Polar Science in Switzerland

Proposed priorities for the Swiss Polar Institute

up to 2025 and beyond

Draft version - work in progress

This paper has been prepared by the Swiss Polar Institute’s Science and Technology Advisory Board on the basis of two (online) stakeholder consultations in 2017 and 2018, namely inputs collected during workshops at the Swiss Polar Day 2018 and a Call for Ideas launched by the Swiss Polar Institute in 2017-2018.

As a strategy, it serves to identify the priorities and initiatives, which should be supported by the SPI up to 2025 and beyond in order to best serve and fill gaps in Swiss Polar science. While a medium term strategy paper, it is SPI’s aim to provide continuity and to embed its activities in a long-term vision.

For the purpose of conciseness, this document groups, under the definition of “Polar”, those issues related to the Arctic, to Antarctica and to comparative studies in high altitude regions. The absence of the specific mention of any one of these regions does not reflect in any way the degree of priority given to science in that region.

FOREWORD

We are living in the Anthropocene, the first era in Earth’s history when processes controlling climate and natural biogeochemical cycles are significantly altered or, in many cases, dominated by human activity. This human influence extends into the most remote and inaccessible Polar and high-altitude regions of our globe, where there is very little direct anthropogenic activity (the Antarctic) or where sustainable use of the limited resources has been a cultural tradition (the Arctic). Its effects are felt from the atmosphere all the way down to the deep ocean and by organisms from the microbial level to the end of the food chain (where again humans represent the most ubiquitous species) with so far unknown long-term impacts on ecosystem services.

This influence is most clearly reflected in

- melting of sea ice, glaciers, ice sheets and thawing of permafrost through accelerating anthropogenic warming in recent decades;
- environmental pollution (including trace gases, anthropogenic aerosols and microplastics) found in the Polar environment even in the most remote areas with impacts on health and the food web;
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- pronounced biodiversity changes in the Polar ecosystems and decline of species adapted to extreme conditions;
- environmental changes impacting on the livelihood of indigenous peoples through the erosion of traditional food resources.

Most importantly, the accelerating human influence on Polar and high-altitude areas hits regions where, due to Polar climate amplification, the change in climatic conditions is two times higher than the global average. In addition, this human influence on Polar regions affects compartments of the Earth System (such as sea ice, glacier and ice sheets and vulnerable ecosystems) that are most sensitive to rapid change in climate and environmental boundary conditions, and whose responses, in return, act as further amplifiers of global climate change.

Understanding the mechanisms affecting and connecting components in the Earth System in Polar and high-altitude regions, as well as the impact of global change on these regions, is central in research related to our present and past climate. In a globalised world, the knowledge drawn from the study of Polar regions and the links shown with systems regulating the Earth’s climate is highly relevant for all societies and policy-makers.

With the high-altitude regions of Switzerland and the European mountain regions being affected by these changes in a manner similar to the high latitudes, the understanding of these processes and feedbacks is not only important to better assess future changes of the global climate system, but also timely and essential to develop suitable adaptation strategies for Switzerland itself.

Swiss research groups are widely recognized as world leaders in fields such as atmospheric observations, climate modeling, paleoclimate reconstructions through ice and sediment cores, and global biogeochemical cycles in high-latitude marine and terrestrial environments. Modeling and observations of the cryosphere, using field experiments and remote sensing, as well as research on permafrost and on atmospheric trace gases, aerosols, and clouds are key topics in which Switzerland is very active both in Polar and high alpine regions. Similarly, Swiss groups are recognised internationally for their work on microbiology, biodiversity and ecosystem functioning in terrestrial and marine environments in Polar regions, with comparative studies in high-altitude regions.

The wide diversity of Swiss Polar and high-altitude research and the heavy logistical demands associated with Polar and, in many cases, high-altitude research require national coordination and international collaboration to maximize the value of the research investment. Moreover, the highly sensitive role of Polar regions and extreme alpine environments in global climate change have brought Polar science increasingly onto the political agenda, with Switzerland playing a growing role in international science and policy bodies related to Polar regions such as IASC, SCAR and the Arctic Council where Switzerland has recently been granted Observer status.

This document outlines the strengths and expertise of the Swiss Polar and high-altitude research community. It also outlines the challenges it faces in order to be able to contribute significantly to international initiatives, and to launch national Swiss initiatives that build on and integrate these strengths in a way that is likely to have a strong impact in terms of knowledge creation, leadership and international visibility. In addition, it recognises that for some science fields, and for the humanities, the existing groups
may be small and would benefit both from new opportunities and from assistance in developing more robust communities.

**Supporting the Swiss polar science landscape - the Swiss Polar Institute**

The Swiss polar science landscape is very diverse. Its scientific activities spread over more than 13 academic institutions (see figure below) and covers areas from climatology, atmospheric sciences, glaciology, biology, technology, and geology through to human aspects related to the polar areas. The **Swiss Committee on Polar and High Altitude Research (SKPH)** of the Swiss Academies of Sciences was founded several decades ago to coordinate, promote and advocate for polar science and to provide scientific advice to Swiss policy makers and the Swiss administration on matters related to polar issues.

SPI works very closely with the SKPH, which is responsible for sending Swiss representatives to the international polar science bodies SCAR and IASC and - since Switzerland became an observing member of the Arctic Council in 2016 - to its scientific working groups. However, in contrast to many other countries, Switzerland traditionally had no central polar research institute or logistics provider, limiting the participation of excellent Swiss scientists to the remote and inaccessible polar areas.

In line with the bottom-up nature of the excellent polar science performed in Switzerland and its multi-institutional approach covering many polar research areas, the **Swiss Polar Institute (SPI)** was founded in 2016 in order to offer new opportunities and funding to researchers based in Switzerland who work in the Polar regions.

The SPI is currently funded by its founding members: EPFL, WSL, ETHZ, University of Berne, and the Editions Pauslen. Its activities and calls are **open to the whole Swiss research community**. While the SPI Secretariat is in charge of daily implementation and work, the institute’s governance comprises a Board of Directors in charge of strategic and financial decision-making and a Science and Technology Advisory Board with leading Swiss scientists and independent international experts who advise the Secretariat and the Board of Directors on scientific priorities and initiatives.

The SPI has launched dedicated **funding opportunities** to complement existing offers and to fill gaps linked to the specific needs of science in Polar regions. The **Polar Access Fund** offers young researchers funding to complement their research with a field trip to a Polar region. The SPI **Exploratory Grants** offer seed funding to start new collaborations and fund logistics related to research projects in those regions. Additionally, students can benefit from SPI funding to participate in international field/maritime schools.

Organising and implementing **scientific expeditions** also forms a core part of SPI’s mission. In 2016-2017, SPI organised the Antarctic Circumnavigation Expedition (ACE) which took 22 international scientific projects on a three months expedition to collect samples and data (oceanographic, terrestrial, atmospheric and cryospheric) from the Southern Ocean, sub-Antarctic islands and the Antarctic continent. A similar circumnavigation expedition around Greenland is planned by SPI for 2019. Other future expeditions as well as the logistic and financial support of Swiss scientists to lead or contribute to major international research expeditions at the three poles are foreseen, depending on future funding of SPI.

SPI has successfully brought in a new dynamic within the Swiss Polar community. SPI is actively supporting **synergies within the Swiss Polar research community** through conferences (notably but not only the annual **Swiss Polar Day**), workshops, information sessions on (external) funding opportunities and training courses. With such events, the SPI aims to foster the knowledge base and create networking opportunities for the broader Swiss Polar community, which ranges from earth sciences through biological and physical sciences to social sciences and medicine. SPI also develops training courses and platforms to share specialised equipment and instruments for the Polar community.
Finally, the SPI also has a mission to perform outreach and communication activities linked to Polar regions and science. To perform such tasks, the SPI partners with schools, museums and other relevant organisations and arranges public lectures and conferences.

For more details, see also www.swissPolar.ch or Twitter @swissPolar
I. INTRODUCTION – Science at the three Poles in Switzerland

Switzerland has a long tradition in Polar research, both in the Arctic and Antarctica. Although Switzerland never had a specific Polar program, the names of de Quervain, Mertz and Forel are landmarks in Polar and glaciological research. The Swiss expertise in Arctic and alpine environments is of internationally recognized importance, both historically and today.

Swiss scientists, over the past few centuries, have developed key scientific expertise and abilities through their work in the Alps. By the early 20th century, Swiss explorers and scientists were also active in the Arctic and Antarctic, making the most of their alpine experience and drawing parallels to the processes they could observe and measure in the Alps - the third or vertical Pole. During this last 100 years, Switzerland has become a major international player both in the field of Polar science, and in comparative studies in high altitude areas, by a combination of internationally renowned Swiss natural science expertise and outstanding technological and analytical capabilities.

In today’s changing climate, scientific expertise related to extreme environments is of the utmost importance. The thawing of permafrost or the absence of multi-annual ice (for example in sea ice or glaciers) can have severe consequences on local economies, energy and food production, weather extremes, safety and (geo-)politics at large. Although the context of such changes varies between high altitudes and high latitudes, understanding the mechanisms and parallels within these processes is crucial at regional and global scales.

Working in Polar environments (including remote high altitude regions in a comparative perspective) presents particular challenges in terms of access, logistics, equipment and safety. Performing scientific experiments and data collection in Polar regions therefore involves extremely high costs and, almost necessarily, international partnerships or collaborations.

The Swiss Polar community is well-networked through its membership and active participation in SCAR (Scientific Committee on Antarctic Research) and IASC (International Arctic Science Committee). The quality of its research output is widely recognised and shown through comparatively high publication records, citation indexes and participation in numerous prestigious international committees (for example the Intergovernmental Panel on Climate Change - IPCC).

However, in spite of the recent launch of the Swiss Polar Institute and the increased strategic importance of Polar regions for the Swiss government, Switzerland still lacks dedicated public funds to enable Swiss scientists to fully engage in the international Polar arena and optimise the benefits from its expertise and experience.
II. SWISS POLAR SCIENCE – An overview of current strengths

Research in Polar regions is performed by scientists from a wide range of backgrounds and skills. Given the rich and very competitive research landscape in Switzerland and the proximity to high-alpine regions, Switzerland has a dense network of research teams working on Polar-related topics.

The map below outlines the origin of faculty that have either participated or have expressed interest in activities, calls or events of the SPI since 2016.

*Note: This map will be updated after the consultation.*

1. Snow, glaciers and ice sheets

Switzerland has a long-standing tradition of research on snow and ice. Starting within the local Alpine environment and largely focusing on high-altitude glaciers, this research activity rapidly expanded to the large ice sheets covering most of the landmasses in Polar regions.

Current Swiss research on Polar ice sheets and glaciers encompasses studies on the stability, dynamical behaviour, mechanisms of ice flow, iceberg calving and mechanical and thermal conditions within and beneath the ice sheet as well as the use of ice cores from glaciers and ice sheets as one of the most important climate archives.
Glaciers and ice sheets mass balance

In recent decades, a particular emphasis has been put not only on the mass balance of Polar ice sheets, but also on high altitude and Polar glaciers. Switzerland has acquired outstanding expertise on this issue which is now of high societal relevance. Indeed, the combined ice masses in alpine glaciers and Polar ice sheets represent the largest freshwater reservoir on Earth. The size of this reservoir is not constant but changing over time in response to climate variations and linked to substantial sea-level variations. Current and future increases in atmospheric temperature will hence induce a sea-level rise, threatening coastal regions and settlements on a global scale. A strong focus of Swiss research in this field has been put on the glacier mass budget and the ice flow dynamics at the west coast of Greenland in the vicinity of Jakobshavn Isbrae.

Swiss researchers also conduct leading research on Alpine and high-altitude glaciers. While these glaciers store much less ice and, thus, are limited in their effect on sea level in the long run, their response time is much faster, and their geographical positioning makes their changes of immediate societal relevance in water and energy supply for high alpine regions in the coming decades.

Polar ice sheets as climate archives

Glaciers and ice sheets also play a role as outstanding climate archives covering many hundred thousand years of climate history; a climate record that can be tapped through targeted deep ice core drilling. Swiss Polar science has considerable expertise in all the relevant fields related to the use of ice as a climate sensor. One of the most prominent examples of this has been the reconstruction of greenhouse gas changes over many past glacial cycles, analysed in Swiss laboratories for large-scale international Antarctic ice core projects. Related Swiss science projects have and will improve our understanding of the response of glacier mass to climate change by observations, forecasting of future ice loss through modeling, reconstruction of past climate and atmospheric composition through ice cores, and by quantifying variations of glacier extent in response to past climate variations. A new major advance in this field is expected from the European project "Beyond EPICA – Oldest Ice Core" in Antarctica with strong Swiss participation, which will extend the ice core climate record over the Mid Pleistocene Transitions, i.e., the last 1.5 million years.

Snow and firn

Research on snow and firn, meaning compacted but still permeable snow overlying ice sheets, is also a trademark of the Swiss research landscape. In this field, Swiss competence is extremely high with a wide range of techniques and a deep understanding of the physics of snow.

Current Swiss research on snow in Antarctica and Greenland includes the mechanisms of snow deposition, metamorphism and transport, as well as surface sublimation, wind erosion and compaction, which all differ strongly from related processes in low latitudes such as the Swiss Alps. The impact of snow deposition on glacier mass budget has and is, for instance, extensively studied near Jakobshavn Isbrae (Greenland) by Swiss-led research teams. Swiss researchers are also strongly involved in the pursuit of a better understanding of snow precipitation on the Antarctic ice sheet and surrounding sea-ice, notably in the vicinity of the Belgian Princess Elisabeth research station in Antarctica.
A detailed understanding of snow properties and structures is essential in order to comprehend mass balance changes of sheets, formation and melting of sea ice, physical and chemical interactions between snow and atmosphere, as well as to understand and anticipate natural hazards such as snow avalanches and slush flows. Switzerland can claim to have leading research groups working in all these fields.

When it comes to physical and chemical properties of firn, the Swiss Research community is regarded as a leader in the move from a qualitative to a quantitative research basis in both areas and has developed world-wide recognized innovations.

Finally, snow amount, structural properties and spatio-temporal distribution also have major impacts on biological processes through snow reflectance, insulating capacity, and mechanical resistance. The Swiss expertise is very welcome at international level to improve measurement protocols and capacities, as well as prediction of snow properties under future conditions. Measurements and predictions can inform a wide range of ecological research, related to the energy and carbon budget at the land surface, to soil microbial processes, effects of snow on vegetation development, and impacts of icing events on wildlife ecology.

2. Polar processes and global systems

The dynamics of Polar atmospheres

Prominent traditional elements of Swiss Polar atmospheric research are the long-term observational activities mainly addressing atmospheric radiation, boundary layer dynamics, and the radiation transfer in snow and ice as well as measurements of the atmospheric trace gas and aerosol composition at the three poles. In recent years, research on this theme in the Polar regions has involved both field measurements and numerical modeling. Particular strengths of Swiss Polar research in this area are the high-tech instrumentation and the capability of performing field measurements under extreme conditions on Jungfraujoch as well as the long time series of observations in Greenland and analysis of ice core archives. Finally, the sophisticated modeling capabilities ranging from high-resolution regional atmosphere-only models to comprehensive coupled Earth system models are a particular strength of the Swiss Polar community.

The hydrological cycle is a key element of the Earth’s climate system in which Switzerland can claim leading expertise. It involves processes that occur on very small scales (e.g. the formation and growth of snow crystals) and large planetary scales (e.g. long-range poleward transport of moist air masses). Stable water isotopes can be used as natural tracers of phase changes along the pathways of water from evaporation to precipitation, and they are among the most important parameters archived in ice cores. Stable water isotopes can now be measured with high resolution in atmospheric vapor and surface precipitation, runoff and snow accumulation samples, whilst the entire hydrological cycle can be simulated with global and high-resolution regional models. The Swiss research community has long-standing, profound expertise in these experimental and modeling techniques, providing a unique opportunity to develop comprehensive research on the hydrological cycle in Polar regions, which would link the timescale of individual weather systems to the longer-term processes that determine the variability of ice core signals.
Energy cycle as driver of change

Ice sheet surface temperatures are controlled by an exchange of energy at the surface, which includes radiative, turbulent, and ground heat fluxes. At the summit of the Greenland ice sheet, at 3300 m above sea level, Swiss researchers have maintained the Surface Baseline Radiation Network (BSRN) experiment since 2000 to detect changes in the radiation at the Earth’s surface which may be coupled to climate changes.

For vegetated and soil surfaces in Polar areas the energy cycle is tightly coupled to the carbon and water cycle. Incoming radiation is strongly influenced by cloud cover, while the absorption and partitioning of radiation at the terrestrial surface is driven by land cover type and its properties. Changes in vegetation, such as shrubification, and soil moisture induced by increasing precipitation and permafrost degradation alter net radiation and its partitioning, with consequences on the thermal state of permafrost soils and their carbon content. Vegetation/energy cycle feedbacks induced by land cover change are expected to amplify Arctic warming. Current Swiss research includes mechanistic modelling of shortwave radiation interaction with vegetation to quantify albedo and soil shading, experimental studies of vegetation type and summer precipitation impact on energy partitioning and permafrost thaw, and pan-Arctic energy budget analyses based on in situ and satellite data. Thus, the Swiss science community is currently well-positioned to improve understanding of feedbacks between climate, vegetation, and permafrost through energy fluxes by linking existing process understanding of energy fluxes with predictions of vegetation dynamics and climate models.

The roles of carbon and nitrogen

The Polar oceans represent key regions controlling marine biogeochemical cycles by nutrient turnover, deep water formation and subsurface water ventilation.

On the one hand, the Southern Ocean has been shown to provide the dominant control on long-term changes in carbon storage in the abyss via iron fertilization of carbon fixation and nitrogen usage at the surface and changes in the volume of southern sourced waters filling deep ocean basins. On the other hand, changes in North Atlantic Deep Water formation are connected with changes in subsurface water ventilation, hence N₂O formation, in oxygen minimum zones via atmospheric and ocean teleconnections. In addition, changes in terrestrial carbon storage in vegetation, soil, peat and permafrost in the north have to be taken into account when quantifying carbon cycle changes both in the past and in the future.

Swiss Polar scientists are closely involved in reconstructing and modeling these changes in biogeochemical cycles through process studies of marine biogeochemistry, using marine sediment cores and greenhouse gases in Polar ice cores as well as through climate models including the full marine and terrestrial carbon and nitrogen cycles.

Monitoring global pollution

Global pollution has been identified as the largest environmental cause of disease and premature death in the world, accounting for three times more deaths in 2015 than AIDS, tuberculosis and malaria
combined. Whilst air pollution is often more easily identified than pollution of soil and water, pollutants, from microplastics to toxic chemicals, affect the whole Earth System. More extensive and targeted monitoring is required to understand the true extent of the threat both to ecosystems and to human survival. Polar or high-altitude observatories remote from direct anthropogenic emissions are particularly important to monitor global pollution levels.

There has been a long tradition of monitoring air components in the Alps, especially associated with the Jungfraujoch Sphinx Observatory, the highest in Europe which is accessible all year round and the only one largely in the free troposphere. This has proven to be an ideal situation for measuring trace gases but also the movement of anthropogenic pollutants from the boundary layer into the troposphere.

This technology and expertise have been deployed also to the Polar regions with recent measurements of anaesthetic gases that have climate change implications and PCBs transported up to Svalbard. This combination of accurate trace gas and aerosol measurements and modelling of transport by air masses has proven to be valuable in understanding the origin of many pollutants in the Arctic.

Studies on the deposition history of persistent organic pollutants (PCBs) in the Alps have provided a clear understanding of the roles of glaciers and snow as repositories, and how the pollutant levels in the Polar regions constitute a record of global contamination of these and other toxic substances.

3. Polar oceans and sea ice

The polar oceans are key components of the climate system and home to unique ecosystems. Anthropogenic climate change affects polar oceans and their ecosystems, including sea ice cover, in an amplified manner due to enhanced warming relative to the global mean and a high level of vulnerability. The polar oceans are warming and acidifying very rapidly with far-reaching consequences for the physical and biogeochemical climate system. In the Arctic, sea ice is particularly affected by large reductions in summer and a persistent loss of multi-year ice. Together with melting permafrost on land, this constitutes a perturbation of the polar area that is unprecedented in many millennia. The warming of the ocean will have global consequences through the acceleration of the melting around the boundaries of the ice sheets in Greenland and Antarctica and in consequence their destabilization and large contribution to sea level rise. The acidification will strongly stress marine calcifying organisms and hence disturb the food chains in the polar oceans. Physical and biogeochemical feedbacks may further impact the global overturning circulation and fluxes of carbon between the atmosphere and ocean. In addition, the opening of the Arctic in summer will increase the pressure by enhanced human activities in this region, such as commercial shipping, exploration, mining, and geostrategic activities. The science community of Switzerland is well positioned to make significant and substantive scientific contributions for a better understanding of many of these issues.

In the area of sea ice and polar ocean research Swiss scientists have contributed to internationally well recognized research primarily in three areas. (i) The snow layer on the sea ice cover determines the energy balance therefore the dynamics of this component. Switzerland is carrying out work on the snow layer and its processes in the Artic and some in the Southern Ocean around Antarctica. (ii) Paleoclimatic studies on marine sediment cores from the Southern Ocean complement the prominent work of Swiss
researchers on the global carbon cycle. Paleoclimatic reconstructions are based on tracer analyses in marine sediment cores and elucidate the processes of the carbon cycle on time scales of centuries to many millennia. (iii) Simulations using a hierarchy of ocean-carbon cycle models are carried out by the Swiss science community and provide a quantitative understanding of past changes, and the current uptake of carbon, as well as of heat, under anthropogenic climate change. Such knowledge is crucial for climate change projections and, more generally, for a better quantification of climate sensitivity.

4. Biodiversity and ecosystem functioning under climate change

Polar terrestrial and aquatic ecosystems are experiencing rapid changes in biodiversity and functions, primarily as a consequence of amplified climate warming. Related increased precipitation, sea ice loss, permafrost degradation and natural hazards, such as river flooding or retarding coastlines, are expected to change landscapes or the marine system at high rate across vast areas. Increasing human activities in the Arctic, including tourism, shipping, and industrial infrastructure will further induce disturbance and disruption to the vulnerable ecosystems. Changes in biodiversity and vegetation structure have consequences for fisheries and availability of subsistence species for Polar indigenous communities. But also other parts of the world will be affected, through ecological teleconnections, such as related to migratory species. The magnitude of feedbacks from Polar ecosystems within the Earth system under increasingly snow- and ice-free conditions remains highly uncertain, however studies indicate their important role in governing fluxes of carbon, energy, water, and nutrients between the atmosphere, geosphere, and hydrosphere. Such feedbacks induced by land cover change are expected to amplify Arctic warming.

The Swiss science community is well-positioned to reduce large uncertainties in the understanding and quantification of feedbacks between climate, vegetation, and permafrost by linking existing process understanding with predictions of vegetation dynamics and climate models. Assessing impacts of climate change on Polar biodiversity and ecosystem functions and identifying adaptation pathways requires coordinated sustained observations, experimental approaches and the identification of areas for conservation of the unique Polar biodiversity, which are key goals listed in international research and policy agendas. Swiss Polar ecological research, with its major historical strength in Alpine ecology, has rapidly expanded over the past years and is increasingly supporting international Polar research agendas. Swiss researchers have made significant contributions to observation-based assessments of biodiversity change, climate drivers of plant growth, and seasonal to long-term vegetation dynamics in Alpine and Arctic tundra. In marine ecology, Swiss scientists investigate biogeochemical cycles, viral and plankton biodiversity, and contaminant burden in fish in the Southern Ocean. Current strengths of Swiss Polar ecology include: (i) experimental research and contributions to international monitoring networks to investigate climatic drivers of biodiversity and ecosystem functions in Alpine and Arctic tundra and freshwater systems, (ii) the prediction of species distributions and ecosystem functions in Polar regions, based on statistical and process-based modelling, and (iii) the relations of phytoplankton with the biogeochemical cycling of iron, nitrate, and phosphate in the Southern Ocean.
Beyond the thematic fields of excellence outlined above, Swiss Polar science can count on crucial transversal competences, notably acquired through the experience of working in high Alpine environments.

**Technology development**

The high latitude environment is a challenge for any measurement system as well as for general infrastructure and offers therefore an opportunity but also the need for technology development. Given the fact that Polar areas have a very low density of environmental observations, improved technology is a key ingredient for scientific progress. Two important areas of such a technology development are energetically self-sufficient infrastructure and measurement installations, and engineering of automated measurement systems, which will work in Polar winter conditions with no light and extremely low temperatures. In both fields, Switzerland has strong expertise as exemplified by successful photovoltaic developments, its strong standing in robotics and its experience with monitoring systems in extreme environments. Miniaturisation can also play a key role in successful missions.

Indeed, the expertise of the Swiss science community in collaboration with industry is well prepared to advance the development of novel technologies (robotics, automated systems, drones, remote sensing systems, environmental analytics etc.) for access to and measurements in remote and extreme environments, and to structure and analyse large data streams from observatories. Technology development including field observations and novel lab analytical techniques, as pioneered at Swiss research institutions, could be the single most important input to advancement of Polar science in particular fields. In addition, following prototyping and testing in extreme environments, such technologies can have a significant impact on innovation, academia-industry collaboration and the potential launch of new start-ups.

Remote sensing observations from satellites, airplanes and drones provide data of continuous spatial coverage across a variety of scales and access to remote areas, and have, for example, revolutionized our understanding of ice sheet dynamics in recent years. Such remote sensing data has been an essential source of information for Swiss science in Polar areas, and continues to be the method of research for mass change and balance of the ice sheets in Antarctica, landscape and vegetation development, and related carbon and energy fluxes at pan-Arctic scale.

The development of infrastructure adapted to high latitudes is yet another key aspect crucial to a better scientific understanding, but also for the economic and social development and integration of Polar regions. Here too Switzerland can count on key competencies and a strong expertise in different fields acquired to a large extent within the context of high mountain research. This is particularly true for fields such as architecture, new material, water supply and management technologies as well as sustainable power generation and storage in extreme environments. In the same way as for the development of novel technologies for Polar science, infrastructural developments for high latitudes could highly benefit from close collaborations between academia and the private sector.

**Data management and modelling**
The strong modelling competence present in the Swiss science landscape coupled with the focus of Switzerland in the field of data science also benefits the Swiss Polar community and should not be underestimated. Investigation of often complex, interdisciplinary and multi-dimensional datasets related to scientific activities in the field is already benefiting from a partnership with the Swiss Data Science Center (SDSC), using the data of the Antarctic Circumnavigation Expedition as a case study. In particular, data sciences and techniques involving the use of machine learning, advanced data analytics, artificial intelligence, signal processing or high-performance computing, can provide novel insights by working across and linking datasets from different fields.

6. Societies in the Arctic and extreme environments

Study of human adaptation to extreme environments is important for understanding our cultural and genetic capacity for survival. There are already significant social sciences and humanities research interests both in the high altitudes and the Arctic to which Swiss researchers have made a variety of important contributions. Yet at present, this has not been linked to natural science research in these areas.

When working and conducting research in these regions, it is crucial to understand the local sensitivities and social contexts. Traditional Arctic communities and those from very high mountain regions, are of great cultural, linguistic, archaeological and anthropological importance for researchers from different fields. Some Swiss groups and institutions, notably museums, have deep ties and are recognised internationally for their work linked to these regions. Switzerland does also contribute significantly in advancing archeological methods in the Arctic developed on ice sites in an Alpine environment and contributing extensively to our knowledge on the Neolithic and Bronze Age, ranging from material culture to population movements and living conditions.

The growing importance of natural resources from the Arctic as well as from high Andean areas and the opening of new transit routes through the Arctic highlight their international economic and geopolitical significance. Switzerland, as a global economic player and a member of both the Arctic Council and the Antarctic Treaty, has a strategic interest in better understanding the developments in the Arctic and in the Southern Ocean and Antarctica.

Last but not least, with experience in nature conservation and local societies in the Alps, but also internationally, Swiss researchers could contribute to the planning and management of protected areas that sustain local livelihoods in these extreme environments.

Note: Inputs from the Social Sciences and Humanities research community would be particularly welcome.
III. INCREASING IMPACT – Growing the Swiss Polar research community

As the chapters above have highlighted, Swiss research is well-placed to contribute significantly to the key challenges identified for the Arctic, the Antarctic. Whilst the immediate emphasis is on science questions exploring their relevance in high alpine communities must also be a future challenge. A number of key framework conditions are already in place, both scientifically and in terms of the representation of Swiss scientists in the relevant international bodies and committees related to Arctic and Antarctic science.

To be able to grow and contribute decisively to tackling global scientific challenges relating to extreme environments, the Swiss Polar Community identified the following “flagship topics” in which it could significantly increase its impact, launch its own scientific initiatives and strengthen participation in international programmes and networks. This would help to raise the profile of the Swiss Polar community internationally and make a difference in major current and upcoming scientific questions.

In these thematic flagships, SPI could play a crucial role by supporting logistics, coordinating research initiatives or expeditions, but also by funding research programmes in a complementary way to the Swiss National Science Foundation or other sources.

Cryosphere through time – processes, feedbacks and responses

Ice sheets, Polar and high mountain glaciers, the snowpack, as well as permafrost respond sensitively to the on-going global warming. The albedo change related to snow, sea ice and glacier retreat are some of the most important feedback processes determining the state and sensitivity of the Earth’s climate system on decadal to millennial time scales. A current Swiss-led study to estimate Earth system sensitivity based on paleo observations suggests that, on millennial time scales, the warming connected to a doubling of CO₂ may be a factor of two larger than customarily constrained by IPCC climate model runs until 2100 AD. The paleo record also suggests that millennial scale sea level rise of at least 6 m is very likely to occur already for a global warming of only 2°C, implying a partial loss of at least the Greenland and West Antarctic Ice Sheet. The current rapid mass loss from glaciers and ice sheets dominates the contribution to today’s sea level rise, but future rates remain uncertain and the related process feedbacks are still poorly understood.

Accordingly, the following overarching, socio-economically relevant questions have to be answered:

1. What are the shorter-term and longer-term responses and the controlling processes of glacier, ice sheet and ice shelf changes on warmer climate boundary conditions and is there a threshold for ice sheet disintegration that can be avoided by mitigation measures of anthropogenic global warming?

2. Can we improve the estimate of the Earth System Sensitivity using novel Polar and high-alpine climate archives that extend our record towards warmer climate intervals than today (for example with higher CO₂) and by using improved quantitative climate proxy information from these archives?
3. What is the coupling and interaction of land ice, ocean circulation and atmospheric CO₂ on multi-millennial time scales and, in particular, what natural greenhouse gas cycle feedbacks (for example from permafrost) are to be expected for a global warming of at least 1.5°C?

Based on the outstanding Swiss expertise in the field of glaciology, snow and ice research and paleoclimate reconstructions on Polar and high-alpine ice cores (see also chapter II), major progress in answering these questions can be accomplished within the coming 5-10 years. This could notably include research activities by the Swiss community

- providing observation-based process understanding of glacier and ice sheet melt and flow dynamics, iceberg calving, interaction with the ocean and ice shelf disintegration for an improved model prediction of total mass balance/sea level changes in the future. This goal must be achieved by integration of field studies in Greenland and Antarctica with the comprehensive Swiss expertise in climate and glacier modelling as well as remote sensing.

- better constraining Earth System Sensitivity and the natural climate/greenhouse gas coupling by extending the paleo record from Polar ice cores to the last up to 1.5 million years. This will provide unrivaled greenhouse gas records over the Mid Pleistocene Transition when ice sheet/climate coupling was substantially different from the late Quaternary record of the last 800,000 years. The extended records will also provide a larger suite of natural templates of the Polar amplification signal for warmer climate conditions than today.

- improving our process understanding of snow-firn-ice transformation and firn processes that affect climate proxy records and influences the mass balance and energy exchange between glacier and ice sheet surfaces and the atmosphere.

- securing precious ice core material from high alpine glaciers that are highly endangered by global warming and glacier melt, and to using these cores as unique environmental archives of natural and anthropogenic changes in mid and low latitudes.

All these research activities take place in the most inaccessible regions of our planet and within a highly competitive research field. Accordingly, close national, international and interdisciplinary collaboration is a prerequisite to successfully achieve these goals. This warrants the complementary expertise required for integrated Polar research and ensures deep field access using international Polar research infrastructure through close collaboration of the SPI with European and other international logistics providers. Targeted co-financing of international ship, aircraft and surface infrastructure needed for individual research activities in Polar regions can be enabled through the SPI on a case-to-case basis, while avoiding the high costs of SPI becoming an independent Polar logistic provider.

The carbon, nitrogen, water cycle nexus – past, present, future

The global cycles of carbon, nitrogen and water constitute central elements of the Earth System and its long-term evolution, including past glacial cycles, present-day climate conditions, and the strongly anthropogenically influenced future of our planet. These cycles link the Earth System compartments,
i.e., the biosphere, land, ocean, ice and the atmosphere. Whilst important research questions exist related to each of these individual cycles, an additional challenge emerges from their intrinsic linkages. Research in this area requires a complementary approach, combining Polar and high altitude observations from long-term monitoring, and field campaigns with comprehensive numerical models. Important overarching questions related to the three cycles include:

1) How important are Southern Ocean freshwater fluxes for ocean stratification and circulation, and eventually uptake of heat and of CO$_2$?
2) How relevant is long-range atmospheric transport for Arctic clouds and air pollution?
3) Can comprehensive Earth system models help assessing the relevant processes that drive the past, present and future evolution of the carbon, nitrogen and water cycles?

Based on the internationally recognized Swiss expertise in these research areas (see also chapter II), major contributions to answering these questions can be made by the Swiss community, in collaboration with international partners, in the coming decade. These include, for example, the following potential research activities:

- Southern Ocean campaign to study the role of freshwater fluxes for CO$_2$ uptake in different climates. It has recently been shown that in addition to the difference between evaporation and precipitation, the melting of sea ice is also an essential contributor to the total freshwater flux. The plan is to study the processes involved with a dense network of ARGO floats in the Ross or Weddell Seas, combined with a ship campaign with supply ships from the U.S. and New Zealand, and mesoscale ocean-atmosphere-ice modeling. Such an initiative would strongly profit from the development of novel sensor techniques.

- Dedicated Arctic field experiments to investigate the role of long-range atmospheric transport for Arctic air pollution, atmospheric composition and biogeochemistry. In most Polar areas anthropogenic emissions are comparatively low and therefore large-scale atmospheric transport strongly affects Polar air composition. A dedicated international Arctic field campaign with aircraft and ships, strongly supported by Swiss Polar research community and its expertise in atmospheric transport, cloud microphysics, aerosol-cloud interactions, and biogeochemistry, would be a rewarding step forward in specifically addressing the importance of long-range transport from densely populated areas of the Northern Hemisphere to the remote Arctic.

- Development of coupled Earth system model to study the long-term evolution of CO$_2$, N$_2$O, CH$_4$ and of different Earth system components. This model would include Polar ice sheets, the biosphere on land, atmospheric chemistry, water, carbon and nitrogen isotopes, and water mass tracers. Such an initiative would be ideal to combine the high-quality numerical modeling expertise in Switzerland in order to develop a state-of-the-art Earth System model with special focus on Polar processes. Specific features of this Swiss Earth system modeling activity would include (i) a strong link to the ice core community, (ii) an efficient implementation also of high-resolution modeling options in collaboration with the Swiss supercomputing centre, and (iii) a focus on studying stable water isotope variability from paleoclimate time scales down to mesoscale processes in individual precipitation events.
Very close national, international and interdisciplinary collaboration is an essential prerequisite to successfully realize these challenging research ideas. An example of a major international initiative to which the suggested Swiss activities could contribute is the recently proposed EU Flagship project ExtremeEarth. These projects aim at modeling a complete glacial cycle with comprehensive Earth System Models (PALMOD), and at understanding and advancing our ability to predict the frequency of occurrence and intensity of environmental extremes (ExtremeEarth), respectively. SPI support will be critical to facilitate the required long-term dedication of the Swiss Polar science community working at the nexus between the carbon, nitrogen and water cycles to successfully perform the suggested activities.

Biodiversity and ecosystem functions

Triggered by climate warming, Alpine, Arctic, and Antarctic biodiversity experienced rapid changes over the past decades. These changes impact resources of local communities, ecosystem functions and feedbacks to climate. However, high uncertainties remain regarding the resistance, resilience, and fate of Polar biodiversity and its links to ecosystem functions. In order to inform climate predictions, biodiversity conservation, and the assessment and mitigation of consequences on society, the following key questions need to be addressed:

1. What is the legacy of past climatic fluctuations on current biodiversity, and the related constraints on future ecosystem responses?
2. What are the status, trends, and drivers of change in biodiversity across Polar ecosystems, where can we preserve Polar biodiversity, and how can we sustainably develop infrastructure while limiting impact on biodiversity?
3. What are the consequences of Polar biodiversity and ecosystems functional change on local and global processes and societies?

The Swiss research community has outstanding expertise in biodiversity and ecosystem functioning research, from soil microbiomes, to plant communities, freshwater and marine systems.

The plan is to integrate this expertise towards a breakthrough in the prediction of biodiversity and ecosystem functions in the coming 5-10 years, through developing a spatial process-based ecosystem model. This model considers the full array of species, including their abiotic and biotic interactions, to predict the future of Polar biodiversity and ecosystem functions, and inform conservation management and sustainable development.

This objective is intended to be met by the development and integration of the following exemplary components:

- Increase our understanding of pre-Anthropocene dynamics of biodiversity shaping current ecosystem structures.
Assess the status of biodiversity and links with ecosystem functions by integrating novel techniques across scales, such as environmental DNA with remote sensing data from drone to satellite level.

Predict connectivity of future populations and effects on genetic diversity, in support of transboundary management and conservation of Polar biodiversity.

Identify present-day main drivers of biodiversity and ecosystem change, and quantify effects on fluxes of energy, carbon, water, and nutrients, and the strength of sources and sinks.

Assess consequences of biodiversity change across trophic levels through food-webs.

Improve ecological modelling (statistical and process-based) through the development of a biome-wide database of existing biodiversity data and the representation of biotic and abiotic interactions.

These components form a major contribution to international science and policy agendas of Polar regions (IASC and SCAR), but also globally (IPCC, UN Convention on Biological Diversity, GEO BON, IPBES). Above objectives are ambitious and need substantial resources for fieldwork, experiments, databases, model development, and international collaboration. The role of the SPI will be to financially match the planned work (e.g. field work, databases, expensive measurements (metagenomics, tracers, drone), facilitate collaboration of researchers at Swiss institutions, and support the identification of funding sources for a programme to develop a process-based ecosystem model, representing key interactions and feedbacks of Polar ecosystems within the Earth system.

Technology in extreme environments

Both Polar and high-alpine regions still contain unexplored environments, whose scientific and practical importance has yet to be determined. The extreme Polar and high-alpine environment is a challenge for any measurement system, as well as for general infrastructure, and offers therefore an opportunity for technology development. Given the fact that the Polar regions have a very low density of environmental observations, improved technology must be a key ingredient for scientific progress. Two important areas of such technology development are firstly, energetically self-sufficient infrastructure and measurement installations, and secondly, engineering of automated measurement systems, which will work in remote regions with extreme environments. In both fields, Switzerland has strong expertise such as exemplified by the successful photovoltaic development, its strong standing in robotics and its experience with monitoring systems in extreme environments. Miniaturisation can also play a key role in successful missions.

Innovative technologies are necessary to explore and record the extreme environments. Some key challenges include:

- Technologies for analyzing subglacial environments without contamination
- Novel technologies for extracting core samples (i.e., from Arctic ice sheets, lake sediments, deep permafrost sediments)
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- Autonomous measurement platforms for atmospheric research and small-scale meteorological monitoring networks (i.e., miniaturization of sensors, low power consumption, efficient power storage during Polar winter)
- Year-round autonomous observational and experimental platforms (i.e., ground-penetration robotic radar vehicle, laser-guided data transfer to satellite)

Remote sensing, drones and other unmanned vehicles:
Remote sensing observations from satellites and airplanes have provided data with continuous spatial coverage and this access to remote areas has in recent years revolutionised our understanding of extreme environments. Satellite and aircraft data are today available in abundance for these remote areas and need to be merged with the in situ field data for calibration, analysed to apply change to process studies, and augmented with high-resolution drone measurements to increase the granularity of geographical coverage. Solar-powered flying platforms have been tested in Polar regions monitoring glaciers and are becoming a primary application, as the midnight sun offers ideal conditions for perpetual flights. Miniaturization of sensors (i.e., gravity meter, lidar, imaging spectrometer) will open a wide field of applications. Investigations of the atmosphere by means of drones can contribute significantly to the investigation of the causes of Arctic climate change, as they provide an insight into ground-level air layers that are not monitored by other measuring stations. Drone imagery acquisition, following standardized protocols, form the backbone for upscaling from in situ plot to pan-Arctic scale to assess and understand vegetation development, biodiversity, snow and permafrost dynamics and related carbon and energy fluxes of the highly heterogeneous Polar terrestrial landscapes and coastal areas. Drones deployment in the Antarctic as well as in Greenland, is still in its infancy.

Future activities and developments where the Swiss community could have a high impact include:
- Develop scalability and limited risks for drones
- Develop efficient and cost-effective observation methods
- Develop drone flight software for repeat surveillance and monitoring in remote regions
- Develop smart drones for field-testing new sensors
- Develop unmanned surface or underwater vehicles (such as underwater gliders) for data collection in Polar waters

To do this effectively new links and networks need to be built between the research groups and industry to facilitate the development of these new tools. In facilitating this, SPI could play an important role.

Modelling and data science
Simulations with complex computer models are now central to obtaining reliable projections of the future climate and for understanding environmental change across a wide range of time and spatial scales. These models are also used by scientists to extrapolate sparse observational data and for exploring the importance of interactions and feedbacks within the Earth System.
The strong modelling competencies present in many parts of the Swiss science landscape, together with a developing interest in Switzerland in handling big data and developing data science tools could also benefit the Swiss Polar community, especially in probing new interdisciplinary questions.

IV. COLLABORATION FOR SUCCESS – Linking up with global Polar agendas

When documenting the strengths and challenges faced by the Swiss research community active in Polar regions, this science strategy naturally highlights the high degree of international collaboration needed in order to pursue Swiss research in Polar regions. This is due to the very complex logistics needed to support such research, the difficulty of obtaining access to these regions as well as the need to share the extremely high costs induced by the technology and logistics involved.

Given the high quality of their research, Swiss scientists are well placed and often invited to join international initiatives both in the Arctic and Antarctic. Additionally, many of their domains of expertise match well the international agendas for research in Polar regions. Switzerland therefore contributes actively to the two international organisations coordinating research in the Arctic and Antarctic, which have each recently published an analysis of the key research questions for their regions.

In its “Horizon scan”, the Scientific Committee on Antarctic Research (SCAR) used a worldwide consultation and an international panel to identify 80 key questions covering all aspects of science. The International Arctic Science Committee (IASC) has undertaken a similar exercise for the Arctic, resulting in the ICARP III report “Integrating Arctic Research – a Roadmap for the Future”, with a much greater emphasis on linkages of the physical and biological systems with society. As yet, no similar attempt has been made for alpine areas globally. With no international organisation taking responsibility for the high alpine regions, Swiss expertise could be harnessed to take a lead in developing an international document of key research questions that complements the existing SCAR and IASC documents.

On the one hand, the development of new international research programmes by both SCAR and IASC centered on key questions and research priorities offers an important opportunity to connect Swiss initiatives directly into global questions with a wide range of partners. On the other hand, the already existing large overlap of the SCAR and IASC science scans with ongoing and projected Swiss research activities in Polar areas underlines the importance and timeliness of Swiss research working at the forefront of current Polar science questions.

In summary, the priorities outlined above align almost perfectly with the international agenda and key topics identified for both poles by IASC and SCAR. Swiss researchers and institutions are present in the governance and thematic groups of both organisations hence guaranteeing that Swiss priorities can be fed into the international agendas but also that the Swiss community is aware of new initiatives and can help shape them.

Switzerland is currently in a position to play a constructive collaborative role in international initiatives. Support by the Swiss Polar Institute also enables Swiss groups to be present in significant international initiatives, for example MOSAIC (2019-2020) or Ice Memory.
V. LOOKING TO THE FUTURE – Making a difference for the Swiss Polar community

In view of the important challenges and crucial role played by the Swiss Polar research community, the Swiss Polar Institute has an important role to play in order to set up and manage a Swiss Polar programme to oversee the activities and developments needed.

In view of the existing strengths but also of the strategic importance of polar-related scientific developments outlined above, the following priorities have been identified as priorities to be developed up to 2025 and beyond:

a) **Build a strong and cohesive community** as well as support **scientific exchange and outreach** on Polar-related topics (including conferences, dedicated scientific workshops, support exchange with international Polar organisations and programmes and structures supporting young Polar scientists such as APECS);

b) **Offer training and logistical support** for the organisation of research expeditions and field work in extreme environments (including: Health and Safety training and support, checklists, coaching and advice);

c) Support the development of **data management, portals and data science** for the benefit of the Polar community in collaboration with existing structures and with the Swiss Data Science Center;

d) Fund **field work, logistics, technological developments and short-term** opportunities for Swiss Polar scientists to complement science funding from sources such as the Swiss National Science Foundations or the EU Framework programmes for all fields of research with a particular emphasis on young scientists;

e) **Launch and manage medium- to large-scale research “flagship” expeditions** (notably by funding the project management, logistics and coordination) and **to contribute to large-scale international programmes and initiatives** related to the thematic flagships and priorities highlighted in this Science Plan.

In order to be able to expand current activities to match the needs, high level of competence and strategic relevance of research about and in polar regions in Switzerland, the founders of the Swiss Polar Institute are working towards establishing the SPI as an institution co-funded by the Swiss Confederation for the period 2021-2024. Such anchoring would enable SPI to offer sustainable support to researchers all over Switzerland but also to launch flagship initiatives and expeditions for and by the Swiss research community.

This Science Plan will remain a living document to match the evolutions of the Swiss polar community. In the short term however, this document will have a crucial role in underlining the importance and variety of the work performed by Swiss polar scientists and create the scientific framework for the near future up to 2025 and beyond.

The authors therefore warmly thank all the contributors from the scientific community who have contributed to this document through the different rounds of consultations in 2017 and 2019, in the Call for Ideas in 2018 and during the many discussions, notably at the Swiss Polar Days in 2018 and 2019.
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Authors
This document has been prepared by the SPI Science and Technology Board (STAB). Members of the STAB are:

Prof. Karin Lochte – Co-Chair, AWI, Germany
Prof. Thomas Stocker – Co-Chair, University of Bern, Switzerland
Christian de Marliave, Editions Paulsen, France
Prof. Hubertus Fischer, University of Bern, Switzerland
Prof. Philippe Gillet, EPFL, Switzerland
Prof. Gerald Haug, ETHZ, Switzerland / MPG, Germany
Prof. Gabriela Schaepman, University of Zurich, Switzerland
Prof. David Walton, BAS, United Kingdom
Prof. Heini Wernli, ETHZ, Switzerland

This document also benefited from contributions from:

Prof. Dr. Loïc Pellissier, ETH Zürich, Switzerland
Prof. Dr. Niklaus Zimmermann, WSL, Switzerland
Prof. Fortunat Joos, Uni Bern, Switzelrand
Prof. Nicolas Gruber, ETH Zurich, Switzerland
Prof. Margit Schwikowski, PSI, Switzerland
Prof. Andreas Vieli, University of Zurich, Switzerland
Dr. Martin Schneebeli, WSL, Switzerland