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.

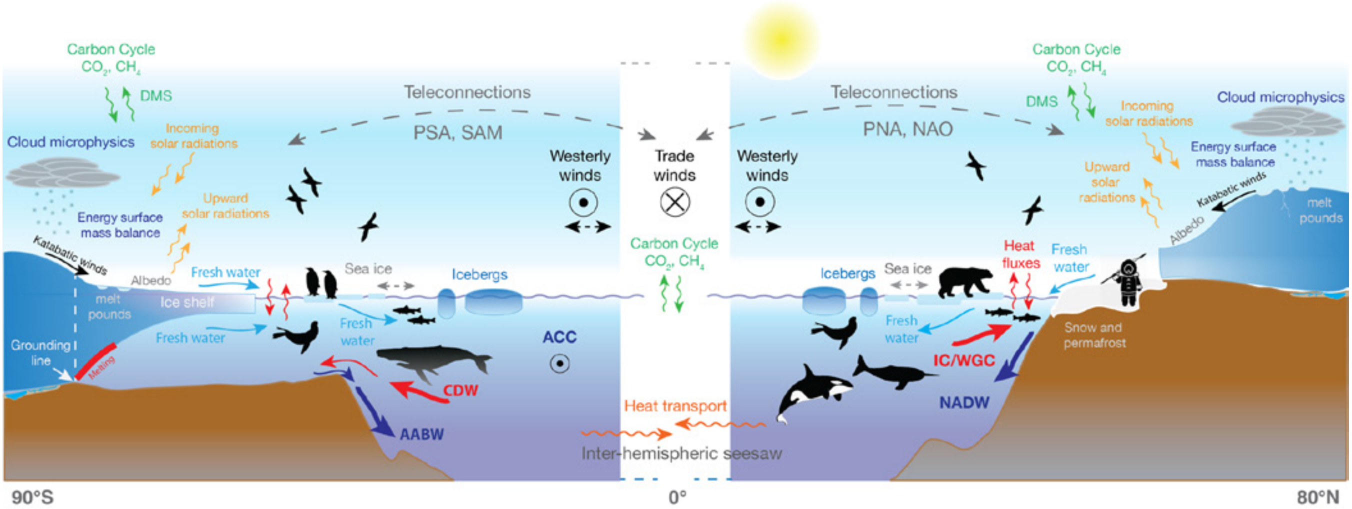


Fig 1. Components of the Polar System and their interactions (non exhaustive). Most of those processes and feedbacks are still poorly understood or quantified and require further observations. Pacific South/North American pattern (PSA, PNA), North Atlantic Oscillation (NAO), South Annular Mode (SAM), Dimethylsulfide (DMS), Carbon dioxide (CO2), Methane (CH4); 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

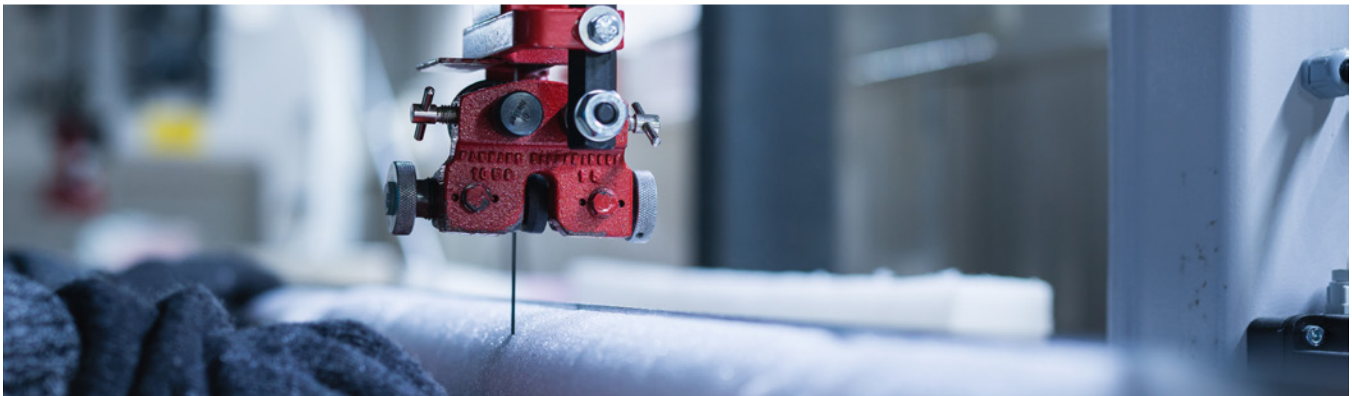
The Antarctic and Greenland ice sheets and the small glaciers across the Arctic, the Antarctic Peninsula and Sub-Antarctic Islands and at lower latitudes hold sufficient water to significantly raise global sea-level over coming decades and centuries. The uncertain stability of these glacial systems, 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.

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)*

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.

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.

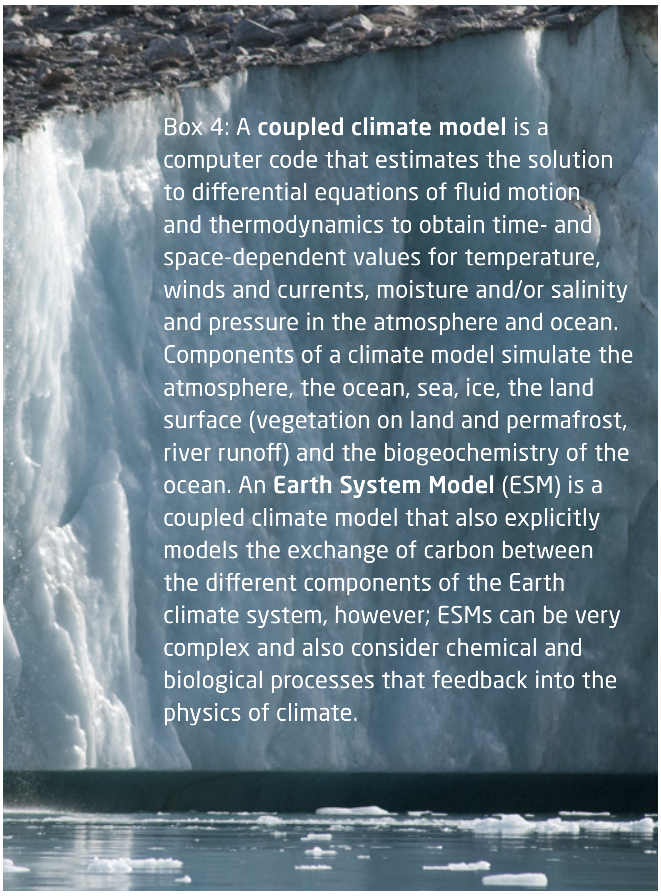


Photo: Peter Prokosch

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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