboration that explores Earth's history and dynamics using ocean-going research platforms (some of which run by the European Consortium for Ocean Drilling http://www.ecord.org/) to recover data recorded in seafloor sediments and rocks and to monitor subsea floor environments.

Table 2: Most important stakeholders to be involved in the proposed research.

Subtopic	Key stakeholder groups (other than researchers)	Reasoning (position, influence, impacts etc.)
The coupled Polar climate system	Local communities and governments	Directly impacted, Changing ice conditions, permafrost thawing
	Arctic Council, Antarctic Treaty Consultative Meeting (ATCM), Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the Council of Managers of National Antarctic Programs (COMNAP), IPCC	Measures, Decisions and Resolutions, which are adopted, provide regulations and guidelines for the management and for conducting scientific research of Polar areas
	Governments and communities outside Polar Regions affected by changes in weather patterns	Directly impacted
	Insurance and reinsurance companies	Economic interest
	Oils and gas, Shipping, Fisheries, Tourism (International Association of Antarctica Tour Operators (IAATO), Ports	Directly impacted, Changing ice conditions
Predictability of the Polar climate system	Local communities and governments	Directly impacted, Changing ice conditions
	Arctic Council, Antarctic Treaty Consultative Meeting (ATCM), Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the Council of Managers of National Antarctic Programs (COMNAP), IPCC	Measures, Decisions and Resolutions, which are adopted, provide regulations and guidelines for the management and for carrying scientific monitoring/ research of Polar areas
	Governments and communities outside Polar Regions affected by changes in weather patterns	Directly impacted, changing water level, changing wind conditions
	Insurance and reinsurance companies	Economic interest
	Oils and gas, Shipping, Fisheries, Tourism, Ports	Directly impacted, Changing ice conditions
Regional impacts and adaptation pathways	Oils, gas and minerals, Shipping, Fisheries, Tourism	Ice conditions; wind conditions
	Local communities and governments	Ice conditions, wind conditions, change in precipitation, seasonally frozen ground and snow conditions
	Governments and communities outside Polar Regions affected by changes in weather patterns	Wind conditions, precipitation, Influence from sea level rise

Expeditions in Antarctic waters are planned for **2018-2021** (IODP Exp. 374 has been successfully achieved in January-February 2018), hence there is a great potential for international cooperation in deep and shallow drilling both in the Arctic and Antarctic waters.

ANDRILL (ANtarctic geological DRILLing) is a multinational collaboration comprised of more than 200 scientists, students, and educators from seven nations. A portfolio of new sites can be potentially drilled in the next 5 years and beyond, with the support of EU partnership.

Antarctic Seismic Library Data System (SDLS) is an international data bank of multichannel seismic stack data collected from Antarctic waters from all nations since the '80, freely accessible for scientific cooperation purpose.

Global Terrestrial Network for Permafrost (GTN-P) is part of GTOS of the Global Climate Observing System, a joint undertaking of the WMO, IOC, UNESCO, UNEP and ICSU.

International Bathymetric Chart of the Southern Ocean (IBCSO) The objective of the IBCSO program is the design and implementation of an enhanced digital database that contains bathymetric data available south of 60S latitude. The outcome of IBCSO will fundamentally be embedded into all future Antarctic data-model projects

The Scientific Committee on Antarctic Research (SCAR) is an inter-disciplinary committee of the International Council for Science (ICSU). SCAR provides objective and independent scientific advice to the Antarctic Treaty Consultative Meetings and other organizations such as the UNFCCC and IPCC on issues of science and conservation affecting the management of Antarctica and the Southern Ocean and on the role of the Antarctic region in the Earth system. In addition to carrying out its primary scientific role, SCAR also provides objective and independent scientific advice to the Antarctic Treaty Consultative Meetings (ATCM) and other organizations such as the UNFCCC and IPCC. The purpose of the annual ATCM is exchanging information, consulting together on matters of common interest pertaining to Antarctica, and formulating and considering and recommending to their Governments measures in furtherance of the principles and objectives of the Antarctic Treaty, The main purpose of the Antarctic Treaty, is to ensure "in the interest of all mankind that Antarctica shall continue for ever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord".

The **Southern Ocean Observing System (SOOS)** is an international initiative of SCAR and the Scientific Committee on Oceanic Research (SCOR). Future data-model projects will potentially well link with SOOS capability, data banks and observatories networks.

The International **Arctic Systems for Observing the Atmosphere (IASOA)** coordinate the development of Arctic observatories, data exchange and knowledge exchange and provide a platform for international networking and cooperation for atmospheric scientists.

The **International Arctic Science Committee (IASC)** is a non-governmental, international scientific organization. IASC promotes and supports leading-edge multi-disciplinary research in order to foster a greater scientific understanding of the Arctic region and its role in the Earth system. Thus, research to improve the understanding of the polar climate system will benefit from the collaboration within the network IASC

The **Arctic Council** is the leading intergovernmental forum promoting cooperation, coordination and interaction among the Arctic States, Arctic indigenous communities and other Arctic inhabitants on common Arctic issues. The work of the Council is primarily carried out in six Working Groups. The most relevant working groups for collaboration on polar climate system are the following:

- The Arctic Monitoring and Assessment Programme **(AMAP)** monitors pollution and climate change in the Arctic, and effects on ecosystems and health of human populations, and provides scientific assessments to support policy-making by governments as they tackle pollution and adverse effects of climate change.
- The Conservation of Arctic Flora and Fauna Working Group **(CAFF)** addresses the conservation of Arctic biodiversity, working to ensure the sustainability of the Arctic's living resources.
- The Protection of the Arctic Marine Environment **(PAME)** Working Group is the focal point of the Arctic Council's activities related to the protection and sustainable use of the Arctic marine environment.
- The Sustainable Development Working Group **(SDWG)** works to advance sustainable development in the Arctic and to improve the conditions of Arctic communities as a whole.

The Arctic Council and its working groups will be relevant for collaboration on the research needed, as they are concerned with climate change and sustainable populations.

Some Asian countries like Rep. of South Korea, China and Japan have new infrastructures (stations and icebreakers) employed for both Arctic and Antarctic scientific surveys. Ongoing projects involve bi-lateral collaborations already at National level, for terrestrial and marine fundamental science and environmental monitoring and there is high potential for further exploitation in international projects including several EU countries.

Enabling Capacities and Resources

The research and development necessary to significantly advance the understanding of the polar climate system will require **enhanced measurement infrastructures** in the Polar regions, new **advanced technologies** to carry out measurements under harsh and cold conditions as well as **supercomputing facilities** and sustained comprehensive **databases.** Furthermore, interdisciplinary and thoroughgoing research on polar climate effects and feedbacks will need strong international circumpolar and interdisciplinary collaboration.

Spring expedition to Samoylov Island *(Photo: Alfred Wegener Institute: Thomas Opel)*

Infrastructures and observations

The number of **observation stations in the polar region** has been increasing over the past years. Many of the stations in the Arctic are INTERACT (International Network for Terrestrial Research and Monitoring in the Arctic) stations and can be accessed by researchers from the European research community. The Antarctic Concordia station is run cooperatively by Italy and France since 2005 and hosts many other countries to develop international scientific projects. However, there is still a need to develop cooperation between the observation stations, in terms of measurement protocols, data sharing, and to identify underrepresented areas in order to be able to evaluate model performance and observe changes in the biosphere and cryosphere caused by increased warming. Thus, a reinforcement of the measurement infrastructure in the Polar Regions from where necessary variables can be extracted is needed.

There are many areas in both the Antarctic and the Arctic margin and Ocean, which are still unexplored because they are too remote to be accessed considering the budget and the logistic needs of national projects. Following the excellent example of the EUROFLEETS 1 and 2 projects that implemented successful cruises in Antarctic (Ross Sea) and in sub-Arctic waters (Svalbard Is. Margin), the EU has recently funded the ARICE (Arctic Research Icebreaker Consortium) project which will give transnational access based on science excellence to six European and International icebreakers in the Arctic as a starting community. This will allow optimization of the resources and enable scientists and students from EU countries that have no or limited access to icebreakers to be involved in international projects. Such initiatives should be broadened in the future to include collaborative surveys in Antarctic waters, where EU (e.g. Sweden, UK, Germany, France, Spain) and non-EU countries (e.g. Norway, Russia, China, Rep. South Korea, USA, Australia) already manage their icebreakers or ice-strengthened vessels in supplying stations and carrying on scientific campaigns.

Remote Sensing constitutes a unique tool for the monitoring of remote and harsh areas of the poles. Depending on orbits and sensors, satellites can observe frequently the poles (i.e. from more than one per day to one per month) and, in some cases, independently from sun illumination and/or presence of clouds. In spite of recent advances and new sensors available, there is the need to better validate satellite-derived products, in order to obtain reliable physical variables. Experimental campaigns, together to the developments of new assimilation techniques, able to ingest the satellite measurements in ESM, are needed. The development of new techniques for the monitoring of new variables which are not available (or not reliable for stakeholders and users) from satellite data is also recommended. Collaborations among nations (National and international Space Agencies) at both EU and extra EU level is typically carried out in space activities and should be enforced in Polar Regions especially for conducting coordinated validation campaigns.

It is difficult to carry out and maintain measurements in harsh and cold conditions as in the Polar Regions. There is a lag of **measurement techniques** to measure in the cryosphere as well as in the ocean and in the atmosphere during the cold and dark season. There is a need to improve the sediment recovery and resolution from coastal shallow and deep sea drilling, both in open and in sea ice infested water in the continental shelf. Therefore, development of advanced measurement techniques is essential.

The existing measurement stations usually have individual **databases** with individual structures and standards, which makes data assimilation and comparison between sites difficult. Standardized and comprehensive databases will improve data assimilation techniques and comparison of circumpolar trends. Thus to ensure that data from the measurement stations are accessible and of a certain standard, fully accessible, quality checked and sustained databases are needed, as well as **super computers** with higher storage capability and higher number of CPUs.

Capacity building

Capacity building to ensure continuous development of knowledge is essential in order to obtain understanding of the climate processes in the Polar Region and to develop mitigation and adaptation strategies. Therefore, education of young scientists working with the polar biosphere, cryosphere and society is of high importance. Introducing the young scientists to interdisciplinary and trans-disciplinary research at different levels will promote a more holistic understanding of the polar system. To gain knowledge it is also essential to build on existing knowledge and local communities often possess knowledge of the past and present state of the cryosphere and biosphere, thus a meaningful community-based engagement can be important for studies of climate effects and feedbacks. The communication between communities and the scientists should be a two-way communication, so the communities also will learn which new results come from the research carried out.

There is a large potential for capacity building in Europe for studying the Polar Regions, since several European countries have had Polar programs for several decades, fund scientific and monitoring projects and run stations and vessels in both Polar Regions that will be synergetic to EU actions. In addition there are supercomputing facilities in Europe that can be employed and clustered for achieving innovative and ambitious projects. EU-PolarNet as well as other coordination and network programs (like the SCAR and IASC programme and sub programmes) are tasked to prioritise main scientific knowledge gaps, to develop networks and strategies for international survey cooperation, organize schools and scientific conferences, therefore there is no need to fund pilot studies, but there is **urgent need to fund scientific actions.** Although National funds and the access to national infrastructures are generally given through competitive internal calls, most countries generally prioritise as strategic those projects that are complementary or joint to EU-projects

Existing large international projects

A large research program which could feed into the research needs is the **Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC).** MOSAiC will be the first year-round expedition into the central Arctic exploring the Arctic climate system. The project with a total budget exceeding 60 Million € has been designed by an international consortium of leading polar research institutions, under the umbrella of the International Arctic Science Committee (IASC). The results of MOSAiC will contribute to enhance understanding of the regional and global consequences of Arctic climate change and sea-ice loss and improve weather and climate predictions. As such it will support safer maritime and offshore operations, contribute to an improved scientific basis for future fishery and traffic along northern sea routes, increase coastal-community resilience, and support science-informed decision-making and policy development. Improved understanding of the impact of Arctic climate change on conditions world-wide will provide stakeholders and decision-makers with improved knowledge for adapting to climate change and develop target oriented mitigation strategies.

The EU project **"Beyond EPICA - Oldest Ice Core: 1.5 Myr of greenhouse gas - climate feedbacks (BE-OIC)"** will recover a 1.5 million year record of climate and greenhouse gases from Antarctica to resolve longstanding questions about the causes of change in the dynamics of climate over this timeframe, elucidating the linkages between the ocean, atmosphere, ice sheets and carbon cycle. This will provide a completely new, paleo-based view of planetary boundaries and will tighten the constraints on the response of the Earth system over various timescales to future greenhouse gas emissions.

Three **IODP expeditions** will collect in 2019-2023 paleoclimate records spanning back to 55 Myr, in different transects across the Antarctic margin to document the Ice sheet variability and sensitivity to different climate local or regional forcing (e.g. past atmospheric and ocean warming). These paleoclimate data are crucially needed for validating model simulations (now based only few records over the entire Antarctic continent) of Ice Sheet collapse and global sea level rise in response of past global warming and high CO2 atmospheric content. Coupled climate models once tested with paleodata, will then be used to predict Ice sheet sensitivity, for global, as well as downscaling climate change and sea level projections.

The results obtained by the Antarctic ice core and sediment core drilling will be of paramount importance for the implementation of future Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) and to the Climate Action objective (#13) of the Sustainable Development Goals of the United Nations that aims to take urgent action to combat climate change and its impacts.

The community that will be involved in the IODP expeditions in 2019-2023 as shipboard and as shore based parties as well as in other projects like MOSAIC, ARICE and BE-OIC is very large and multidisciplinary, including geosphere, hydrosphere, cryosphere and biosphere studies. These kinds of international projects represent examples of potential capacity building by optimizing the cooperative use of infrastructures (vessels and laboratories) and of international, national and EU funds for the post-cruise science data exploitation and data-model integration. These expeditions will develop several PhD and post-doc projects, that will be funded at National level, although the amount of funds will differ from country to country and the support from a coordinated EU action will help to reinforce the European participation, allowing also the EU countries that have not develop Antarctic programs yet or that have low budget to be included. IODP proposals aimed to collect paleoclimate data from the Arctic complement the Antarctic expeditions. One of them initially scheduled for being achieved in 2018 in the Central Arctic Ocean was postponed to 2021 because of lack of enough funds. In this case the support from EU and the partnership with Russia (presently not IODP member) would be challenging.

The way forward and key action areas

The development of coupled climate models is advancing fast as well as model downscaling for climate change projections, which give prospects for guidance of polar stakeholders and local communities in the development of adaptation strategies. At the same time, the pressing effects of climate change call for immediate actions. To support and enable guidance based on regional climate predictions and local severe weather warnings, the following steps have to be taken:

- **Increase policy awareness of threshold of changes and hazard**s as a result of climate change effects. This is an important first step in order to take action to develop regional climate change projection tools and to plan adaptation strategies. As part of this, indigenous rights and knowledge should be considered.
- **A more accurate understanding of the coupled Polar climate system** has to be reached. An improved understanding of key processes can be achieved through intensive measurement campaigns to study processes controlling the exchange between the different components of the Polar system and through careful analysis of existing data from long term measurements from coordinated observation infrastructures. Strengthening the Polar observation infrastructures through joint networks and standardized measurement methods is essential in order to carry out a more precise model initialization and for obtaining comparable data set circumpolar.
- We need to coordinate existing data into **common databases.** A first step is to integrate different data among disciplines at different time scales and spatial resolution to understand modern and past environmental dynamics and processes
- **Implementation and clustered use of infrastructures with supercomputing capabilities** to perform coupled models and data-model past, present and future climate and environmental simulations is needed.

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EU-PolarNet
White Paper No. 2

Footprints on changing polar ecosystems

Processes, threats, responses and opportunities for future generations

Arctic Fox *(Alopex Lagopus)*, Lena Delta *(Photo: Peter Prokosch)*

"Under extensive reshuffling of the world's biota, how should conservation goals and strategies for policy and implementation be developed to maximize long-term resilience of biodiversity and human systems? How should natural resource management across diverse, multiuse, multiscale land and seascapes be integrated to maximise resilience of both human and natural systems? How should specific threats and stressors (including their interactions) be managed while minimizing impacts on valued ecosystem assets?" Pecl et al. (2017) Science 355, 1389

Motivation and Background

Humans are increasingly leaving footprints on global ecosystems and these effects are strongly felt in the Polar Regions with largely unknown consequences. Today, we are facing a unique opportunity – the ability to build a knowledge base and provide science-based advice for decision-making in order to minimize these "footprints". We need research to characterize, quantify and minimize these footprints to secure sustainable use of ecosystem services.

Recently, the EU has acknowledged the need to carry out more research in Polar Regions, as the rate of change in polar biological systems has increased substantially in recent decades and is likely to continue on the same trajectory in the future. Such changes will have major consequences at different scales for ecosystems and societies, causing high socio-economic and ecological costs for European nations. Direct and indirect effects of these perturbations of e.g. climate patterns and ecosystem services will hugely impact Europe. Despite differences between the Arctic and Antarctic, for example the extent of human population in the area, many issues regarding the two Polar Regions can be similarly addressed.

The Polar Regions provide unique opportunities for strengthening international collaboration, and the EU can take an opportunity to lead multidisciplinary research efforts. These can contribute substantially to identifying gaps of knowledge in polar ecosystems' structure and function, predicting the rates and effects of change, assessing the risks to ecosystems, and providing advice for managing polar ecosystems. This research has the potential to initiate a virtuous circle of interactions between science, environment and society and to make a real difference, as the future trajectories of change can still be positively influenced by policy and management actions. Examples where the EU is already an active collaborator include the involvement to the activities of the Commission for the Conservation of Antarctic Living Marine Resources (CCAMLR), and the participation of 13 European countries in the Antarctic Treaty System (ATS). Corresponding involvements in the Arctic area include the Arctic Council and its various working bodies.

Expedition Cruise tourists experience autumn colors on the West-coast of Greenland *(Photo: Peter Prokosch)*

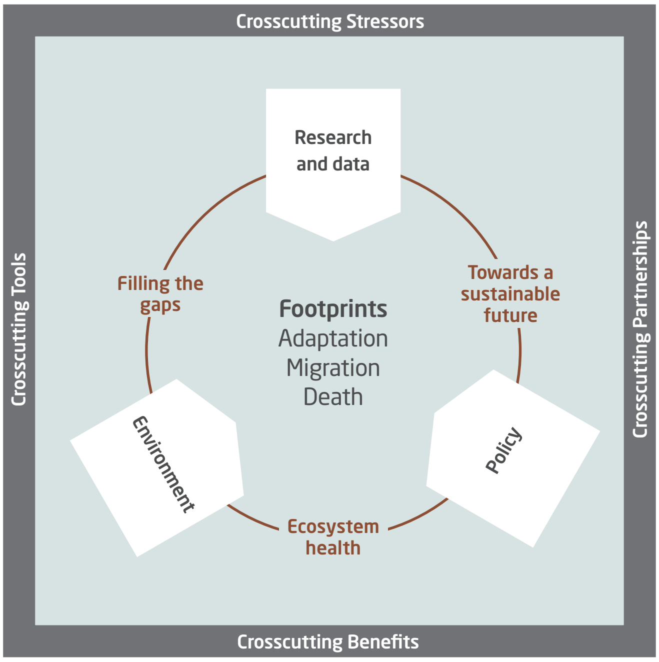

Fig. 1. Interlinkages between biological processes, threats, responses and opportunities towards a sustainable future. Crosscutting Stressors include anthropogenic climate change, ocean acidification, pollutants & contaminants, invasive species. Crosscutting Tools include funding, new technology, education and outreach. Crosscutting Partnerships include and indicate more international and interdisciplinary collaboration and coordination, and better information sharing. Crosscutting Benefits include improved infrastructure and logistics, open communication with all stakeholders, and data and benefit sharing.

The EU-PolarNet project conducted an on-line consultation to which more than 500 stakeholders from 36 countries responded. The main topics in polar biology raised by the stakeholders are covered in this white paper with a particular emphasis on the effects of global change on polar ecosystems, the need for multi-faceted, cross-disciplinary research, science-based management, and the concerns of future ecosystem services that the polar ecosystems are able to provide.

A strong initiative from the EU for supporting research should address three main objectives:

1. Improve the understanding of the current structure and function of polar ecosystems, and how they will change under predicted environmental pressures
2. Identify the most relevant ecological indicators to evaluate risks to the polar ecosystems and services they provide, especially to their biological components
3. Provide relevant and timely scientific advice to decision-makers for sustainable management of the polar areas under a changing climate

These footprints on the polar ecosystems, their impacts and possible management strategies should be approached by the above objectives, forming a logical system of information flow and chain of actions (Fig. 1). These three intertwined steps will compile, process and provide the necessary ecological science needed by White Paper No 3 Managing human impacts, resource use and conservation in the Polar Regions and White Paper 4 The Road to the Desired States of Social-ecological Systems in the Polar and complement the coupled climate models by White Paper No. 1 "The coupled polar climate system: global context, predictability and regional impacts.

Why is it important?

The often-heard saying is "What happens at the poles does not stay at the poles". Changes in polar areas have pronounced effects on lower latitudes through a variety of feedback mechanisms. The Polar Regions are strongly affected by climate change and an increased anthropogenic impact. The importance of the poles for global environment and scientific research is reflected in the dedication of the Antarctic continent to Peace and Science by the Antarctic Treaty since 1959, as well as in its status as a Natural Reserve designated by the Madrid Protocol in 1991. In the Arctic, climate stressors are mingled with multiple pressures from economic development, such as exploitation of mineral and energy resources, fishing, tourism, shipping and transport (The Arctic environment - European perspectives on a changing Arctic, EEA report n° 7/2017). Economic activities in the Antarctic are limited to tourism and bioprospecting, and in the Southern Ocean, the exploitation of marine living resources.

An important difference is evident between the northern and southern Polar Regions: there is strong connectivity between the Arctic areas via both land and sea, and the northern latitudes; whereas the Antarctic continent and the Southern Ocean are separated from other southern continents because of the strong Antarctic Circumpolar Current system. Despite their differences, both Polar Regions act as natural laboratories capable of providing valuable information about biological and ecological processes at high latitudes, due to the relative simplicity in polar ecosystem structure. Although life in Polar Regions is very challenging in many respects due to the harsh environment, these areas host an abundant and remarkable diversity of organisms, characterized by specific adaptations and fragilities. In general, living organisms have three choices to respond to the pressures imposed by rapidly changing environments: adapt, migrate or die. Polar organisms are well adapted to their environment, but they typically have limited migration options. On the other hand,

Polar Campion *(Silene uralensis ssp arctica)* in Arctic desert. Picture taken on Nordauslandet Svalbard. *(Photo: Ronald J. W. Visser)*

Loss of Ice in Greenland; Icebergs in Disco Bay *(Photo: Peter Prokosch)*

local species are also threatened by an increasing number of invasive species migrating from temperate regions. As the global climate changes, human well-being and ecosystem functions are increasingly affected by the shifting biogeography of life.

The values that are found in both Polar Regions include aesthetic values and wilderness experiences that are difficult to quantify in monetary terms but have immense human and cultural importance. Iconic polar fauna, e.g. penguins, Arctic foxes and polar bears, and the threats to their existence, have helped to raise public awareness of the high risks posed by global climate change in Polar Regions. At the same time, a wider picture of polar ecosystems and their importance must be presented in education and outreach activities, and get the public to understand and support the need of protection of all polar organisms and their environments. Moreover, both regions host important biological, genetic and chemical resources, which can be harnessed as assets for the "green economy" that can benefit both local communities and European societies (e.g. EU strategy on Blue Growth). The ecosystem services that need to be fostered include inter alia food, fresh-water and the maintenance of an equable climate, specifically provisioning of fishery products, nutrient cycling and the maintenance of biodiversity. The prerequisite for the understanding of the polar ecosystems and their services is a strong knowledge base in biology that requires EU and polar countries to generate science and understanding for conveying management solutions for future generations.

The research program proposed here is characterized by the extensive use of innovative new technologies allowing collection of scientific data from previously inaccessible areas as well as during winter. The establishment of a sustained network of long-term observatories in the Antarctic, following the experience in the Arctic, will enhance this aspect even further. The explicit transdisciplinary approach, involving the participation of biologists, sociologists, specialists of new technologies, economists, climate modellers, engineers, together with local communities, will enable development of a strong and global understanding of the interactions studied, provide a suite of tools that can be used to monitor the environment and raise warnings, and inform decision-makers on the basis of scenarios and models. A dedicated education and outreach component will be developed to ensure efficient communication and cooperation between all actors and to raise the awareness and support from the general public, including the European taxpayers.

Why now?

There is general consensus that strict climate targets set by the Paris Agreement in 2016 require immediate, qualified joint actions and adaptation at all scales (local, regional and international). Strong and accurate forecasting abilities are needed to ensure adaptation to forthcoming climatic and environmental changes. Another urgent need concerns the rate of extinction of species that is estimated to be 100 to 1,000 times more than that considered natural. Large numbers of species will likely disappear if no action is taken for their conservation, and an estimated 30% of all mammal and bird species will be threatened with extinction this century. The international aspect of research should enable solutions that transcend the local and national governance levels and coordinate them to address questions of global relevance.

Various international agreements and organizations (e.g. IPCC, IPBES) require timely and relevant scientific advice. We need long-term monitoring to understand the changes to ensure a qualified response to these requirements. A few long-term monitoring programmes are underway in the Polar Regions – showing us the enormous importance of having long term datasets from these regions. Unfortunately, large parts of the polar area have very few such programs – especially the Antarctic continent that has long been inaccessible and has a patchy network of scientific stations dating back from around 60 years. An example of an essential, successful long-term monitoring was the ozone measurement carried out at the Halley station in Antarctica, proving the existence of the ozone hole, and underpinning the Montreal protocol – one of the very successfully implemented international treaties. Thus, we need to strengthen the existing long-term monitoring programmes and implement further monitoring programs in parts of the Polar Regions particularly sensitive to a changing climate. A strong focus should be put into coordinating the programmes, ensuring interoperability of systems and securing systematic data collection, storage and stewardship following the FAIR principles to maximize the usefulness of the data.

The rapid changes in the Arctic and Antarctic ecosystems are causing widespread societal impacts. The cumulative effects of climate and anthropogenic changes, e.g. increased maritime transport, extraction activities, undoubtedly pose high risks for the polar environments and their biodiversity. However, if immediate and effective measures would be taken, sound stewardship of the Polar Regions is still possible and can make a significant difference for their future. The EU has played an important role in multilateral environmental agreements in the past, and can mobilize support for the kind of international agreements needed to address the threats to Polar Regions and their ecosystems. Indeed, the pressures and impacts are not limited by national frontiers, nor should measures to mitigate the consequences be.

Atlantic walrus *(Odobenus rosmarus)*, picture taken in Svalbard *(Photo: Ronald J. W. Visser)*

Societal relevance

The target group of the results from the proposed research programme include the European Commission and other European and national policy-makers, their advisors and funding agencies, academia and national research bodies.
The societal relevance of the proposed research programme includes (relevant European Sustainable Development Goals; SGDs are indicated):

- filling in gaps in the knowledge on ecosystem structure and function from both Polar Regions in order to provide scientific advice for managing the consequences of climate change and mitigating impacts on ecosystems and societies that depend on them. SDG 13.
- conservation, restoration and sustainable use of ecosystems and their services, which is a key for sustainable polar societies. SDG 14, SDG15.
- involving local communities in the generation of knowledge by participating in data collection and co-management, and in utilizing the toolbox for assessing ecosystem health. SDG 12
- promoting education and capacity building for innovative solutions in order to ensure the destiny of polar societies is in their own hands by broadening understanding on ecosystems and how they can be managed in a sustainable manner. SDG 4, SDG 9.
- healthy ecosystems that are the essential requirements for resilient and sustainable communities, and further for human health and wellbeing. Feeling part of the natural environment and being able to carry out traditional life with socio-cultural practices related to the native biodiversity is also essential for mental well-being in local and indigenous Arctic communities. SDG 3, SDG 6, SDG 11 (cf. also The One Health Initiative)

Research needs:

Subtopic 1: Filling the gaps

Recently, there have been several initiatives, e.g. the SCAR Horizon Scan for the Antarctic and ICARPIII for the Arctic, that identified pertinent knowledge gaps and urgent needs for research on polar ecosystems structure and function that should be addressed in the next decade. These major themes include the question of how threshold transitions will vary over different spatial and temporal scales and how they will impact ecosystem functioning, from genes to communities, under future environmental conditions. Other research themes involve the complexities of multiple stressors and their synergistic effects, as well the genomic and physiological basis of adaptation of polar organisms and communities. Further aspects of ecosystem structure and function that currently remain unexplored, are:

- Marine and terrestrial food webs, particularly in the coastal, deep sea and under-ice environments, possibility of co-evolution between species or disruption of key interactions
- Adaptation and resilience – or extinction and collapse – of species and ecosystems in response to global change
- Impacts of invasive species and range shifts of native species on polar ecosystems and human well-being

The EU has already made an effort by issuing an H2020 call addressing the aspect “Changes in Arctic Biodiversity” but there are still major gaps in knowledge on the diversity of polar ecosystems. A large-scale monitoring system of the Polar Regions should be able to deliver standardized, high-quality data on a range of essential biodiversity variables. Examples of these variables were proposed by the Group on Earth Observations Biodiversity Observation Network (GEO BON). Coordinated sampling and assessment has the potential to minimize the

Snow petrol *(Pagodroma nivea)* near Rothera research station, Antarctica *(Photo: Ronald J. W. Visser)*

Svalbard reindeer *(Rangifer tarandus platyrhynchus)* in June, Nordeskioldkysten Svalbar *(Photo: Ronald J. W. Visser)*

costs while increasing the usefulness of the obtained parameters. A harmonized monitoring system will make extensive use of remote-sensing technologies, in addition to local biodiversity assessments. The expected knowledge gain will contribute to a comprehensive understanding of biodiversity changes (taxonomy, life history, genetics) and modifications of ecosystems structures and functions (e.g. food web interactions, productivity, role in element cycles). This will contribute a crucial component to the One Health Assessment approach and also enable the stakeholders and right holders to make informed decisions about their future.

The involvement of local communities in sampling and monitoring, supported by modern technologies, has the potential to mobilize and involve traditional knowledge and raise awareness in the communities of the impacts of and potential responses to environmental changes.

Due to the large geographic and temporal scale of the data collection requirements, a well-designed data management plan is necessary and should be one of the first steps of any project. The collected data should be deposited to a public repository and open to all users (e.g. through the AMD). In addition, the biological material should also be deposited in public repositories or BRCs (Biological Resource Centres), some of which are available and supported by the European Research Infrastructures as part of the Horizon 2020 programme. For example, deposited microorganisms have the potential of being highly useful for research and in developing innovations for bioeconomy.

Subtopic 2: Assessing ecosystem health

Based on the improved knowledge of ecosystem structure and function, a toolbox should be developed that will allow stakeholders to reliably assess the state of ecosystems. To achieve this, there is a need to develop a set of genuine ecological indicators to identify and quantify thresholds and risks. These indicators are to be selected to synthetize a variety of relevant variables and enable researchers to explain the changes of the biodiversity and ecosystems. Examples of such indicators are physical-chemical parameters, indicators of the pressures on biodiversity, (e.g. concentration of particular contaminants such as plastics), species-based indicators of biodiversity changes (e.g. the status of key species such as Antarctic krill), and loss of genetic diversity of certain populations (e.g. large marine mammals, endangered seabirds, key microbial species, and commercially important species). In addition, reference sites covering key habitats need to be identified and integrated into a network of long-term observatories, together with existing monitoring sites.

Subtopic 3: Towards a sustainable future

Improved knowledge of polar ecosystems and a robust toolbox of ecological indicators and modelling approaches are needed for creating future scenarios and predictions, and for providing scientific advice for management and policy making. The models of biodiversity and ecosystem function will be complemented by models focusing on socio-economic aspects, generated by research dealing with 'Humans and Resources', as well as with coupled climate models that will be downscaled in 'Climate and cryosphere' research activities. In addition, the effects of planned management measures aiming at mitigating the negative impacts and maximising the resilience of natural and human communities in Polar Regions will be simulated.

There are existing polar platforms for collating and analysing data, and for synthesizing conclusions for sound, science-based advice for decision-making. In the Antarctic, mechanisms to nurture the interactions between scientists and decision-makers are organized through the ATS. For example, the network of Antarctic Specially Protected Areas (ASPA) is a science-based management tool to protect biodiversity and ecosystems. Another example is the ecosystem-based management approach that is applied by CCAMLR to ensure the conservation of the Antarctic marine ecosystem and avoid overexploitation of species. The Arctic Council with its working groups such as CAFF (Conservation of Arctic Flora and Fauna) and PAME (Protection of the Arctic Marine Environment) forms another example of a potential platform where comprehensive, holistic modelling would be capable of providing scenarios and advise for policy-makers. In addition, designing a network of protected areas with sustainable harvesting strategies for natural resources is underway for the Arctic.

Relevant cooperation partners and stakeholders

Ecosystem health of the Polar Regions is essential for all stakeholders, directly for the human populations in the Arctic and indirectly for everybody in Europe and elsewhere, since the Polar Regions have a more-than-regional, global significance, for example with regard to climate change and sea-level rise. In this respect, key stakeholders with a special interest are:

- Polar research and coordination organizations and other scientific communities (for example, IASC, SCAR, and EPB) that will gain a major boost for developing key polar science contributing to major developments in understanding polar biology while promoting international cooperation among polar countries and communities
- Intergovernmental organizations, such as the Antarctic Treaty System (ATS) and Arctic Council (AC), as well as their subsidiary bodies, whose policies and recommendations rely on the research carried out in the Polar Regions, particularly linked to protection of the environment and minimization of human impact (for example, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) or the AC working groups on the Conservation of Arctic Flora and Fauna (CAFF) and Protection of the Arctic Marine Environment (PAME)) The obtained data can be placed in a more global context by the activities of organizations like the Convention on Biological Diversity (CBD) and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES).

Emperor Penguins *(Aptenodytes forsteri)* in Antarctica *(Photo: Alfred Wegener Institute / Stefan Hendricks)*

- Non-governmental organizations and agencies interested in the conservation and sustainable management of polar ecosystems (for example, the Antarctic and Southern Ocean Coalition (ASOC), the World Wide Fund For Nature (WWF))
- Agencies and organizations with global interests in climate, oceans, shipping and biodiversity, as the expected findings from Polar Regions are relevant to model scenarios on how the global climate and oceans may change in the future in relation to biological and physical processes (particularly for the Arctic) and affect human safety in the Polar Regions (e.g. relevant to FARO and COMNAP). Such work is also relevant for the development

Polar bear *(Ursus maritimus)* feeding on narwhal *(Monodon monoceros)* North of Svalbard *(Photo: Ronald J. W. Visser)*

of the Polar Code by the International Maritime Organization (IMO).
- Arctic countries and various other countries with polar interests, organizations of Arctic indigenous peoples as well as local Arctic communities
- Private and public corporations interested in exploiting polar biological resources, such as fisheries, biotechnological, food and pharmaceutical companies
- Education and outreach organizations, such as the Association of Polar Early Career Researchers (APECS), and Polar Educators International (PEI), that will benefit from an international effort to understand polar biology and how it can be protected. Scientific efforts to understand the life history of polar animals, such as polar bears and penguins, will provide the basics to introduce educational concepts of a wide range of disciplines to all generations.

Enabling capacities and resources

Capacity building

In general, significant efforts and resources need to be devoted to capacity building, as well as to public education and outreach. Capacity building is crucial for safeguarding the major role of European research in polar biology. Therefore, it is essential to create and maintain an effective infrastructure and/or network to nurture, develop and help establishing world leading polar scientists at European institutions. There are already various international initiatives that can contribute to this objective, such as the International Master in Applied Ecology, the UArctic network and International Antarctic Institute. Strengthening public education and outreach is also a pertinent action, since for most Europeans, the Polar Regions still seem to be "far away" and, hence, not necessarily of the highest importance. To remedy this misconception, researchers need to clearly communicate that the processes occurring in polar areas have a significant impact on the rest of the world, including Europe. The EU project Edu-Arctic is a good example of initiatives in this direction (although confined to the Arctic).

Svalbard reindeer *(Rangifer tarandus platyrhynchus)* in September *(Photo: Ronald J. W. Visser)*

Resources and logistical support needs

A new research programme on polar biology will require new facilities, technologies and efforts in coordination:

- **Improved polar research infrastructure:** vessels, stations, aircraft, satellites and in-situ and remote observations, monitoring and telecommunication
- **Better coordination:** The current network of field stations on land, and moorings and research vessels at sea needs to be coordinated in a complementary manner with compatible instruments and communication protocols. The FAIR principles for data management are the basis for long-term and efficient knowledge integration and (re)use of results.
- **New modelling techniques** e.g., coupling of ecological models with climate and socio-economical models
- **New technological requirements:**
  - Automatization for facilitating long-term, year-round observations in remote areas
  - Miniaturization for boosting in situ- and rapid analysis (e.g. high-throughput genetics, physico-chemical probes)
  - Use of remotely operated devices to explore inaccessible areas or to minimize environmental impacts (e.g. aerial vehicles, gliders, rovers) and ad-hoc communication systems to guide these devices and ensure data collection.

The EU has the capacity to help build such programme by:

- coordinating the polar infrastructures of European research institutions
- facilitating trans-national access to existing infrastructures and data sources
- establishing and funding of new long-term observatories
- encouraging international cooperation and exchange of scientists among European countries and beyond

There are already various European and other international projects, initiatives and organisations that contribute to such efforts to a certain extent - for example the EU Infrastructure project INTERACT (International Network for Terrestrial Research and Monitoring in the Arctic), the H2020 projects INTAROS (Integrated Arctic Observing System) and ARICE (Arctic Research Icebreaker Consortium: A strategy for meeting the needs for marine-based research in the Arctic), the FP7 project DEVOTES (DEVelopment Of innovative Tools for understanding marine biodiversity and assessing good Environmental Status), the IMBer project ICED (Integrating Climate and Ecosystem Dynamics of the Southern Ocean), the German cluster FUTURE OCEAN, the Arctic Science Partnership and the SCAR programme SOOS (Southern Ocean Observing System) as well as international organizations like EU-PolarNet and the European Polar Board. Technologies developed for the European Space Agency's missions, like the ExoMars rover, can be inspirational for observation, sensing and sampling purposes in the Polar Regions.

Way forward and key action areas

To fully address the polar biology needs outlined above, it is essential to have actions at different levels that are supported by the EU:

- Publish coordinated calls for seed money to implement new polar research programmes and long-term observation sites, especially at remote places in Polar Regions. Furthermore, coordination and standardization of monitoring protocols need to be developed and resources need to be allocated to the design and implementation of standardized data management, to ensure interoperability and making the best use of existing and accumulating data sets. In addition to programmes focusing on either the Arctic or the Antarctic, explicitly bi-polar approaches should also be encouraged and funded.
- Lead concerted international actions (involving EU countries and countries worldwide) to establish coordinated research and subsequent science-based and scenario-based advice for fast action in management and international policies. In the Arctic, cooperation between the EU, its Arctic member states (Sweden, Finland, Kingdom of Denmark) and other Arctic Council member states (Norway, Russia, Canada, Iceland and the US) and implementation of the Trans-Atlantic Research Alliance between EU, US and Canada, are necessary for ensuring coordinated activities (research, monitoring, management) at a pan-Arctic scale. In addition, fostering the involvement of indigenous Arctic peoples and local communities across national borders is crucial for sharing all useful information and experience with them, and for ensuring their broad involvement in ecosystem assessments.
- Support capacity building, promoting excellence at the level of universities and research institutes, to create and establish world leading scientists (and their teams) in polar biology.
- Nurture public education and outreach initiatives to demonstrate the relevance of polar biology in the Worlds ecosystems. Such initiatives may use the earlier work as background and starting point, e.g. the work done in connection with the International Polar Year.

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EU-PolarNet White Paper No. 3

Managing human impacts, resource use and conservation of the Polar Regions

Research vessel in the Arctic Ocean *(Photo: Alfred Wegener Institute / Mario Hoppmann)*

Humanity and the Polar Regions

As human activities exert intensifying pressures on the Polar Regions, concerns about their impacts are becoming increasingly acute. The changes wrought by these pressures carry with them the potential to alter the role the regions play in regulating global climate and other systems, and in providing other important ecosystem services. They may also change societies' relationships with one another. While it has become common knowledge that climate change is driving often dramatic changes in the Polar Regions - and at a much faster pace than elsewhere - human activities impact the poles through other channels as well. Various forms of pollution, transport, tourism, migration, infrastructure, and the pursuit of natural resources, combine to exert substantial impact.

The pressures driving change in the Arctic and Antarctic often originate far from the poles, through human activities such as the burning of fossil fuels or from use of chemicals and plastics. As the Polar Regions become more accessible and as the resources these regions possess become more accessible, the increasing human presence results in more direct impacts. Some changes are beneficial, as when new technologies and economic development improve living standards and increase the life opportunities for people in Arctic communities. However, there are detrimental impacts too, with increased waste, and disturbance of critical local or regional ecosystems undermining traditional livelihoods and causing other social disruption.

It is therefore imperative to strengthen scientific and policy understanding of the Polar Regions. In particular, it is urgent to improve understanding of how human interaction with polar environments can benefit people and societies, and how human activities can be pursued in ways that can at the same time protect and conserve the unique characteristics of these regions. In the Arctic, it is important to develop and optimize the sustainable use of resources for the benefit of local communities – and humanity in general although it should be considered that non-development of resources may be preferable in some cases. In the Antarctic, the imperative lies primarily in protection and conservation in accordance with the Antarctic Treaty System that supports peaceful use of the region, promotes science and other international cooperation and prohibits extraction of mineral resources.

In this context, **a strong EU research policy initiative should encompass these key elements:**

- A social-ecological systems perspective in which ecosystems and the human activities that impact those ecosystems, including resource use, are considered inseparable.
- A focus on critical thresholds beyond which return is unlikely in the near term. This directs attention to the feedbacks that influence such extreme shifts, especially those that can contribute to crossing thresholds.
- Attention to cumulative effects and extended causal relationships that play out over temporal and spatial scales, particularly interactions between people and nature.
- Development of metrics or indicators to monitor the status and resilience of social-ecological systems.
- Comprehensive analysis of governance and management systems for steering human activities in nature, their capacity to integrate and employ diverse knowledge to inform choices, and to make rapid adjustments as new knowledge is made available.

[1] See "definition of terms" at the end of this document

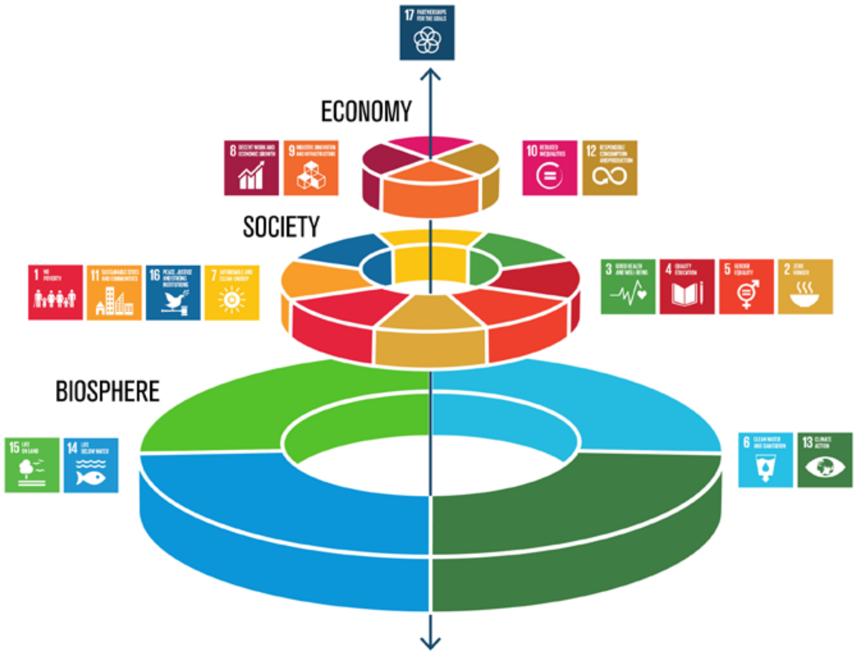

Fig. 1: UN 2015: 2030 Sustainable Development Goals *(Graphics by Jerker Lokrantz/Azote)*

The need for such integrative efforts is well-recognized. The UN Agenda 2030 Sustainable Development Goals are considered interdependent and indivisible. At the same time, Figure 1 illustrates how the achievement of economic and social goals is entirely dependent on meeting goals related to the biosphere. Deeper understanding of the interactions between these goals in the Polar Regions is crucial, particularly where dependency relationships between goals make attaining some goals contingent on attaining others.

The European Environment Agency's 2017 report on "Transitions to Sustainability" highlights the fact that while understanding of the systemic nature and multi-causality of environmental challenges is essential, research regarding how these challenges can be effectively navigated remains separate, and employs different disciplinary perspectives and methods. In order to respond effectively to the pace and breadth of change seen in the Polar Regions, far more effective integration of different types of knowledge - and to link knowledge with corresponding policy and with practice - is crucial. The level of sophistication regarding the organizational and institutional conditions required to break down the boundaries between the various disciplines has increased markedly over the past decade, as expectations have grown from multi-disciplinary projects to producing transdisciplinary insights. These efforts can and should be further developed and applied in the Polar Regions.

Similar, but with important differences

Although the Polar Regions share many similar characteristics, there are also fundamental differences. These include not least, the geopolitical differences pertaining to national sovereignty and international agreements that define shared goals and permitted activities. While the Arctic Ocean is itself an international area, the lands that define its shores are the territory of five Arctic countries which, together with Sweden, Finland and Iceland cooperate under the auspices of the Arctic Council (AC) and are home to indigenous populations who have lived there for thousands of years. The Antarctic is a continent under international governance through the Antarctic Treaty System (ATS). Parts of Antarctica have been visited for 200 years, but most permanent stations have been established since the Second World War, and many areas still remain unvisited.

In the Arctic, the overarching challenge is to combine improved human well-being and more resilient communities with environmental protection and sustainable management of resources - in a context of extraordinarily rapid change. In recent years' these efforts have often entailed increased participation by local communities, in particular indigenous communities, and efforts to integrate scientific and Indigenous Knowledge.[2]

Somewhat different challenges have emerged in the Antarctic, in particular, the need to manage the impacts of an increased human presence from science, fishing and tourism activities. Human interaction with the Antarctic is limited by an international treaty to peaceful purposes, including scientific discovery. Sustainable use or pursuing resource benefits excludes mineral extraction, while fishing the region is secondary to ecosystem conservation (as set out in the CCAMLR Convention).

In both instances, the fundamental imperative is to develop the knowledge needed to manage human activities in relationship

[2] There is an ongoing discussion about terminology that most suitably characterizes the knowledge held by indigenous peoples, including "Traditional Knowledge," "Traditional Ecological Knowledge," and Indigenous Knowledge. The term Indigenous Knowledge (IK) is used here to encompass all these types of knowledge.

to these sensitive and critical regions. This requires a far greater capacity to balance competing societal goals and increasing resource needs, with the need to exercise stewardship of the ecosystems that constitute our life support systems. Recognising these, this White Paper has three core themes:

1. The importance of conservation of the Polar Regions to preserve their intrinsic value, for humanity, including for future generations.
2. The need for sustainable resource utilisation in light of changing environments and expanding human needs.
3. With particular relevance to the Arctic, the importance of organizing resource and economic development in ways that benefit the people of the region including indigenous populations, and in particular those whose livelihoods have been disturbed and disrupted by human impacts from activities taking place or directed from far away.

Gaps in research and knowledge needs

In order to make wise decisions on issues of conservation and the use of resources provided by polar social-ecological systems, this White Paper addresses the most fundamental needs for societally-relevant research for the Polar Regions: 1) the need for deeper understanding of human impacts in complex, interlinked systems; 2) the need for more precise indicators and informational feedbacks to guide decision-making and management processes, as well as an improved capacity of those systems to incorporate and make use of relevant knowledge; and 3) a stronger understanding of the dynamics of knowledge integration, with a focus on strengthening methods for effectively bridging between scientific disciplines and the natural and social sciences, and also for incorporating the humanities and integrating Indigenous Knowledge. It is also important to extend such efforts to strengthening the links and interactions between science, policy and practice. These are described in greater detail under each sub-topic.

Subtopic 1: The direct and indirect impacts of human activities

This sub-topic addresses the need to better understand and quantify human impacts in complex, interlinked systems. Closer examination of human impacts where a long-term presence has left unwanted side-effects warrants particular attention. The cumulative effects of smaller impacts can also generate unwanted changes, and this is especially important where impacts themselves become drivers of further change through sequential or cascading effects.

A. Past presence – historical legacy of human activity

The legacy of decades of focused domestic, commercial and governmental activity in the Polar Regions, at a time when environmental standards were not always high, has resulted in major environmental damage at some locations. Pollution has led to impacts upon wildlife reproductive success and caused changes in biological community structure and function. In some instances, these changes have spilled over to impact human populations, for example, through contamination of traditional food sources. In Antarctica, the initiation of substantial human activity in the late 1950s produced contaminated soil and waste estimated to be of the order 1–10 million m^3. With a longer human presence and mineral resource extraction, transport and military base activities going back decades, the Arctic is much more widely impacted. Due to the cold and often dry conditions, natural remediation processes that work elsewhere are slow or ineffective in polar soils. **Research questions: What methods are available, including remote sensing techniques and community-based**

Port of Murmansk, Russia *(Photo: Peter Prokosch)*

Tourism in Antarctica *(Photo: Peter Prokosch)*

monitoring, to help determine the extent of contamination? How can we prevent mobilisation of contaminants and facilitate remediation of sites contaminated by fuel spills or other hazardous substances at a large scale and low cost?

B. Cumulative and cascading impacts

The importance of combined or accumulated impacts of multiple stressors is a key consideration in establishing likely future scenarios. Approaches to management of potential and actual human impacts have shifted decisively from a focus on individual stressors or species towards ecosystem-based approaches. Along with this shift, a variety of conceptual, methodological and practical challenges have emerged for analysis of cumulative and cascading impacts. This shift to system approaches has increased the importance of clarifying and examining the wide range of operating assumptions used. Further systematizing of methods is important for considering not only stressors, but also their human-induced causes and the effects of subsequent environmental change on both Arctic and other communities. **Research questions: How can we improve understanding of the consequences of sequences of human-induced change on polar ecosystem services? What kinds of new methods are needed to effectively integrate both quantitative and qualitative data, fill critical data gaps, and analyse the likely effects of crossing thresholds that are likely to be irreversible in the near term? What tools and processes have proven effective in helping communities cope with these consequences and manage a resilient societal development in the region?**

In the context of complex systems, it is especially important to strengthen understanding of conditions in which impacts can themselves become stressors driving further change - either through reinforcing feedback effects, or through cascading impacts. For example, while anthropogenic climate change is the dominant driver of change in the Polar Regions, it is experienced most tangibly through cascades of impacts on changing snow and ice cover, on permafrost, on species migration, and on accessibility for human activities. The decline of snow and ice cover produces reinforcing climate feedbacks through reduction of albedo, yet it may also precipitate human responses that are less predictable, but potentially reinforcing. While an increasing systems orientation within the natural sciences makes examining feedbacks and cascading effects part of a natural progression, currently the role of societal responses to ecosystem changes in these broader causal cascades is seldom considered. **Research questions: How can we improve our understanding in sequences of impacts that spread, and that alternate between human activities and ecosystem change? How might crossing multiple thresholds interact to generate feedbacks that drive additional change that may be disruptive or dangerous?**

Subtopic 2: Choices about resource use, conservation and related impacts

This sub-topic addresses the need for more precise indicators and informational feedbacks to guide decision-making and management processes, as well as an improved capacity and interest of the people, organizations, and institutions involved to incorporate and make use of relevant new knowledge.

As environmental change in the Polar Regions makes these areas more accessible, opportunities to exploit their resources and space are increasing. In the Antarctic, science, tourism and, to a lesser extent, fisheries are expanding. In the Arctic, receding ice and snow are opening new potential shipping routes, easing access for extraction of minerals and other resources and setting the stage for other kinds of commercial development. Species migration and changing ice conditions are opening for new or expanded fisheries. As a result, the tensions between competing imperatives are intensifying. Where and to what extent resource, transport, and other opportunities should be pursued - and where and to what extent should the resources, the intrinsic values, and the spaces be protected and conserved? Embedded in these questions is the way in which informational feedbacks are managed and utilized to guide decisions about conservation and resource use. Here the challenge is partly a lack of information. However, even more lacking is the availability of composite metrics characterizing human-ecosystems interactions that can be integrated into policy and management practices. Currently available indicators offer an inadequate representation of the complex interactions between people and polar ecosystems.

For example, educational levels or household income provide important information, yet they tell us little about people's interactions with nature or the ways that knowledge of ecosystems or traditional livelihoods interact with conventional systems to help provide for material and spiritual well-being. Therefore, there is an urgent need for research related to specific types of human activity that are rapidly expanding in one or both Polar Regions, and to management approaches and the kinds of indicators used to assess status and provide decision support.

A. Management/Governance of expanding human activities

Most human activities already generate impacts, and there is little doubt that further expansion on current trajectories could have consequences both for the Polar Regions and beyond. **With each of these trending activities, three of the central questions are: How can the activity be managed within ecosystem constraints? Can indicators be developed that more precisely describe interactions and feedbacks between human activity and ecosystems changes? How can further development be pursued in ways in which significant benefits accrue to local communities (Arctic)?**

Increasing Tourism: Across all the Arctic nations, tourism activity is estimated at over 10 million visitors per year and the numbers have increased in the past decade. Antarctic tourism is largely focused in the Antarctica Peninsula and nearby islands. Here, cruise tourism has increased 8-fold in the past 25 years with almost 350,000 passenger landings. Most of these landings are at a small number of visitor sites, and tourism continues to expand and diversify in more land-based activities. **Research questions: How can increasing tourism in the Polar Regions be effectively regulated to ensure its sustainability? What social and environmental risks do cruise ships and infrastructure development pose to these areas? What is the scope for consistent and dedicated monitoring of tourism impacts, particularly at highly visited sites? What are the social impacts of cruise ships on local communities and research facilities, including cultural changes and effects of increased local monetary wealth? How can ecotourism activities be anchored in and organized by local indigenous communities in ways that support and foster traditional livelihoods?**

Expanding transport links: Expanding opportunities for transport in the Polar Regions take many forms: establishment of rock, blue ice or snow airstrips to deliver better air-links, construction of road networks, and of wharf facilities in new areas that have been opened up to vessels due to sea-ice decline. Such developments make access to once remote locations easier, but

Cruise Ship Greenland *(Photo: Peter Prokosch)*

Antarctic Dumont-d'Urville-Station *(Photo: IPEV)*

may have both social and environmental impacts. Impacts upon indigenous communities may result from changing economic conditions and the influx of new people, traditions and ways of life. **Research questions: How can transport and other marine activities be developed that avoid disturbing current and future networks of marine protected areas? How can regular traffic be managed to benefit and not disrupt the livelihoods of local Arctic communities? How can fuels used in shipping best be transitioned to cleaner, more environmentally friendly alternatives?**

Environmental impacts of improved transport links include the introduction of alien species, which is a major driver of biodiversity loss globally, with the Polar Regions predicted to be especially vulnerable, particularly in light of regional climate change. **Equally applicable to both marine and terrestrial polar environments, research questions may include: which pathways for alien species introductions present the greatest risks and which locations are most vulnerable to invasion? What biosecurity techniques are most suitable to reduce introduction risk and what methods can be used or developed to respond to existing invasions? How can the risks of inadvertently transporting indigenous species between the different polar bioregions be reduced?**

Land use: There is an urgent need for improving predictions of how the human footprint in the Polar Regions is likely to change, so that both social and ecological factors are given adequate consideration and management. For example, only 0.18% of the Antarctic continent is exposed rock. In parts of the Antarctic Peninsula, relatively flat, ice-free, coastal land suitable for station construction is a real non-renewable resource that is running out. In some areas, all sizeable ice-free promontories are either sites of research stations, visitor sites, or protected areas. This highlights the conflict between human activities and conservation of ground for penguin colonies, seal haul-out sites and vegetation - a conflict that will only become more severe as human presence increases. Evidence of past human presence is also important. Historical sealing sites provide vital material evidence of 19th century use of the areas yet are difficult for the untrained eye to comprehend and appreciate. In the Arctic, land use planning and land claims negotiations are often related to contemporary impacts from past transgressions and are part of reconciliation and tackling the socio-economic and cultural consequences of those actions. Constructive outcomes from negotiations facilitate cultural revival that can positively influence social well-being and health. Land use planning and extraction of renewable and non-renewable resources also raises questions of land use, infrastructure development and rights. Increased coastal erosion is affecting both settlements and archaeological sites, especially in non-consolidated permafrost terrain. Co-design and stakeholder engagement processes – including meaningful consultation with affected indigenous communities – can mitigate negative consequences from such activities and help ensure local benefits. Knowledge of land use and conservation and sustainable modes of extraction needs also to consider power relations between the involved stakeholders. **Research questions: How can available knowledge be used to facilitate adaptive planning of future human activities to take into account conservation of existing wildlife and biodiversity and cultural heritage? How can co-design and consultative processes help ensure meaningful engagement, local benefits and proper attention to ecosystems impacts?**

Harvesting of renewable resources: Many renewable resources in the Polar Regions are subject to exploitation and this will change as global requirements for resources continue to increase. Fishing, use of space for renewable energy production (wind farms, etc.), biological prospecting, and even use of freshwater resources are all poorly understood potential impacts on polar ecosystems. Sustainable fishing, although closely regulated in the Southern Ocean by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), may be vulnerable to increasing variability in species populations, linked to climate change impacts. **Research question: how can our understanding of fish stock sustainability and resilience be improved by integrating data on oceanographic, climate, ecosystem and harvesting interactions?**

Extraction of non-renewable resources: The paradox of sustainability of a non-renewable resources requires particular attention. Extraction of non-renewable resources poses special challenges and initial assessment and ongoing monitoring of environmental, social and economic impacts from extraction of non-renewables is crucial. Systematic measures for the prevention of negative environmental and societal impacts must be developed, with integrated long-term monitoring systems as well as mechanisms for proper compensation when negative impacts do occur. Impact and Benefit Agreements for local populations are increasingly common in the Arctic, although the extent of use varies among countries. Social Impact Assessments (SIA) and Environmental Impact Assessments are valuable tools, yet also require further research in order to improve their integrated application as well as development of international benchmarks and standards. **Research questions: in what ways can research and policy effectively tackle the whole extraction cycle from exploration to the final stage of closure of operations and related remediation and reclamation activities? How can mining and even hydrocarbon extraction be pursued to ensure they are informed and guided by Agenda 2030 goals? What specific approaches to co-design for land-use planning, industrial development and assessment of social and socio-economic benefits have proven fruitful, and how might good practices be improved, expanded and scaled up? Where problems do occur, especially offshore, how can search and rescue operations be prepared for and organized more effectively?**

Research vessel in the Arctic Ocean *(Photo: Alfred Wegener Institute / Mario Hoppmann)*

B. Linking knowledge and decision making

A core theme of this White Paper is further developing and expanding the application of methods for linking knowledge and decision-making in ways that more closely reflect interactions between people and nature. This includes use of tools that already exist but are not yet sufficiently embedded in practice. Here we emphasize three key areas where research can play an important role in carrying this forward.

1. Indicators and effective management/governance processes

Sustainable Development Goals (SDGs) – Important work is already underway to identify Arctic-specific aspects of the SDGs, and it is important that further development with targets continues, as is being done elsewhere (with no native populations, the social-focused SDGs are likely to be less broadly applicable in the Antarctic). In addition, new research recently published by Weitz et al.[3] (2017) takes a system approach to examining the relationships between the SDGs and each of the target points to the importance of understanding how actions in pursuit of one goal can be expected to influence performance on others. The interaction matrix is currently being tested by the Swedish steel industry to increase the understanding of where actions taken to realize the SDGs can be most effective. The Finnish Arctic Council Chairmanship (2017-2019) is prioritizing developing ways to adapt the SDGs to the Arctic context. **Research question: How can further analysis and evaluation of these types of tools and processes be developed to support effective and strategic implementation of measures aimed at achieving Agenda 2030 in a Polar context?**

Indicators of social-ecological resilience – Indicators of social-ecological resilience encompass nature-human relationships, and inherently, the capacity of a community to effectively navigate an uncertain future. Approaches for developing Arctic-specific indicators have been proposed, yet these efforts to develop robust indicators of social-ecological resilience remain

[3]Weitz, N., Carlsen, H., Nilsson, M. and Skånberg, K. (2017). Towards systemic and contextual priority setting for implementing the 2030 Agenda. Sustainability Science. https://dx.doi.org/10.1007/s11625-017-0470-0

Drilling and core sampling on the Arctic Coring Expedition on Lomonosov Ridge in the Arctic Ocean in summer 2004. *(Photo: IODP, H. Paelike)*

in their early stages. Meaningful efforts would examine the relationship between market and semi-subsistence economies, how indigenous and conventional knowledge interact and may complement one another, and between systems of legal rights and community capacity to organize and cooperate effectively (social capital). **Research questions: How can resilience indicators be developed through community-based participatory processes, while also being scalable to a pan-Arctic level? What types of indicators of social-ecological resilience might be applicable to the Antarctic?**

Capital Accounts – These accounts are a method of measuring and valuating resource stocks and flows where human activity draws on ecosystem services. While some of these accounts are available in the Nordic countries and could be available for Arctic-specific analysis, preliminary research suggests significant variation between countries. Significant differences remain in the degree to which such accounts are available, and in the extent to which they are used or able to be used in management and decision-making related to regulatory efforts such as the EU Water Framework Directive. **Research question: What are the practical and institutional obstacles to using such accounts for policy development and ecosystem-based management? What are the conditions under which regulators would be able to actively incorporate and apply such knowledge? How can the data and accounts be further developed and made more complete and more usable?**

2. Ecosystem-Based Management (EBM)

Ecosystem-based management has been embraced by the EU in areas such as the Water Framework Directive and others, while international Conventions such as the Ramsar Convention on Wetlands have shifted from their original bird species protection focus towards an ecosystem approach. Both of these agreements are highly applicable in the Arctic; however, there are numerous challenges to retooling former management practices to accommodate what amounts to a more complex approach to managing complex systems. One could argue that the conceptual or paradigm shift has taken place in these areas of management, but the systemic changes needed to fully implement that shift require much more work. **Research questions: What are the institutional, political and practical obstacles to adopting and implementing EBM on a larger scale? What lessons do successful implementation of EBM approaches offer for further development and implementation of the model?**

3. Participatory approaches to planning and management

Participation in decision and management processes by stakeholders and rights-holders is an important norm and expectation both within the EU context, and also in the work of the Arctic Council. It is also one of the conclusions of the Arctic Resilience Report (2016) that capacity for adaptation to climate and other environmental changes is greatest where communities have a strong ability to organize themselves to manage challenges and pursue shared goals. Effective participation in planning and management can be considered self-reinforcing, since it can both exercise and increase the ability to effectively contribute. One important type of process that is currently receiving well-deserved attention is participatory scenario development and analysis, where participants develop and work through contingencies in possible future scenarios. Prediction is often problematic where human choice and impacts are concerned. This means that exploration of multiple potential futures through scenario analysis is likely to be more valuable in practical terms. **Research questions: Which methods that employ co-design approaches in research, planning and management have proven fruitful? Further research that both uses participatory methods and tests possible variations could make an important contribution to developing and maintaining the capacity for effective management in rapidly changing Polar Regions.**

Subtopic 3: Strengthening integration

This sub-topic concerns the development of research to establish a stronger understanding of the dynamics of knowledge integration, with a focus on strengthening methods for effectively bridging between scientific disciplines, including between natural and social sciences and humanities, and for integrating

Indigenous Knowledge. Responding effectively to the pace and breadth of change also requires strengthening the links and interactions between science, policy and practice.

The Arctic Council has issued a number of statements in Ministerial Declarations and other directives emphasizing the importance of knowledge integration. One focus is to more effectively incorporate Indigenous Knowledge into the efforts of the Council's scientific Working Groups (WGs). The other regards strengthening of the WGs coordination and collaboration across their respective disciplinary and topical boundaries. Research funding calls at both national and European levels increasingly include an expectation of interdisciplinary collaboration and inclusion of relevant stakeholders as active partners. While such efforts speak to the importance of knowledge integration, they say less about how this can be effectively pursued and achieved. This points to knowledge integration itself as an important area for additional research, and for developing, testing and scaling up effective practice through scientific projects that incorporate, develop and test integrative methods. Where "interdisciplinary" points to real collaboration across disciplinary boundaries, "transdisciplinary" is indicative of such collaboration producing breakthroughs in knowledge, methods or fields of study.

"Silos" are not unique to scientific inquiry; policy institutions and communities of practice also construct specialized organizational structures in the form of ministries and specific types of NGOs. The focused knowledge development that defines disciplinary silos has been invaluable, as has the specialized knowledge held by Indigenous Peoples, by policymakers and by practitioners. This importance is captured in an alternative description of disciplinary silos as "cylinders of excellence", in recognition of the knowledge and expertise that has been developed. Nevertheless, many of the key insights needed to inform wise policy and management decisions and more effectively manage human activities ourselves in the context of global sustainability challenges lie in the spaces between these well-developed areas of specialization. Filling these key knowledge gaps can only be managed through effective transdisciplinary teamwork - in itself an area of knowledge.

A. "Team Science" for the Polar Regions

As understanding of the importance of integrating different types of knowledge has grown, research on the factors that influence effective scientific collaboration itself has also increased and is sometimes described as "the science of team science." For example, researching breakthrough discoveries in the biomedical sciences, sociologist Rogers Hollingsworth identifies characteristics at both individual and institutional/organizational levels that contribute to integrative and path-breaking work. At the individual level, scientists whose experience and training bridge multiple disciplines contribute to both greater capacity to communicate across disciplinary boundaries and also in the kind of curiosity and interest that motivates such efforts. On the institutional/organizational level, conditions that entail longer-term, intense contact and interaction have proven extremely important. Hollingsworth's observations suggest two crucial elements that need to be developed. First, both the knowledge "silos" and the bridging of those silos are important in scientific discovery. Second, both individual characteristics and institutional/organizational conditions matter a great deal. For a variety of reasons much of the study of scientific collaboration has focused on either biomedical science or on teams that have produced other breakthrough discoveries. Yet, there are circumstances unique to the study of the Polar Regions, and to integrating biophysical sciences with the social sciences and humanities that may merit focused attention. **Research questions: How can the relevant insights of both "sustainability science" and the study of team science be operationalized in polar research? Communication and personal relationships that bridge disciplinary training have been found to be extremely important, but are there particular requirements for effectively bridging the wider differences between natural and social sciences? Do circumstances unique to Arctic or Antarctic social-ecological systems research create a need for particular kinds of skills, organizational structure or leadership? What are the time and effort requirements that come with learning to effectively communicate between biophysical and social sciences and humanities? How do these requirements differ for integrating scientific and indigenous knowledge, and what are the strengths and shortcomings of currently established inter/trans-disciplinary research methods?**

B. Bridging science to policy, policy to practice

It is also well-established, dating back to the German sociologist and economist Max Weber that the differing logics and values that guide science and policymaking represent important challenges, yet these differences are essential. The wide gaps between what is known and understood about resource conservation and use related to the Polar Regions, and how that knowledge is reflected in policy, suggest there may be circumstances specific to these regions that need to be accounted for. **Research questions: What methods have proven effective in communicating between science and policy, and how do these apply to circumstances unique to the Polar Regions? Since comparatively few countries have territory in the Arctic and the Antarctic is treaty governed, what communications and other tools that are polar-specific can be used to inform relevant policy in such countries? How can both localized livelihoods and the ecosystem functions of the Polar Regions be emphasized and balanced in a policy context with the sometimes more obvious opportunities presented by potential new transport routes, new tourism destinations, mineral and food resources?**

C. Achieving trans-disciplinarity with a social-ecological systems perspective

It has been noted previously that the research policy initiative urged by this White Paper seeks knowledge about how to more effectively and wisely manage human activities and resource use within the limits of the ecosystems upon which people depend - in a context that is rapidly changing due largely to anthropogenic forces. This, in turn, entails study of the causality of complex social-ecological systems, with cascades and cumulative effects, and with a particular focus on human activities that especially impact the Polar Regions. Such research on complex systems interactions and feedbacks, with human activities playing a central role, requires effective integration of knowledge about the system in question, and also about the people and institutions conducting the research. It is neither necessary nor possible for research projects to tackle all of these kinds of bridging challenges simultaneously, yet it is essential that such bridging is part of an overall mix.

Historically, science has tackled the problem of complexity by isolating and studying the phenomena of interest to understand its properties. In contrast, this White Paper urges a systems approach that examines the phenomena of interest – management of human impacts, conservation and use of polar resources – in the system of which it is a part. Such an effort entails major challenges, especially with the inclusion of humans in the system definition. "Fractals" provide a useful metaphor to characterize the approach proposed in these pages. With fractals, smaller scale expressions of a phenomenon contain all the elements of the larger scale version of the phenomenon. Similarly, by focusing on the specific kinds of resource-related human activities that are identified in Sub-topic 2, human impacts and social responses in polar ecosystems remain in focus. Existing insights and new research questions regarding effective collaboration, trans-disciplinarity and other forms of knowledge bridging, also remain a key element of research and research practice. It is important to acknowledge that the kind of integrative efforts emphasized here are already being pursued in some specific projects and particular settings. These efforts can help point the way, and point to a final **research question: What new knowledge is needed to scale up these approaches, and to address the key gaps identified in research design to accelerate the development of effective responses to the changes seen in the Polar Regions?**

Relevant Cooperation Partners

It is important to include all stakeholders and rights-holders in the Arctic and Antarctic as participants in this research agenda. Effective engagement fundamentally requires knowledge of the diverse perspectives, motivations, values and insights to optimally balance choices regarding conservation and resource use - and managing the pursuit of resources within the constraints of polar ecosystems. An adequate and proper balance will be a moving target, requiring ongoing monitoring, recalibration and revision of earlier decisions. Monitoring and risk assessments therefore depend on input from a diversity of stakeholders, and research efforts should be truly collaborative and aiming at the co-production of knowledge and a sharing of responsibility.

Arctic stakeholders	Antarctic stakeholders
National, regional and local governments of Arctic territories and their collaborative fora. For example: • Arctic Council and its working groups: AMAP, CAFF, PAME, SDWG	Governments of claimant states and signatories to the Antarctic Treaty and its components. For example: • Antarctic Treaty Consultative Meeting (ATCM) • Commission for the Conservation of Antarctic Marine Living Resource (CCAMLR) • Committee for Environmental Protection (CEP)
International Arctic Science Committee (IASC)	The Scientific Committee on Antarctic Research (SCAR)
Arctic local and indigenous communities	National Antarctic Programmes and the Council of Managers of National Antarctic Programmes (COMNAP)
NGOs • National and international • Locally-organised campaign and pressure groups	NGOs • National and international
European and global public interest • News media • local cultural groups • Heritage / Museums	European and global public • News media • Cultural groups • Heritage / Museums
Business and Industry sectors: • Fisheries, shipping and logistics • tourism • renewable resources • non-renewable resources (oil and gas, and mining) • development of new technology • insurance solutions • biological materials (bioprospecting)	Business and Industry sectors, including: • Tourism • Fisheries • Infrastructure services

Enabling Capacities and Resources

One important goal with this White Paper is to identify potential actions that can contribute to strengthening collaboration across traditional scientific disciplines and established advisory groups to encompass a social-ecological systems perspective. A number of new and ongoing projects of the Working Groups (WGs) of the Arctic Council (AC) either have strong potential or are already exploring such collaboration. Yet, realizing this more extensive collaboration would require increased capacity for the Working Groups.

Especially with issues of resource development and conservation in the Polar Regions, communication and research coordination are an essential function. This includes communication to effectively manage connections between diverse types of researchers, between Working Groups where projects are collaborative, also including representatives of the Arctic's Indigenous Peoples through the Permanent Participants. Given that many critical decisions will be made outside the Polar Regions, communications between researchers and decision makers at local, national and international levels are essential.

In the Antarctic, the Treaty Parties are becoming increasing aware of the need to develop more integrated reporting systems on environmental and human variables across the different regions of the continent and the Southern Ocean, to facilitate more effective governance of the Treaty area. For example, the Committee for Environmental Protection is developing mechanisms to identify and devise specific actions to prepare for, and build resilience to, the environmental impacts of climate change. However, opportunities for improved communication between different scientific disciplines, and between scientists and policy-makers within the Antarctic Treaty System, have been identified. EU Members comprise over 40% of the Consultative Parties that participate in decision-making at the annual Antarctic Treaty Consultative Meeting. The EU is exceptionally well-placed to drive forward research and communication, with over 20 Antarctic research stations and permanent field camps operated by EU nations, so that improved management outcomes can be delivered.

Funding and international cooperation

International collaboration is essential for this work, not merely because the Arctic extends beyond Europe and human engagement in the Antarctic involves numerous countries and stakeholders from around the world, but also because this work builds on existing research on Arctic and Antarctic issues. To make the most of existing expertise and capacity around the world, we need to reach out to the international community and we need to connect with all stakeholders and rights-holders. These will include: Arctic and Antarctic collaborators, IASC member states and SCAR participants, National Antarctic Programmes and Antarctic Treaty Consultative Parties, tertiary and research institutions and their networks, Indigenous Peoples, and European Institutions. For such cooperation to be adequately realized, funding will need to made available support the kind of time and effort required to build shared understandings, common language, and personal relationships that make it possible to effectively bring to bear the kind of diverse expertise needed to tackle the social-ecological challenges being experienced in the Polar Regions.

Way Forward and Key Action Areas

1. Engage iteratively with policy-makers to develop a focus on the existing and likely future threats to polar ecosystems and communities.
2. Identify available data sources for environmental and social variables required to assess systemic impacts upon Arctic and Antarctic environments.
3. Identify gaps in knowledge and initiate or enhance monitoring activities to strengthen future predictions of environmental impacts and trends in Polar Regions.
4. At policy-relevant spatial scales, integrate available environmental and societal knowledge to model future scenarios.
5. Use topical areas involving resource conservation and use (land use, tourism, transport, fishing, resource extraction) as focal areas for research on strengthening knowledge integration that can be incorporated into strengthened regulatory and management practices.

An Increasing Level of Urgency

Significant change has always been the reality of the Polar Regions. Yet a new urgency is brought by the unprecedented pace and breadth of that change, the potential disruptive impacts on both ecosystems and human populations, and the need to manage resource use and nature conservation in the Polar Regions with a wisdom and effectiveness never before as necessary. This translates to an urgent need for integrated knowledge on social-ecological systems that also incorporates aspects of resilience:

1. The breadth and pace of social and environmental change

With variation based on which Polar Region one is examining, changes in the Polar Regions include climate change, ocean acidification, ozone depletion, changing weather patterns, altered sea-ice extent, biological population range shifts, changing connectivity of biological populations (fragmentation and homogenisation), loss of livelihoods, and collapse of communities. There are of course important differences that depend on which Polar Region is being considered. Both are more sensitive to many global stressors than other regions, with impacts that are felt more acutely than anywhere else.

2. The unevenness of change and critical thresholds

While existing research attests to rapid change in the Polar Regions, it also points to some processes being non-linear, as some system feedbacks further accelerate the pace of change. This is most obvious with the loss of snow and ice, the disappearance of which leaves darker sea or land surfaces that absorb far more heat, which in turn accelerates warming. There are, however, many other geophysical, biological and social systems processes prevalent in the Polar Regions that display amplifying feedbacks and self-reinforcing characteristics. This means that changes in social or ecological systems can frequently be cumulative, cascading and interactive. The presence of critical thresholds or "tipping points" means that beyond a certain point, systems are unlikely to recover to their previous state within decades or even centuries. The danger with such tipping points is that they are often difficult to identify except in retrospect, and some features, once lost, are forever lost and cannot be recovered. In 2016, the Arctic Council's Arctic Resilience Report identified 19 such potential systemic thresholds or tipping points that have been reported in the scientific literature. Many of these thresholds apply equally well to Antarctica, with, for example, predictions of dramatic melting of what was considered 'permanent' ice on the Antarctic Peninsula by the end of the century leading to changes in biodiversity and increased risk of invasive species.

3. Social and ecological systems are highly interconnected, both within the Polar Regions, between the poles and other regions, and across scales from local to global.

We have already noted how the increase in human activities in the Polar Regions generates local impacts. In the Arctic, these come from increased economic activities, including tourism, transport and efforts to secure both finite and renewable natural resources, much of which is driven by interests outside of the region. In the Antarctic, these impacts are generated from an increased human presence through expanding tourism and establishment of research stations and provision of infrastructure. Yet, many of the most powerful drivers are generated by human activities taking place far from the Polar Regions. One critical effect is that the causal links between many human activities and their harmful societal and ecological consequences are blurred both by time, and by geographical distance. Coastal erosion caused by intensified storms and a lack of dampening landfast sea ice, infrastructure collapse due to permafrost thaw, ecosystem effects of accumulating chemicals and plastics, are difficult to connect directly to the activities that produce these changes. This distance between cause and effect adds to the challenges of understanding causal relationships and sequences; it also complicates the process of curbing, managing or modifying the human activities that are ultimately the source.

4. Effective management under changing conditions

The pace and scope of change is generating increasing scrutiny of the Polar Regions not only from researchers, but also from both new and established stakeholders interested in pursuing opportunities for securing and/or utilizing polar resources. The Polar Regions are opening up with increasing speed. In the Arctic, this is contributing to more localized developments such as demographic change and relocation and migration, contributing further to conditions of rapid change. The Antarctic is also seeing intensified pressure on the 0.18% of the continent that is ice-free ground. The tourism industry has increased dramatically in the past two decades, with current numbers close to

Tourists visiting Antarctic Glaciers *(Photo: P. Prokosch)*

50,000 individual tourists landing each year, at numerous locations mostly situated on the Antarctic Peninsula. The region is also seeing an increasing number of research stations being constructed, predominantly on scarce coastal, ice-free ground. As a consequence, existing management and planning mechanisms may not be keeping up effectively. It is essential that modes of management and planning for the use of polar resources are strengthened, with better integration of newly emerging knowledge and more effective use of that knowledge for setting priorities and managing dynamically and adaptively. Because of the differences between the Arctic and Antarctic in activities and international agreements, questions of effective planning and management will necessarily differ. In the Arctic, the need is to understand how to successfully balance conservation and exploitation, and to ensure social and economic development for the people of the region. In the Antarctic, guided by the Antarctic Treaty System, further knowledge on which to base decision-making is crucial.

5. Urgent need, yet important opportunity

The need for knowledge integration to inform the balancing of conservation and use, planning and management, has arguably never been more urgent. However, as the challenges are now broadly understood, we may be better prepared to act now than at any time previously. Communication between research communities, policymakers, practitioners and local communities is often difficult. However, awareness of the need for bridging knowledge systems, and for bridging science, policy and practice, has explicitly been on the agenda for at least a decade. Expectations of inter-disciplinarity in research projects have increased to go well beyond simply including both social and natural scientists and humanities in research projects, or requesting consultation with stakeholders and rights-holders. A growing body of research has identified the characteristics and conditions that provide opportunities for breakthrough thinking and integrative thinking through "team science" and other forms of collaboration. Similarly, calls for integrating conventional science with different knowledge systems (for example, Indigenous Knowledge and local knowledge) are being taken seriously. Equally important are calls for not merely handing over the finished products of scientific research to policymakers and stakeholders, but also including local peoples' interests and insights when designing and conducting research (co-design).

Definition of terms

Resources. We use the word 'resources' in a broad manner to cover both harvestable and non-harvestable, renewable and non-renewable resources. In addition to direct economic/societal benefits, the less tangible benefits of undisturbed nature and cultural heritage in both a localized and broad sense are also important. Ecosystem resources include food (fish/shellfish, plants, livestock, terrestrial and marine wildlife), freshwater, raw material (minerals, wood) and energy (fossil and renewable energy resources), although in the Antarctic, only fish and krill are allowed to be taken. Cultural resources include aesthetic and intangible values (wilderness or spiritual), cultural heritage and landscapes. Clearly, many polar resources are finite and non-renewable. Without suitable and adaptive management and planning, resources may be lost, or used in a sub-optimal manner, depriving future generations of opportunities. Furthermore, polar resources may yet be undiscovered or not considered as resources according to present thinking.

Use: Resource 'use' includes not only resource utilisation (e.g. mineral resource extraction, use of space to develop transportation infrastructure), but also resource conservation/preservation (e.g. protection of habitats, landscapes and heritage, and stewardship of resources for use by future generations).

Stressors and change drivers: Many of the dominant stressors impacting the Arctic and Antarctic originate from outside the Polar Regions (long-range transported pollutants, climate change, ocean acidification, demand for energy and raw materials, demographic change). Yet, a growing human presence in both regions is also producing stresses. Interactions between stressors - with some stressors causing or exacerbating others - are often poorly understood, but potentially powerful. Increasing pressure is largely due to activities undertaken on an industrial scale.

Human activities: Housing/urban development, transport activities (roads, rivers, ocean routes, airfields), mining/drilling (extraction), energy generation (wind/solar farm, power stations), fishing, hunting, harvesting (crops and livestock), research (including bioprospecting), tourism, and indigenous dwelling, spiritual and subsistence activities.

Impacts: Impacts on ecosystems: pollution, species invasion, habitat loss, extinction, wildlife disturbance, water availability, energy input, etc. Impacts on people: heritage loss, wealth generation, changing societal values, etc.

Ecosystem services: Ecosystem services are the direct and indirect contributions ecosystems make to human well-being. These "services" support human survival and quality of life either directly or indirectly.

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EU-PolarNet White Paper No. 4

The road to the desired states of social-ecological systems in the Polar Regions

Reindeer herd (Rangifer Tarandus) in Finnmark, Norway *(Photo: Lawrence Hislop)*

Background and Motivation

The future development of social-ecological systems of the Polar Regions depends on our ambition and capacity to meet changes and to navigate towards a sustainable future. Research can and must play an important role in this process. The sustainable development goals of the UN are useful guidelines in this, but their indicators are not always fully relevant in the Polar Regions. In order to be able to make the right decisions in the future development of social-ecological systems, this white paper addresses the most fundamental need for any societally relevant research for the Polar Regions: the identification of what the different Arctic and Antarctic stakeholders see as the desired future states of the Polar Regions and the assessment and proactive development of pathways that allow us to come as close as possible to reaching those desired states.

Life and societies are constantly in flux, and change needs to be accepted as a constant and also, as an opportunity. The changes taking place in the Polar Regions are not only of great consequence to people living and working there, but also to the entire global community – not least because of the role that the Polar Regions play in the regulation of the global climate system. These regions serve as the world's barometer for transformation caused by climate change and the way we respond to it.

The changes we are experiencing affect our pathways into the future. However, unless we proactively shape these pathways, the changes thrust upon those in the Polar Regions may not necessarily be positive ones. To enable positive change, we need to understand where the different stakeholders[1] want to be in the future, keeping in mind that resilient and sustainable ecosystems are needed to support these futures.

The research proposed within this theme aims to:

1. Identify the desired future states at different levels (local, regional, national etc.) envisioned by stakeholders in the Polar Regions;
2. Develop a suite of key polar indicators necessary to assess the state of the social-ecological systems in the Arctic and Antarctic; and
3. Provide guidance on optimal pathways towards the desired states ensuring just transitions.

Research addressing these three aims will also enable us to create guidelines for sustainable monitoring and regular assessments that allow us to assess our progress towards the desired states.

Heading out for seal hunting *(Photo: Lawrence Hislop)*

[1]Throughout the paper, we use the term stakeholder to describe anyone with an interest, concern or 'stake' in the Polar Regions, including communities, individuals, organisations, governments and other right-holders.

Kangaamiut, West-Greenland *(Photo: Peter Prokosch)*

To achieve the above, the research proposed takes into consideration the interests of decision-makers who want to have access to succinct, problem-focused/targeted (research) results and recommendations. This white paper builds on existing research, adding novel research as needed, with the overall goal of producing targeted and succinct summaries for decision-makers.

Due to the problem-focused approach required to deliver the research proposed in this white paper, the work is necessarily 'post-disciplinary', involving a range of different capacities and methods and with strong contributions from the natural and social sciences. A 'post-disciplinary' approach acknowledges that social phenomena transcend the boundaries of any conventional academic disciplinary inquiry and aims at assessing phenomena holistically and in an integrated fashion.

European governments are at a crossroads with regard to the future stability and sustainability of a strong and relevant European community, in relation to (a) climate-change preparation and mitigation, and (b) ensuring European and global security, not only in terms of a more conventional view of security as public safety but also water, food, energy, health and environmental security. These challenges are explicitly pertinent for the northern Arctic parts of Europe.

The Arctic and the Antarctic play a significant part in this – a little more than 4 million people live in the Arctic, with about 1.2 million people living in the European Arctic (excluding Russia). Fifteen European countries (12 within the EU, including the UK, plus Norway, Russia and Ukraine) are decision-making parties to the Antarctic Treaty System and have active National Antarctic Programmes of research. The EU countries of Sweden, Finland and Denmark are members of the Arctic Council, as are the European countries of Norway and Iceland. Climate-related changes are amplified in the Polar Regions, positioning the Polar Regions as a bellwether of global change, and proactive action is required to mitigate and minimize the impacts resulting from these changes. In the Arctic, the social-ecological systems are further pressured by social changes, e.g. related to migration, urbanization, and health-related issues.

The future of the Polar Regions is intricately entwined with the future of Europe (and the rest of the world), and without a better understanding of the perspectives of those most engaged with the Polar Regions, be it as the space where they live; in terms or renewable or non-renewable natural resources on Polar lands and in Polar marine environments; or through economic, environmental or political ties, we cannot positively affect, let alone shape, the decisions that will decide our common futures.

Furthermore, understanding the perspectives and values of all polar stakeholders offers an opportunity to optimize all policies and to avoid potential conflicts, which will ultimately reduce costs.

Finally, the current sustainable development agenda, primarily defined by the UN Sustainable Development Goals (UN SDGs), although global in reach and ambition, has not been designed with the Polar Regions in mind. As a result, UN SDGs, and their respective indicators, are not specific enough to give guidance in all decisions made concerning Polar Regions. This white paper aims at filling this fundamental gap by suggesting a suite of polar indicators and by adapting the UN SDGs to suit the Polar Regions.

So far, we do not have a solid understanding of which desired states have been identified by the range of stakeholders in the Polar Regions. Without knowing the desired states, we cannot even begin to direct pathways towards achieving optimal health and functioning of the social-ecological systems taking into consideration the needs, values and perspectives of the different stakeholders. Until the currently implicit desired states are made explicit, conflict over the future of protection and utilisation will be inevitable. The rate of change in the Polar Regions and the variety of stressors already impacting them mean this dialogue is urgent.

In addition, while we are tasked with achieving the UN SDGs across the world, the poor fit of the related SDG indicators to the Polar Regions means that we are unable to effectively assess and track the pathways towards achieving the SDGs in the Polar Regions. There is a dire need for a suite of polar indicators that allow us to cross-reference to the SDGs while having an appropriate tools to monitor change in the Polar Regions. Developing such a suite of polar indicators will necessarily inform work on a post-2030 development agenda.

Not committing to the activities outlined in this white paper means that we may miss a unique opportunity to be prepared for the future in the Polar Regions, to build an informed post-2030 development agenda and to link the SDGs to developments and change in the Polar Regions.

Now, we are also in a position to build on, integrate and expand existing knowledge regarding different stakeholder values and needs, which has been developed over the last decade.

Societal Relevance

The research proposed in this white paper has direct links to and contributes to issues involving governance in the Polar Regions as it will clarify the range of interests, perspectives and values of different stakeholders, including policy-makers. Thus, it will allow a more targeted approach towards sustainable development and resilience in the Arctic, and to effective integrated environmental management and informed decision-making in the Antarctic. The research proposed will ensure that ecosystem services are being valued and considered in decision-making.

The proposed research assists in the co-production of knowledge and the co-determination of desired futures for the Arctic and Antarctic. In the Arctic, this work will improve disaster preparedness and address food, water and energy security, sustainable economic development and the improvement of available hard and soft infrastructure.

Furthermore, the proposed research has integral components related to climate justice, equity and fair access to services, especially as the identification of desired states and the transition towards those desired states are concerned.

The research suggested in this white paper will contribute to making the SDGs and their indicators relevant for the Polar Regions (which is likely to also benefit other areas, such as high mountain regions), thereby contributing to capacity building and education among polar stakeholders, specifically including Arctic communities and indigenous right-holders.

Finally, the proposed research offers governments and governmental bodies, including the European Union and its member states, a framework of advice in developing their Arctic and Antarctic policies.

Remnants of a village, Siberia *(Photo: Peter Prokosch)*

Research Needs

While there are obvious similarities between both Polar Regions, they differ from each other in many important respects. Many of these differences – such as the absence of permanent local or indigenous communities in the Antarctic and differences in type and severity of historic environmental impacts – influence the potential pathways toward the desired states. Furthermore, the causes of change, and the type and extent of change, differ between both Polar Regions. Consequently, there may be regionally different desired states and different sets of suitable governance actions.

To clarify the desired states in the Antarctic, it is important to connect the research strongly with the history of Antarctic sovereignty and the Antarctic Treaty System (see Box 1 for further information). Several components of the governance system frame the research on the desired states for the Antarctic. These include (a) the designation of Antarctica as a natural reserve devoted to peace and science, (b) the explicit recognition that certain values (including intrinsic and wilderness values) should/do apply to the Antarctic, (c) the General Principles of Antarctic Tourism, adopted by the ATCM in 2009, and (d) the importance of certain principles, such as the precautionary principle in managing human activities in the Antarctic.

In the process of identifying and agreeing on the desired states in the Arctic, we need to acknowledge and understand an even wider community of stakeholders. The Arctic consists of eight Arctic countries and more than 40 different Arctic Indigenous Peoples. It is experiencing increasing interest from around the world – from researchers, environmental protection groups, tourists, and businesses interested in hydrocarbon and mineral exploration, fisheries, the transport industry, telecommunications, etc. This is reflected by an increasing number of states and organizations that are currently, or wish to become, observers to the Arctic Council. All of these people and organizations have different interests in the Arctic, and their desired future states have many possible conflicting facets.

It is also important to acknowledge the rapid changes that occur in the Arctic, which can dramatically affect people's lives and ecosystems. Climate change is a major concern, which is compounded by rapid economic developments and social and cultural transformations.

The Arctic Council plays an important role in facilitating cooperation in the Arctic. The Arctic Council is committed not only to maintaining peace, stability, and constructive cooperation in the Arctic but also to the wellbeing of Arctic inhabitants, sustainable development and the protection of the Arctic environment.

As the Arctic is not homogenous, there are likely to be significant differences in the desired states envisaged by the eight Arctic Council member states and the Council's six permanent participants who represent the Arctic's indigenous peoples.

A thorough understanding of these different desired states both in the Arctic as in the Antarctic should form the basis for the roads to be taken towards the future of the Polar Regions.

Box 1: Background on Antarctic sovereignty claims and the Antarctic Treaty System

As no international consensus could be reached on the territorial claims in Antarctica during the first half of the 20th century, the region became a subject of a unique international governance system. Twelve EU Member States (including the UK) are among the 29 Consultative Parties that take decisions on the governance of the Antarctic at the annual Antarctic Treaty Consultative Meetings (ATCMs). Several EU Member States are also Contracting Parties to the Convention on the Conservation of Antarctic Marine Living Resources and Members of the Commission under this convention.

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 agreements achieve within the Antarctic Treaty System should mean with respect to regulating and managing change in the Antarctic. Consequently, these stakeholders may have different perspectives on the question, to what extent changes are desirable, and whether governance action is needed? Furthermore, for all involved countries and stakeholders, there may be many different other sources and motivations that may inform 'their' views on what a desired state in the Antarctic should mean. Examples include economic interests, good relationships with other countries or stakeholders, lack of knowledge, etc.

Gaps in knowledge & research needs

Gaps in knowledge relate to the components of the desired states of the social-ecological systems in the Polar Regions, as well as to the type and extent of climatic changes as well as changes in human activity in these regions. This also implies gaps in knowledge in relation to action that would be needed to ensure that developments will move in the direction of the desired states. Even when we have increased knowledge of the desired direction of governance, we still need to understand which instruments (governmental, intergovernmental, self-regulatory, and other instruments, or a mix thereof) offer the best chance of success.

To address those gaps in knowledge, we will need to
1. Identify the desired future states envisioned by stakeholders and 'right–holders' for the Polar Regions (Subtopic 1);
2. Develop a suite of polar indicators necessary to assess the state of the social-ecological systems in the Arctic and Antarctic (Subtopic 2);
3. Create guidelines for sustainable monitoring and regular assessments that enable us to assess our progress towards the desired states (Subtopic 2); and
4. Provide guidance on optimal pathways towards the desired states ensuring a just transition (Subtopic 3).

The three subtopics for the research proposed are described in greater detail below.

Subtopic 1: Desired States

A desired state (see Figure 1) is an integrated value-based concept of ideal futures for different stakeholders that is holistic in nature and captures all research disciplines, indigenous peoples' knowledge and stakeholders' input. Different "desired states" are possible at different levels (local, regional, national and international, and depending on the different stakeholders consulted). Mapping desired states involves identifying and understanding the different stakeholders' perspectives, interests, values and motivations.

The concept of desired states is a truly post-disciplinary concept that draws together knowledge and research from the social sciences and natural sciences. The latter need to provide insights that allow us to understand the structure and characteristics of polar ecosystems over the next decades. Without better projections of environmental change and social pressures (ideally delivered by coupled-system models at regional and global scales), we do not know which species will survive in the Polar Regions and which will invade them, and how those changes will impact sustainable livelihoods in the Arctic and effective ecosystem-based management of the marine and terrestrial environments in the Antarctic.

Knowledge about the desired states and a better understanding of where stakeholders see themselves in the future, will enable governments to optimize policies and avoid potential conflicts, which in turn will result in cost savings, in particular as transaction costs are concerned. It will also contribute to a more re-

The road to the desired state of the social-ecological systems

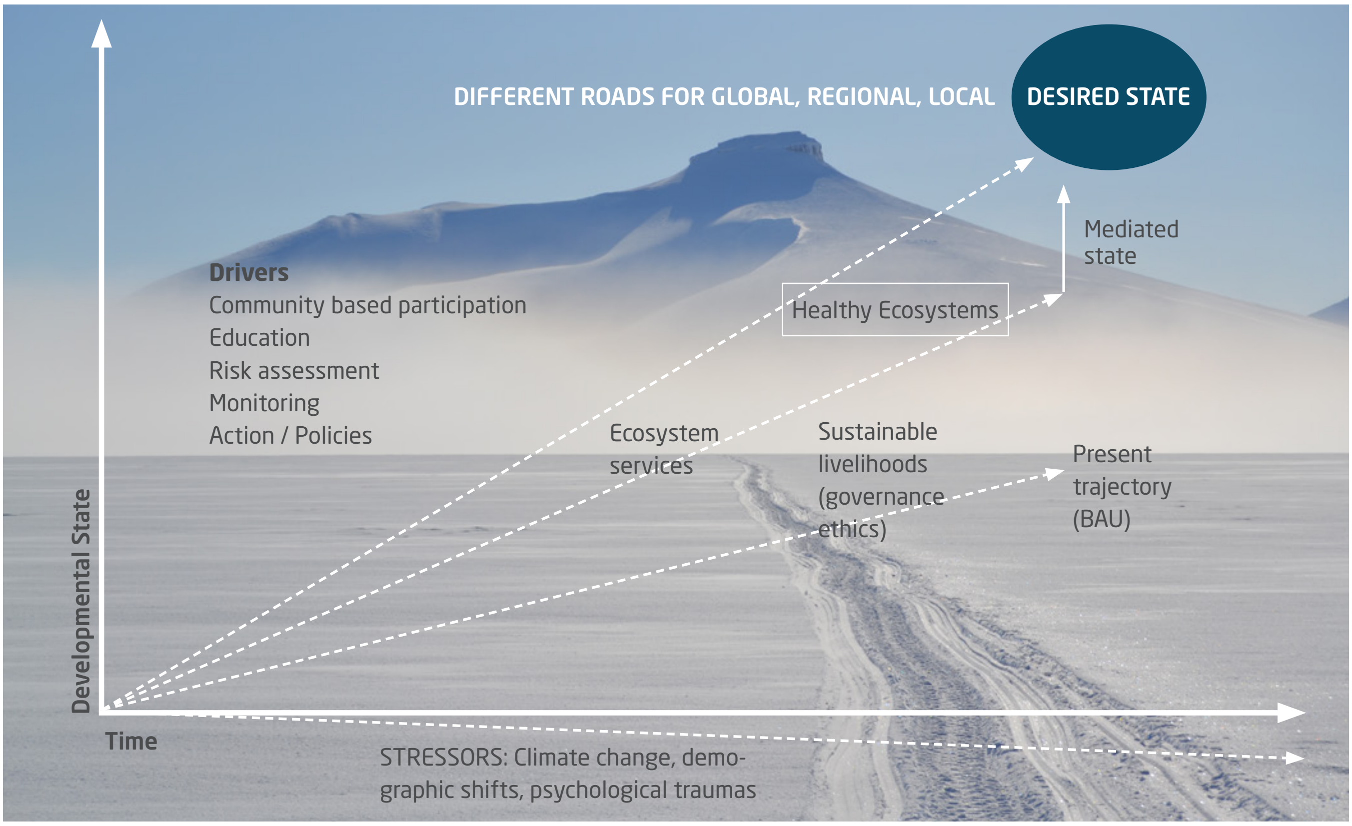

Fig.1: Pathways to the desired states of social-ecological systems

alistic and advanced understanding of future changes and the response they demand.

A desired state may not necessarily be very different from what we have today, i.e. not everything needs to change to achieve the greater common good.

To reach the desired states we need to harvest the best available knowledge of the already existing work and to develop tools of how we use this in order to get to a higher level. Communication and education are some of the tools used in this framework to facilitate pulling together existing research and involving the wider research and stakeholder communities.

Subtopic 2: Assessments for healthy polar social-ecological systems

In 2015, the global community adopted Agenda 2030 for sustainable development and set 17 goals to guide global efforts in that direction. There have been concerted efforts toward a concretization of the SDGs through the identification of targets and indicators -- a global indicator framework developed comprises 232 individual indicators. However, this framework largely overlooks the Polar Regions, creating a lack of tools by which we can measure progress towards achieving the SDGs in the Polar Regions.

There is a particular lack of indicators that measure the state of the Arctic and Antarctic social-ecological systems. For instance, the present SDG indicators do not include a single indicator focused on the cultural wellbeing or retention of ancestral languages (the only indicators that partly refer to culture are 4.7.1 on the global citizenship education and 11.4.1 on the total expenditure per capita spent on the cultural and natural heritage). These cultural assets are, however, of existential value to the indigenous peoples and communities in the Arctic. Similarly, the economic indicators associated with the SDGs do not recognize the importance of a mixed economy or any lifestyles that are (partially) based on subsistence, and the only indicators (10.7.1 and 10.7.2) on migration do not offer any information on the rapidly changing situation in the North, or on how fast population and demographic shifts affect the lives of people in the Arctic.

In order to understand the developments in both Polar Regions, while taking their multi-level connectivity with global trends and changes into consideration, it is imperative to construct a set of polar indicators that are representative of the Arctic and Antarctic. Although some of these polar indicators would be applicable and relevant to both Polar Regions, some of them need to remain distinct in recognition of differences between the two regions that we have already touched on in the previous section.

The state and changes in the Polar Regions are to a large extent driven by compound processes related to climate change, and indicators to track and assess change in the biophysical environment need to be developed and reviewed on a regular basis. At the same time, we also need to take into consideration other anthropogenic impacts on the polar environments as well as rapid changes in people's lives in the North, and in the scale and scope of human engagement with the Antarctic. People's lives in the Arctic, and many facets of human interactions with the Antarctic, are tightly connected to nature and rely on it for survival, health and cultural, mental and social wellbeing. Polar indicators need to be able to properly reflect and account for those vital social-ecological interactions.

Some work, mostly in an Arctic context, has already been carried out to date that would aid the development of such indicators. For example, a suite of Arctic Social Indicators were proposed by the Arctic Council Sustainable Development Working Group, and a current project funded by the US National Oceanic and Atmospheric Administration looks into possibilities for defining relevant indicators to assess biophysical changes in the Arctic. Yet, those initiatives represent fragmented and disconnected efforts – not a comprehensive and integrated suite of polar indicators that will have to include relevant elements from the biophysical, socio-cultural, and politico-economic environments as well as account for their very often coupled nature.

Such a suite of indicators will necessarily have to be co-produced by experts and stakeholders, including indigenous representatives, and will have to be validated with local communities in the Arctic and Antarctic stakeholders as feasible and required.

Sustainable Monitoring

Indicators are only useful if the relevant information is collected on a sustained, i.e. long-term, basis. This has been a problem for many small-scale research projects, as they typically do not concern themselves with the sustained collection of information beyond the project's duration. This was also a problem with the Millennium Development Goals, where 46% of the data needed were not available for reporting at the end of 2015, and the challenge is apparent for the present UNECE member countries with regard to their ability to produce data in support of SDG indicators. When selecting appropriate indicators, it is necessary to compare the amount of data already provided (and their potential use for assessing progress) with the cost of creating the necessary soft infrastructure to collect the relevant data.

In summary, there is an urgent need not only to develop a set of accurate and relevant indicators for the Polar Regions but also to ensure that monitoring, i.e. the collection of data for those indicators, is feasible and, most of all, sustainable to enable us to observe changes in the complex polar social-ecological systems on a long-term basis. Further:

- whenever possible, data and information should be collected by local stakeholders and indigenous people without creating any additional burden or pressure for them;
- in uninhabited regions that are difficult to access (including many marine areas) or in areas with limited seasonal access (certain terrestrial areas in winter), data collection will need to be strengthened[2]; and
- the use of new technologies (e.g., remote sensing, improved connectivity, phone apps) can support data collection by local stakeholders as well as remotely.

The data collected for a suite of polar indicators would also serve as the basis for *One Health Assessments* for the Polar Regions.

[2]However, we should not lose sight of the costs vs. benefits of strengthening data collection in those regions. It may be prohibitively costly to collect data in remote and uninhabited regions, and we should keep in mind that significant benefits could be derived by strengthening data collection in other regions for a much lower cost.

One Health Assessments

To comprehend and effectively support positive developments in the Arctic and Antarctic (in the Antarctic, such positive developments will be primarily directed at the conservation of the Antarctic environment), a new approach is needed. This new approach involves a comprehensive and integrated assessment of polar social-ecological systems that recognizes the interwoven nature of human activities and socio-cultural systems with the biophysical environment. It is no longer sufficient to treat those as separate systems; they form comprehensively integrated components of the social-ecological system and the health of each of this system's components affects the overall system health – hence, the need of a One Health Assessment (From 2015 to 2017, the One Health Assessment approach has already been successfully tested in the Arctic Council's One Health project).

Existing systematic assessments – for example, risk assessments, environmental impact assessments and social impact assessments – are well recognized and established methods for evaluating states of environment, society or various economic developments. However, none of these existing assessments takes a holistic approach to the overall health of social-ecological systems, which we see as a precondition for reaching the desired states for any community or stakeholder group.

There is a critical need for the development of a new approach to assess social-ecological systems, and the One Health Assessment is such an approach. Its advantage lies in drawing on previously conducted work and frameworks, such as the Arctic Social Indicators framework, UN Happiness Index or UN food security indicators. For the Polar Regions, a One Health Assessment would rely on polar indicators developed within the research proposed in this white paper. However, the application of a One Health methodology has much broader relevance and could be adopted for many other regions – both within the European Union as well as beyond it, informing development work carried out in other parts of the world.

Subtopic 3: Just transition

It is important to turn inevitable changes (see Box 2) into pathways, or 'just transitions', by controlling and directing them to aid our progression towards a desired state. There are different types of changes, each necessitating differentiated strategies and techniques, to affect and utilize them most effectively and efficiently. We may wish to channel our efforts towards the prevention of certain changes, while we may wish to redirect others. Those major changes that cannot be prevented or sufficiently steered in a foreseeable timeframe (e.g., climate change) require adaptation and resilience if we are to approach desired future states.

Environmental management in the Polar Regions has had to grapple with economic development in the Arctic and been affected by changing dynamics in the Antarctic regime, primarily resulting from growing membership to the Antarctic Treaty System and the increasingly different interests of member states.

Box 2: Changes in the Polar Regions

- Climate change;
- Changes in our knowledge about climate change and possible consequences;
- Changes in the terrestrial and marine ecosystems (e.g., increase of non-native species, changes due to climate change or pollution, etc.)
- Changes in desires of state governments and stakeholders regarding the use of natural resources in the Arctic or Antarctic;
- Direct and indirect changes in the governance system, such as the increase of Contracting Parties to the Antarctic Treaty, or the increase of observers to the Arctic Council;
- Changes in other international governance systems, or changing international relations between state governments, that may influence governance in the Polar Regions, such as developments in the frameworks of UNCLOS, the Convention on Biological Diversity, developments in the Arctic Council;
- Changes in the scale and character of habitation in the Polar Regions (such as the number of research stations, the type and volume of infrastructure to support research, demographic shifts and economic development in the Arctic); or
- Socio-cultural changes.

Polar governance and management to date has not taken us on a road to a balanced and healthy social-ecological system; on the contrary, several problems have occurred. There is now an urgent need to rebuild the foundations upon which development and nature conservation in the Arctic and nature conservation in the Antarctic rest, and this will require a greater acknowledgement of the delicate balance and interwoven character of socio-ecological systems and will require partnerships with a strong focus on justice, ethics and moral choices. This aim echoes objectives outlined in White Paper WP no 2. Different stakeholders have different moral and ethical foundations and may have a different take on what justice and fairness imply. It is important to consider different stakeholders' needs and their differing perceptions of what 'just transitions' towards desired states means. Implicit assumptions, perspectives and convictions need to be made more explicit to enable a balanced and just transition towards the future.

Just transition can mean:

- Preventing undesirable change that would constitute a risk for the desired state(s);
- Steering change towards the desired state(s); or
- Adapting to change that cannot be preventing or steered (e.g. climate change) towards the desired state(s).

In any case, 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 (in the Antarctic, environmental health and protection are paramount), which embraces not only the final outcome but also the process itself, including specific responsibilities and changes.

A just transition has different parameters for the Arctic and the Antarctic. While the latter has a stronger emphasis on preserving the Antarctic environment through a system of international agreements, Arctic transitions have to take into consideration the complexity of different Arctic regions and their populations. In the Arctic, not only are there different value bases, there are also varying moral, political and socio-economic subsystems which will require nuanced and targeted transitions towards the desired states. One key challenge is to mediate these differences and, at the same time, not to lose direction. There is a need to further improve the definition of 'just' steps and how to evaluate them is of essence in this subtopic.

The research that is needed to support a just transition includes increased knowledge of changing ecosystems in the past and in the present. Monitoring, risk assessments, predictions, modelling, and new technology are all essential tools. It is also important to identify what "just" steps can be taken to reach the desired states and how it can be ensured that the entire transition process remains as fair as possible. Here, it may be imperative to take a community-based approach where bottom-up initiatives play prominent roles. Moreover, researchers need to develop new forms of collaboration where disciplinary approaches are still valuable, but transformed into capacities that are needed for navigating the possible pathways towards the desired states in truly post-disciplinary fashion.

Relevant Cooperation Partners

All stakeholders in the Arctic and Antarctic need to be included in this research as it must draw fundamentally on their perspectives, motivations and values to identify not only the desired states but also the optimal pathways towards those desired states. Monitoring and risk assessments also depend on input from those stakeholders. The research needed should be truly collaborative and aiming at the co-production of knowledge by the researchers involved and other stakeholders.

Subtopic	Key stakeholder groups (other than researchers)	Reasoning (position, influence, impacts, etc.)
Desired States	Parliamentary and policy partners, incl. Arctic Council and non-polar states (Arctic & Antarctic)	Directly involved and necessary (decision bodies)
	Local and indigenous communities, citizens (Arctic)	Directly involved and necessary (decision bodies)
	International networks and agencies (including NGOs, business and regional networks)	Needed for positive outcome
	Polar organizations, including COMNAP, SCAR, IASC, IASSA, UARCTIC, ATCM, CCAMLR, CEP and Arctic Economic Council (Arctic and Antarctic)	Policy function and know-how
	Media (Arctic and Antarctic)	Outreach and communication capacity
	Business and Industry sectors (Arctic and Antarctic)	Economic interest, significant impacts
Assessments for healthy polar social-ecological systems	Parliamentary and policy partners, incl. Arctic Council and non-Polar states (Arctic & Antarctic)	Directly involved
	Local and indigenous communities, citizens (Arctic)	Directly involved
	Polar organizations, including COMNAP, SCAR, IASC, IASSA, UARCTIC, ATCM, CCAMLR, CEP and Arctic Economic Council (Arctic and Antarctic)	Policy function and know-how
	Business and Industry sectors (Arctic and Antarctic)	Economic interest, significant impacts
Just transition	Parliamentary and policy partners, incl. Arctic Council and non-Polar states (Arctic & Antarctic)	Directly involved
	Local and indigenous communities, citizens (Arctic)	Directly involved
	Polar organizations, including COMNAP, SCAR, IASC, IASSA, UARCTIC, ATCM, CCAMLR, CEP and Arctic Economic Council (Arctic and Antarctic)	Policy function and know-how
	Business and Industry sectors (Arctic and Antarctic)	Economic interests, significant impacts

4-Wheeler, a way of transport in the road-less tundra in summer for Inuit in Pond Inlet, Canada *(Photo: Peter Prokosch)*

Enabling Capacities and Resources

The focus of this white paper is to enable a concrete contribution to the work of the European Union in its relationship to the Arctic Council and the Antarctic Treaty System. Moreover, the Social, Economy and Culture Expert Group (SECEG) of the Arctic Council gives the Sustainable Development Goals top priority, as do ongoing Horizon 2020 funded Polar projects (INTAROS, NUNATARYUK).

For survey, coordinating, and synergy purposes it is important to establish firm platforms at and between the European universities engaged in Polar research. One such initiative is Arctic Five that includes the universities in Umeå and Luleå (Sweden), Oulu and Rovaniemi (Finland) and Tromsø (Norway) in an effort to improve the Arctic sustainable development research.

Communication and research coordination are essential (including communication between researchers and decision-makers at local, national and international levels) to effectively navigate the roads towards the desired states. There is a risk of losing direction if important stakeholders are disconnected, or if they do not understand each other.

Sustained and adaptable capacity-building amongst stakeholders to facilitate the co-production of knowledge is equally important for a just transition. Furthermore, education and outreach to the wider public require constant development, utilizing new technologies and interactive platforms that can support knowledge sharing and dissemination, collaborative scenario development, and strategic planning. The ambition is to provide free and readily available access to indicator databases and platforms that enable us to share indicators, related indicator datasets, community-based survey results and innovative research approaches. There is a need to adopt existing information systems to meet the specific needs for facilitating and tracking the transition towards the desired states.

Funding and international cooperation

International collaboration is essential for this work, not merely because the Arctic extends beyond Europe and human engagement in the Antarctic involves numerous countries and stakeholders from South America, North America, and Australasia, but also because this work builds on existing research on Arctic and Antarctic issues. To make the most of existing expertise and capacity across the world, we need to reach out to the international community and we need to connect with all stakeholders, including:

- Arctic and Antarctic collaborators,
- IASC member states,
- NAPs and ATCPs,
- Tertiary and research institutions and their networks, and
- Indigenous Peoples (to enable the co-production of knowledge).

Due to its strong focus on knowledge co-production, the work proposed will recognize the existence of different values for protection of the Antarctic (intrinsic and wilderness values) and sustainable use and development of the Arctic, where the research will also acknowledge differentiated societal rights that include, but go beyond, basic human rights and explicitly include indigenous rights.

Way Forward and Key Action Areas

First of all, it is advisable to set aside seed money for pilot studies to develop the overall approach described in this white paper, or elements of it (i.e. identification of desired states, indicator development, and One Health Assessment).

Further, in order to facilitate the co-production of knowledge in the Arctic, funding is required to enable stakeholders to be assembled so they can contribute to the identification of desired

Diving for marine observations in Antarctica *(Photo: CNRS/Michel Calzas)*

states and pathways towards these states. Without funding for this initial work, the participation of those local stakeholders cannot be guaranteed, and the wider research community and stakeholders cannot be adequately engaged and consulted. In the end, to undertake the main part of the research, larger consortiums of researchers and stakeholders/rights-holders will be required, and specific efforts will be needed to assemble these into cohesive research communities.

Regarding the SDGs' indicators for the Polar Regions important and initial tasks include:

- examination of the existing SDGs indicators' framework and seeing what indicators of it, if any, apply to the Arctic/ Antarctic/or both;
- examination of what other indicators for the Polar Regions have been used/proposed in social science projects (e.g. Arctic Social Indicators, Arctic Human Development Report, ECONOR), it will be equally essential to reach out to natural scientists and representatives of indigenous and local communities to have their input at this stage already;
- estimation of how much data for the indicators we currently use is collected, even if this data is stored in various forms, locations and institutions; such information could be a great starting point to show where in fact we are standing when it comes to present knowledge about Polar SES .

Finally, it is important to establish a relationship with non-Polar partners involved in the work with the implementation of Agenda 2030, and specifically the SDG indicators. We are convinced that our efforts will add significant value to the general process.

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EU-PolarNet White Paper No. 5

Advancing operational informatics[1] for Polar Regions

Wind generator at the Neumayer Station III in Antarctica *(Photo: Alfred Wegener Institute / Thomas Steuer)*

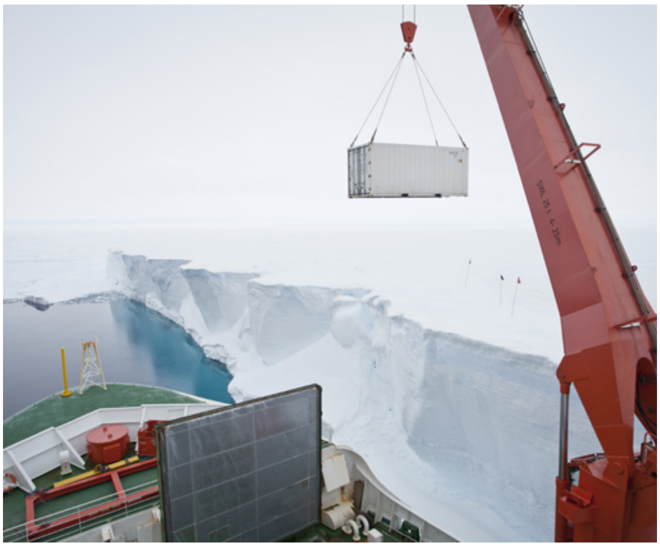
Motivation and background

The Polar Regions are characterised by low levels of communication technology, stemming from poor connectivity of ground-based systems to mobile and satellite platforms. Anyone who has worked in the Polar Regions will testify to the slow and expensive download rates, and the inability to exchange information efficiently between users. This makes the use of novel, innovative and emerging digital technologies impossible to utilise fully in the high latitudes.

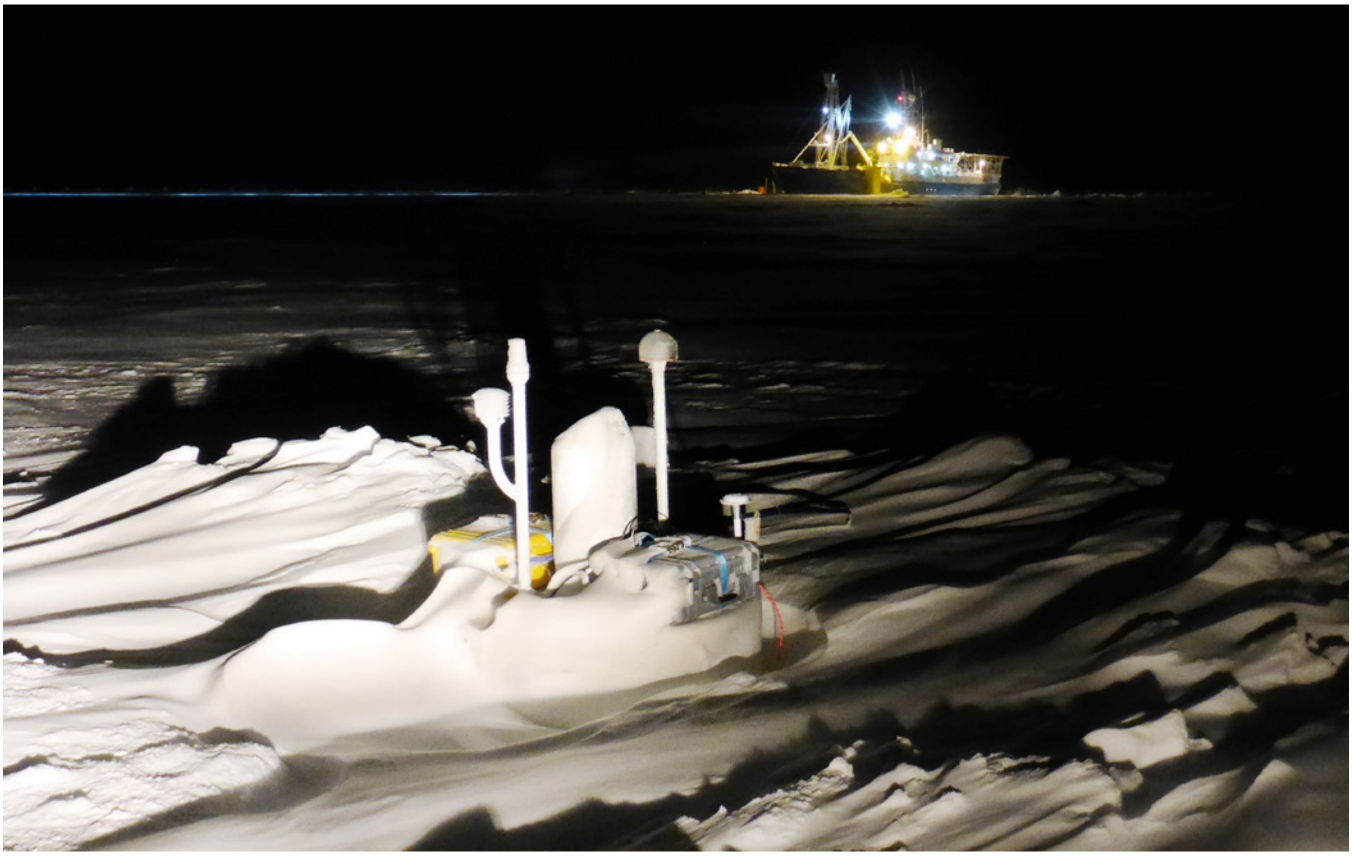
Many parts of the world have experienced a 'data revolution' advancing areas of scientific research, business and industry, education and societal well-being in numerous exciting ways. However, as recognised by the Joint Statement of Ministers (on the first White House Arctic Science Ministerial; 28 September 2016, Washington, DC, USA) **"many areas of the Arctic are data-sparse, and in some parts the paucity of observations is compounded by the lack of universal access to data. These shortfalls hinder scientific progress, the development of value-added products and services, and the formulation of innovative strategies for managing social and environmental changes in the Arctic and beyond."**

The solution to this widely-acknowledged problem is an internationally-agreed effort to introduce effective data and information systems to the Polar Regions (e.g. taking an informatics approach). The benefits would be three fold. **First,** for science, access to data offers opportunities to widen our observation pool and to link such observations to numerical models of natural processes. There is also opportunity to form intelligent systems, allowing information to be gathered autonomously and effectively as needed, and exchanged with users across short timescales. The outcome will be a step-change in our ability to understand the physical and natural changes occurring in the Polar Regions. **Second**, for business and industry, data systems will aid navigation of ships, allow marine resources to be tracked and measured, and form shared records on which regulation on important extractive industries can be formed. Access to data is linked to economic growth and jobs throughout the world, and the Polar Regions are no different. **Third**, for society, the benefits are also significant in terms of avoidance and mitigating both natural and man-made disasters, education healthcare, and

[1] Definition: "Informatics studies the representation, processing and communication of information in natural and engineered systems. It has computational, cognitive and social aspects." (University of Edinburgh, School of Informatics 2017).



Research vessel Polarstern resupplying the research station Neumayer Station III in Antarctica *(Photo: Alfred Wegener Institute / Thomas Steuer)*



Norwegian Research vessel „Lance" and IAOOS buoy in the Arctic Ocean (Photo: Michel Calzas, CNRS)

a better understanding of the manner in which changes in Polar Regions impact weather and climate over Europe (teleconnections).

While informatics has grown to the benefit of many regions of the world, the Polar Regions have been left behind. A concerted understanding on how to remedy this problem is critical to science, society and business and is overdue.

In this White Paper, we detail the research needs of operational levels of informatics in Polar Regions, and how scientific discovery will be a major beneficiary. We also discuss how the approach will improve societal well-being and lead to business opportunities and economic growth.

The challenge is significant, however. For example, it is unclear how operational informatics is best implemented in the Polar Regions, and what the cost/return of investments would be. Similarly to the Arctic Science Ministerial (2016), we are convinced, however, that having access to data and information would lead to substantial benefits to research, society and business.

As a first step toward enhanced informatics in Polar Regions, **we recommend the EU commission a formal scoping study** of the problem, pulling expertise in informatics together with knowledge of polar conditions and existing operations systems. Only then can we fully understand how the Polar Regions problems with information access and sharing can be understood, planned and implemented.

Societal Relevance

An effective data and information system in the Polar Regions will improve interoperability and exploitation of distributed datasets allowing enhanced services and information systems for society, industry and science. The following Business and Society sectors will benefit substantially from the development of such a system in the following ways:

Business

Informatics will assist the Business Community of the Polar Regions through enabling: (1) Project assessment and feasibility studies (economics, risks, environmental evaluations, operational considerations etc.); (2) Business opportunities in implementing these services; (3) Commercial services based on research-driven informatics systems (e.g. Copernicus); (4) Trade and supply chain management; (5) Organisations overseeing adherence to standards and regulations; and (6) Safe and responsible tourism (e.g., NW Passage, Arctic and Antarctic Cruises).

Society

For society, the benefits of informatics are also significant to areas such as: (1) Regional development; (2) Community development (communications between communities); (3) Standards and permitting (international, regulations, sustainable management of resources); (4) Educational services (across the full spectrum of delivery - schools, universities, distance learning, professional training etc.); (5) Cultural exchanges - connect EU and Arctic residents; (6) Disaster preparedness and early warning systems; (7) Search and rescue operations; (8) Navigation and logistical services; (9) Capacity, capability and efficiency in public management; (10) Security issues (such as border control); (11) Health services (basic, emergency, epidemiology); (12) Urban and infrastructure planning; and (13) Safeguarding subsistence resources (reindeer herders, artisanal fisheries, etc.).

Global Sustainability Goals

Research in enhanced informatics in the Polar Regions is aligned with the seventeen UN Sustainable Development Goals (SDGs) in a variety of ways. A table summarizing these links is given below. We draw attention to the following SDGs, where we think particularly strong positive impacts exist:

Research Needs

Our strategy is to recommend, facilitate and promote research that can deliver operational levels of informatics. In doing so, the outcomes will support the development of four other WPs (Climate and Cryosphere (WP#1), People and Societal Issues (WP#4), Polar biology (WP#2), and Natural Resources (WP#4)) to reach their specific goals.

The development of polar informatics will address current limitations in collection, integration, processing and communication of information. Importantly it will build on developments in relevant domains including new communications networks, data management, cloud-computing and information visualisation. The development of informatics tailored to the specific needs

Sustainable Development Goal	Explanation	Relevance to the Polar Regions
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	The Polar Regions, should be a major recipient of progress in SDG9, and much of this White Paper is a consequence of the present-day lack in infrastructure
11 SUSTAINABLE CITIES AND COMMUNITIES	Make cities and human settlements inclusive, safe, resilient and sustainable	There are numerous cities in the Polar Regions, and because of the harsh environments surrounding them, there is an urgent need to consider ways to make them safer and more resilient, as well as sustainable
13 CLIMATE ACTION	Take urgent action to combat climate change and its impacts	The Polar Regions are seeing some of the greatest impacts of climate change on the planet – through polar amplification of atmospheric warming and through the melting of ice
14 LIFE BELOW WATER	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	The oceans are a major source of food and income for the Polar regions, and their sustainable use and management is key to future prosperity.
15 LIFE ON LAND	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Polar regions land use change needs to be managed sustainably, if we are to maintain ecosystems and their natural services
17 PARTNERSHIPS FOR THE GOALS	Strengthen the means of implementation and revitalize the global partnership for sustainable development	The Polar Regions are very much an international space, where collaboration is both natural and essential or tackling the major problems that exist, such as access to data and information.

3 GOOD HEALTH AND WELL-BEING · 4 QUALITY EDUCATION · 8 DECENT WORK AND ECONOMIC GROWTH · 10 REDUCED INEQUALITIES · 16 PEACE, JUSTICE AND STRONG INSTITUTIONS

By establishing an infrastructure for informatics in the Polar Regions, and delivering on the above SDGs, we assert that there would be significant benefits to commercial, industrial and public services. This is manifested in further SDG progress in health, education, economic growth, reduced inequality justice.

Electromagnetic (EM) induction sounding for ice thickness measurements is a technique that can achieve long profiles of some kilometer length. The accuracy and robustness of the EM method has been evaluated by comparing coincident drill-hole and EM measurements. *Photo: Alfred Wegener Institute / Stefan Hendricks*

of the Polar Regions requires a coordinated research effort. This will address relevant aspects specific to the Polar Regions including limited communications capabilities, the harsh and remote environment, and limited in situ observations. The result should be a better connected information network, providing tools for easier exploitation of information by all stakeholders in the Polar Regions.

Subtopic 1: Communication systems

Key Message 1. Polar Regions are data poor and lack communication infrastructure for reliable and effective data sharing for research, services and societal needs.

Communication methods are limited, costly, and often unreliable in Polar Regions. Providing high-speed, low-cost, and reliable communications to Polar Regions will open the door for innovation and economic development. The ability to exchange information and data will enable rapid advancement of polar science, thereby adding value to existing and planned polar and climate research initiatives and permitting truly ground-breaking research to be undertaken in the future. Real-time access to data and information will increase situational awareness in general and promote safer maritime navigation and 'Safety of Life at Sea' (SOLAS), and general economic development through more accurate and timely assessments of environmental conditions and human impacts. High-speed, affordable communications will benefit all Arctic residents through access to information and education (from pre-K to university and professional development) and will decrease response times during emergencies (disease/medical, weather-related extremes, oil spills, etc.). Improved communications will also promote health and well-being of Arctic residents through developments such as tele-medicine and cross-cultural exchange.

Research is needed to adapt existing communications technology, and to implement and evaluate emerging technology, with the goal of establishing a polar communication network that:

- Can withstand harsh and variable environmental conditions;
- Is accessible (affordable, scalable, and user-friendly);
- Minimizes impact or damage to polar ecosystems and heritage sites (low footprint, green tech);
- Provides high speed/bandwidth in all polar locations (not only in population centres or high-density shipping lanes); and
- Enables links to be made between measurements from all components of earth and climate systems: atmosphere, ice, land and ocean.

Linking observations with models, and information interoperability (Subtopics 2 and 3), will have a much greater stakeholder impact if the communication problem is solved. Stakeholder activities in Polar Regions are increasing and we must put a communication system in place that can handle current and future needs.

One area of interest with a large degree of overlap in science, industry and society that will benefit from communication capabilities is surveying and mapping, as vast areas of the poles do not have modern accurate maps and hydrographic charts. Accurate maps and charts will aid in navigation of both ships and aircraft and high-resolution bathymetry is critical to improve coupled models. Improved communications, complemented by advances in sensors and models, and interoperable data standards, will enable the type of rapid mapping that is required in the context of climate change. Raw field data can be processed in real-time using cloud-computing services.

Global Navigation Satellite System (GNSS) augmentation services need to be developed, and a polar network of Continuously Operating Reference Stations (CORs) should be expanded. Increased communication capabilities will also allow ships to receive important weather-related and sea-ice information, and also to transmit environmental data to scientists and Joint Rescue Coordination Centres (JRCCs). Finally, communication capabilities, in addition to providing societal benefits like healthcare and education, will allow citizens to participate in research initiatives.

Research on board of Polar6 aircraft near Rothera Station, Antarctic Peninsula (*Photo: Alfred Wegener Institute, R. Ricker)*

We are aware of ongoing subsea telecommunication (fibre optic) cable projects in the Arctic – such as the Quintillion Project (cable from NE Asia to Alaska and onwards to Europe along the Northwest Passage) and Arctic Connect (cable from NE Asia to Russia and onwards to Europe along the Northeast Passage). The Quintillion Project is already providing for the first time broadband Internet services to Alaskan Arctic communities ranging from Nome to Prudhoe Bay. Further developments along these lines are welcome and should be planned in an integrated, inter-connected manner.

Subtopic 2: Linking observations and models

Key Message 2: We must address the deficiency of observations in Polar Regions and the inability to assimilate existing and future observations into Earth System models and weather and climate prediction.

Compared to most other parts of the globe, there is very limited collection of in situ observations from the Polar Regions. The deficiency of polar in situ data limits the development and accuracy of earth system, climate, and weather models. The lack of observations is, in part, due to the vast, remote and harsh environment, which makes collection from the ground, ships and aircraft both logistically and financially prohibitive.

The situation would be improved by the deployment of many more sensors and instrument platforms. However, developments are required in several aspects, listed below, to tailor them to the polar environment:

- Sensor 'ruggedisation' to cope with low temperatures, harsh and variable conditions;
- New battery technologies and power options to allow long-term autonomous operation;
- Low cost, miniaturised technologies allowing deployment of large numbers of sensors; and
- Transferring to biodegradable components or developing options for instrument recovery to minimise the environmental impact.

In addition, new sensors will need to include advances in communication technologies data compression and transmission. Developments should consider the creation of smart sensor networks (with variable sampling rates and AI-based autonomous tasking) and integration with expanding polar communications networks (including new satellite communications and fibre-optic options). These advances should allow increasing volumes of data, required in real-time from the polar land surface, ocean and under ice.

A step-change in the availability of polar in situ or remote observations will also require improvements in the methods to assimilate these data into earth system climate and weather forecast models. New research efforts are required to improve operational assimilation and quality control methods, addressing both in situ and remote sensing (satellites, aircraft, drones etc.) observations.

Furthermore, even the most advanced models use parameterisations of unresolved, sub-grid-scale processes. Examples include small-scale turbulence and ice-ocean interactions. Studies have noted that critical climate processes, like deep-water formation, exhibit strong sensitivity to the type of parameterisations employed. Observations in key regions, and of critical processes, will enable better models with increased ability to predict processes, events and their impacts.

Subtopic 3: Information and interoperability

Key Message 3: Interoperability and exploitation of distributed data will provide useful information in a collective sense for science, society, industry and operations in Polar Regions.

The aforementioned advancements in data collection and earth systems modelling will provide more value to EU stakeholders if they are easily accessible and useable. The breadth and scope of data collection initiatives and platforms means data will be delivered by an increasing number of distributed repositories. It is essential that open interoperable standards are developed and promoted to ensure these data can be contributed by, and are accessible to, the largest possible audience.

A key aspect will be development of two-way communications links to allow community-based observations to be contributed to and shared (e.g. mobile phone sensor networks). Development of standards must happen in close collaboration with existing initiatives and established data management approaches (IASC Arctic Data Committee and SCAR Standing Committee on Antarctic Data Management). Further development of cloud-based data exploitation platforms is also required. These are currently under development in some sectors (e.g., EC DIAS system), but need to be promoted and extended for the Polar Regions. These technologies provide access to data, software tools, virtual development environments and computer processing resources in an online cloud infrastructure. This has a key benefit of democratising access to both big data and high performance computing resources required to develop and deliver information and information services. Effort is required to ensure these platforms are developed according to specific data requirements, software tools and access needs of the social and scientific polar communities who will benefit from them.

The integration of data and improved communications bandwidth should be considered the basis to develop new data mining, information extraction and visualisation tools. These will increase the value of available data, making them more easily understood and delivering easily digested material for wide syndication. A focused effort should consider appropriate tools and visualisation options for the Polar Regions, including real-time visualisation applications from remote devices.

Relevant Cooperation Partners

To deliver informatics infrastructure, it is important to work alongside a number of organisations to ensure fit for purpose and value for money.

In the Arctic, it is important to recognise the contribution and assets linked to the Arctic states – Russia, USA, Canada, the Nor-

Sector	Stakeholder	Reasoning (position, influence, impacts, etc.)
Logistics	Arctic Council Nations, First Nations	Proximity, assets, people
	IASC, ATCM, COMNAP, SCAR	Multi-national discussion and planning
	ESA	Assets and platforms
Science community	IASC; SCAR; ATCM	Means to engage the scientific community with long-term planning of infrastructure
	CCAMLR; COMNAP;	
	FARO; ISO	
Industry and business	Arctic Economic Council; World Economic Forum;	Offering investment and financing
	investment and finance sector; insurance industry;	
	fishing; shipping (IMO, Polar Code, ISO, classification societies;	Matching regulations and planning
	tourism (e.g., IAATO, AECO);	
	extractive industries (mining, oil-gas exploitation);	
	aviation and space sector	
Public	Arctic regional governments, coastal and local authorities	Beneficiaries of enhanced informatics, allowing long-term planning and growth
	EU citizens	Improved access to education, health and environmental prediction

dic Countries, as well as the First Nations – in fully implementing the recommendations in this white paper. We also see a major engagement with China, Japan and South Korea in developing the ideas outlined here.

For the Antarctic, the role of the ATCM will be critical to engaging multiple nations in a collective effort. Additionally, COMNAP has a significant role to play. The SCAR Horizon Scan based COMNAP ARC initiative identified "new and improved satellite sensors, including appropriate coverage and availability" as one of the major cross cutting technology requirements for the Antarctic.
For both Polar Regions, space technologies will play a very important role in delivering operational informatics. This will require dedicated activity and cooperation from the European Space Programme delivered by the EC and ESA.

The following three stakeholder groups will benefit from improved operational informatics in the Polar Regions.

Science (research) community

The whole scientific community will benefit greatly from increased communication abilities, expanded in situ sensor networks allowing continuous real-time monitoring, and enhanced modelling and data sharing to advance our currently limited understanding of the polar environments and the numerous changes taking place there due to climate change (as mentioned, stakeholders include: IASC; SCAR; CCAMLR; COMNAP; FARO; Arctic Council; ATCM; Arctic Council research agreement; ISO; and others).

Industry and business

It is generally agreed the main driver of near-future socio-economic development in the Arctic region is natural resource exploitation. But it is very important to focus also on local and regional value-creation and development that will benefit local people and the Arctic regions themselves (boost regional economic development and job creation as well as healthcare and well-being). Increased communication networks, observations, and information availability is essential for innovative industrial development and investments, regional planning and feasibility studies, environmental impact assessments, transportation and logistics systems, and for all infrastructure development in general (stakeholder include: Arctic Economic Council; World Economic Forum; investment and finance sector; insurance industry; fishing; shipping (IMO, Polar Code, ISO, classification societies; tourism (e.g., IAATO, AECO); extractive industries (mining, oil-gas exploitation); aviation and space sector; and many others).

Public

Governmental bodies such as Arctic regional governments, coastal and local authorities, will benefit from enhanced communication networks and information sharing for their decision-making, governance and urban and regional planning. Enhanced informatics will improve the formulation of local and national policy, plus the monitoring of policy implementation and effectiveness. EU citizens and organizations tasked with weather prediction and response to extreme events (storms, floods, etc.) will benefit from an improved understanding of the changing polar en-

Nothern lights above the Arctic Ocean *(Photo: Alfred Wegener Institute / Stefan Hendricks)*

vironments and access to improved environmental information services, e.g. national weather services. Changes in polar environmental conditions can affect the lives of EU citizens through teleconnections, but a full understanding of the range and scope of the problem requires the approach proposed here.

Enabling Capacities and Resources

The EU has the capacity, expertise and links to Polar Nations to lead this initiative. Through its existing strengths in polar research, Europe is ideally placed (with its core infrastructure, academic and industrial expertise, partnerships and economic strength) to form a bespoke (tailored to the needs of the Polar Regions, primarily) informatics system that will lead to advances in our understanding of processes and change in these remote and challenging environments.

The EU is a major contributor to polar research. Over the past decades the EU efforts have been devoted to improve Arctic observation and monitoring programmes as well as to fund numerous research projects to better understand the Arctic and the ongoing change (e.g. INTAROS; APPLICATE, Blue Action, Nunataryuk all funded in H2020), but Arctic systems, their functions and possible responses to various drivers are still largely unknown due to a lack of proper communication and informatics technology.

EU space programmes are also supporting research in the Polar Regions. The operational infrastructure and services of Copernicus will provide input to polar research activities, including weather monitoring, monitoring of climate variables and ice thickness, and improved ocean modelling. The development of polar informatics to better address the current limitations in collection, integration, processing and communication of information will add value to these Copernicus services.

We also have to acknowledge important data management initiatives related to both poles, which will strongly benefit from better communication and data collection and which already are working on interoperability standards, like the Sustaining Arctic Observing Networks (SAON), the "International Polar Data Forum", the Arctic Data Committee (ADC), and the Standing Committee on Antarctic Data Management (SCADM).

The way forward and key action areas

The development of operational informatics will be of considerable cost. **To prepare the ground for such work, we believe a formal EU scoping study is needed.** Such an investigation will draw together expertise in informatics and technology, who may have no previous connections to polar research with those who have experience in polar research and activities. It should involve researchers, technicians, industry and stakeholders. The study should include an implementation plan, a cost analysis, an environmental evaluation and an economic impact assessment.
The scoping study, in line with the subtopics described in this white paper, should have following attributes that would lead to a prioritisation of efforts to maximise returns on investments.

1. Identify existing and required communications systems and standards that would best connect Polar Regions to each other and with external agencies.
2. Consider how best to link measurements of the natural environment with models, allowing better forecasting and prediction capabilities.
3. Study how informatics in the Polar Regions can enable interaction and interoperability of measurements.

It is probable that a single study is best suited, as integration across the subtopics is a necessity. It is also essential to engage with stakeholders identified in this white paper.

The scoping study should form a time-frame over which advances can be developed, their financial requirements (including installation and maintenance) and likely benefits in short, medium and long term.

The scientific drivers demand that the scoping study should consider both Polar Regions, but not necessarily in the same manner as they have different needs, stakeholders and constituencies.

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Capacities and cooperation partners needed for implementation

There is a large potential for capacity building in Europe for studying the Polar Regions, which draws on European-funded scientific and monitoring projects, operational stations and vessels in both Polar Regions and existing supercomputing facilities. Nevertheless, the research and development necessary to significantly advance the understanding of the polar systems will require enhanced measurement infrastructures in the Polar Regions, new advanced technologies to carry out measurements under harsh and cold conditions as well as supercomputing facilities and sustained comprehensive databases. Furthermore, integrated research yielding effective solutions will need strong international circumpolar and interdisciplinary collaboration. Significant efforts and resources need to be devoted to build capacity for creating and maintaining an effective research infrastructure and a better coordination of these assets. Capacity building should also be aimed at public education and outreach, to communicate that the processes occurring in polar areas have a significant impact on Europe and the rest of the world.

Answering the full scale of research questions needed to understand the changes in the Polar Regions is beyond the capabilities of any one nation acting individually. Bi- and multilateral cooperation with partners outside of Europe is needed to meet the depth and geographic scale of these challenges. In the Arctic, it is important to recognise the contribution and infrastructures linked to the Arctic states – Russia, USA, Canada, the Nordic Countries, as well as the First Nations – in fully implementing the recommendations of the white papers. However, significant benefit would be achieved through engagement with IASC as it includes all countries engaged in Arctic research and in all areas of the Arctic region. For the Antarctic, the role of the ATCM and SCAR will be critical to engaging multiple nations in a collective effort. Additionally, COMNAP has a significant role to play.

The research needed could benefit from co-designed programmes based on international cooperation, coordination of observational strategies and monitoring stations, sharing data acquisition programmes and the built-in interoperability of databases and supercomputing resources. For both Polar Regions, space technologies will continue to play a crucially important role in data collection. This will require dedicated activity and cooperation from the European Space Programme delivered by the EC and ESA. Coordinated sampling and assessment has the potential to minimise costs, both financial and environmental, while increasing the usefulness of the obtained parameters. The involvement of local communities in sampling and monitoring, supported by modern technologies, has the potential to mobilise and involve traditional knowledge and raise awareness. A well-designed data management plan is necessary and the collected data should be deposited to an openly accessible public repository.

The outputs of the research recommended in the white papers will address many different stakeholders and right-holders such as indigenous people, the public and private sectors (e.g. oil and gas, fishing, shipping, tourism and port industries, insurance sectors) as well as local governments and communities. These stakeholders and right-holders in the Arctic and Antarctic need to be included at an early stage of the proposed research as it fundamentally draws on their perspectives, motivations and values. In addition, there are many other relevant cooperation partners at all levels local, regional and international including: research and coordination organisations and other scientific communities; intergovernmental organisations, such as the Antarctic Treaty System (ATS) and Arctic Council (AC); and non-governmental and private organisations.

Outlook

The process used to develop the White Papers allowed and encouraged independent development of ideas by each of the writing teams. Nevertheless, clear common threads have emerged. Independently, three of the five working groups highlighted an urgent requirement to develop standardised metrics, or 'indicators', of change for the Polar Regions. While each team developed a specific focus relevant to their expertise and subject area, there is a common realisation that while some established long-term measurements, especially those relating to parameters in the physical environment, show clear, rapid and profound changes (e.g., the 30-year satellite record of ice loss in the Arctic and in Antarctic), there are many aspects of change in the Polar Regions for which measurements are sparse, poorly standardised and too short in duration to allow us to discriminate trends from variability. This is particularly true for ecosystems and socio-cultural change.

Similarly, the standardised metrics of change established elsewhere around the world are often wholly inappropriate for application to the Polar Regions. For example, a specific issue identified in White Paper 4 is that the indicators adopted to monitor progress towards the UN Sustainable Development Goals are poorly-adapted, and arguably require special interpretation or even modification to be applicable to either the Arctic or Antarctic.

The White Papers highlight indicators that are particularly pertinent to the subject area, as follows:

- **White Paper No. 2** (Footprints on Changing Polar Ecosystems) advocates 'Ecological Indicators' that will allow the assessment of ecosystem health and change;
- **White Paper No. 3** (Managing resource use, conservation, and human impacts of the Polar Regions) recommends both the requirement of indicators of effective management and governance, and indicators of social-ecological resilience. Furthermore, it highlights the potential of Natural Capital Accounts as one method of measuring and valuating resource stocks and flows where human activity draws on ecosystems services; and
- **White Paper No. 4** (The Road to the Desired States of Social-ecological Systems in the Polar Regions) advocates indicators to measure the state of Arctic and Antarctic social-ecological systems.

Nothern lights above the Arctic Ocean *(Photo: Alfred-Wegener-Institut / Stefan Hendricks)*

Finally, while White Papers Nos. 2, 3 and 4 each demonstrate the requirement for specific indicators to be selected, developed and maintained, there is also the potential that a collaborative, interdisciplinary effort to develop such indicators would provide a more coherent and comprehensive result. Such a result could strengthen the capacity to effectively measure and monitor the state, magnitude and rate of change of the Polar Regions their mutual connection and, with the low latitude change and most importantly, the social, cultural, commercial and ecological interactions with the physical environment.

We would like to thank all participants of the EU-PolarNet White Paper Workshop for their valuable contributions, their time and commitment:

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Imprint

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Publisher:
EU-PolarNet
Represented by Coordinator Antje Boetius
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Design: Glinsmann Design

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

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Research in Hornsund, Svalbard *(Photo: Witold Kaszkin)*

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