SWISS POLAR
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Polar Science in Switzerland

Proposed priorities for
the Swiss Polar Institute (SPI)
up to 2025 and beyond

This paper has been prepared by the Science and Technology Advisory Board of the Swiss Polar Institute (SPI) on the basis of two stakeholder consultations carried out during workshops at the Swiss Polar Day 2018 and a Call for Ideas launched by the SPI in 2017-2018. A draft version of this document was also issued for consultation in February 2019.

As a strategy, it serves to identify the key priorities and initiatives for support by the SPI up to 2025 and beyond, in order to best serve the Swiss polar community and to fill gaps in Swiss polar science. While it presents a medium-term strategy, it is nevertheless SPI's aim to provide continuity and to embed its activities in a long-term vision.

For the sake of simplicity, this document often groups issues related to the Arctic, to Antarctica and to comparative studies in high-altitude regions under the term "polar". Failure to mention one of these regions specifically is not a reflection on the priority given to the science in that region.

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EPFL · WSL Swiss Federal Institute for Forest, Snow and Landscape Research WSL · ETH zürich · Universität Bern · Paulsen

Foreword

We are living in the Anthropocene, the first era in Earth's history when processes controlling climate and natural biogeochemical cycles are being 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 as yet unknown long-term impacts on ecosystem services. This influence is most clearly reflected in the following changes:

- Melting of sea ice, glaciers, ice sheets, thawing of permafrost and occurrence of extreme weather events, through accelerated anthropogenic warming in recent decades.
- Pronounced biodiversity changes in the polar ecosystems and decline of species adapted to extreme conditions.
- 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.
- Environmental changes impacting on the livelihood of Indigenous Peoples, through the erosion of traditional food resources.

Most importantly, the accelerating human influence especially affects polar and high-altitude regions, where the change in climatic conditions is twice as high as the global average (polar climate amplification). In addition, this human influence on polar regions affects compartments of the Earth system (such as sea ice, glacier, ice sheets and vulnerable ecosystems) that are most sensitive to rapid changes in climate and environmental boundary conditions, and whose responses in return act as further amplifiers of global climate change.

In a globalised world, the knowledge drawn from the study of polar regions and the links shown with systems regulating the Earth's climate are highly relevant for all societies and policy makers.

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 are highly relevant for all societies and policy makers.

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

Swiss research groups are widely recognised as world leaders in fields such as atmospheric observations, climate modelling, paleoclimate reconstructions through ice and sediment cores, and global biogeochemical cycles in high-latitude marine and terrestrial environments. Modelling 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-altitude regions. Similarly, Swiss groups are renowned for their work on microbiology, biodiversity and ecosystem functioning in terrestrial and marine environments in polar regions, and comparative studies in high-altitude regions.

The diversity of Swiss polar research and the heavy logistical demands associated with polar and in many cases high-altitude research, require both national coordination and international collaboration to maximise the value of the research investment. Moreover, the highly sensitive role of polar regions and alpine environments in global climate change have increasingly brought polar science onto the political agenda, with Switzerland playing a growing role in international science and policy bodies related to polar regions, such as the International Arctic Science Committee (IASC), the Scientific Committee on Antarctic Research (SCAR) and the Arctic Council, where Switzerland was granted Observer status in 2017.

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 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 fields of science 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.

1 Introduction

Science at the three poles in Switzerland

Switzerland has a long tradition in polar research, both in the Arctic and Antarctica. Although Switzerland has never had a specific polar programme, the names of de Quervain, Mertz and Forel are landmarks in polar and glaciological research. Swiss expertise in science performed in polar and high-altitude environments is of internationally recognised importance, both historically and today.

Over the past few centuries, Swiss scientists 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 experience in high altitudes and drawing parallels to the processes they could observe and measure in the Alps – the Third or Vertical Pole. During the 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 natural sciences expertise and outstanding technological and analytical capabilities. This comprises the full spectrum from field observations, in situ process studies and remote sensing to modelling of Earth system components.

In today's changing climate, scientific expertise related to extreme environments is of the utmost importance. The thawing of permafrost or the thinning of glacier and sea ice 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) presents particular challenges in terms of access, logistics, equipment and safety. Performing scientific experiments and data collection in these regions therefore involves extremely high costs and international partnerships or collaborations are practically a necessity.

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The Swiss polar community is well networked through its membership and active participation in SCAR and IASC. The quality of its research output is widely recognised and evident in the comparatively high publication records, citation indexes and participation in numerous prestigious international committees (e.g. Intergovernmental Panel on Climate Change; IPCC).

However, in spite of the recent launch of the SPI 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 to optimally benefit from its expertise and experience.

2

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-altitude regions, Switzerland has a dense network of research teams working on polar-related topics. The map on page 10 outlines the institutional location and fields of study of the researchers that have either participated or expressed interest in activities, calls or events of the SPI since 2016.

SWISS PUBLICATIONS RELATED TO POLAR SCIENCE

Over the last 20 years, the growth rate of Swiss polar publications has been about twice as high as the global growth rate of publications in this field.

The Web of Science database shows that the Swiss polar community is increasingly competitive in terms of publications related to polar science. The graph below takes into account all publications related to the following keywords: Arctic, Alaska, Yukon, Southern Ocean, Svalbard, Baffin Bay, Chukchi Sea, Davis Strait, Greenland, Foxe Basin, Tundra, Nunavut, Inuit, Inupiat, Yupik, Antarctic, Siberia, Iceland, ice caps.

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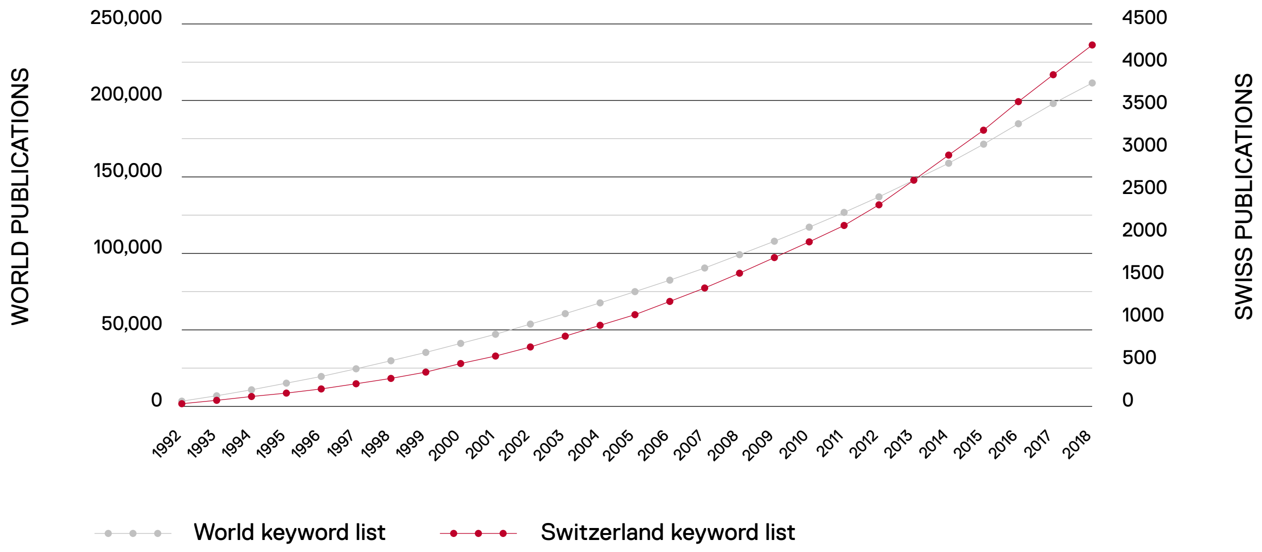
EVOLUTION OF POLAR RESEARCH PUBLICATIONS
WORLD AND SWITZERLAND



Polar sciences in Switzerland

1 Eawag
Swiss Federal Institute of Aquatic Science and Technology
Dübendorf (ZH)

Hydrology, limnology, sediment coring, biogeochemistry

2 EMPA
Swiss Federal Laboratories for Materials Science and Technology
Dübendorf (ZH)

Oceanography, atmospheric composition, technology development

3 ETHZ
Swiss Federal Institute of Technology in Zurich
Zurich (ZH)

Climate, biogeochemistry, glaciology, sea-ice, hydrology, oceanography, environmental physics, meteorology, atmospheric dynamics, aerosols, remote sensing, technology development, hydrology, surface-atmosphere interaction, ecosystem functioning, biodiversity, biology, robotics, marine micronutrients, permafrost, wireless sensor technologies

4 UZH
University of Zurich
Zurich (ZH)

Glaciology, climate, biology, ecosystem functioning, biodiversity, surface-atmosphere interaction, biogeochemistry, remote sensing, technology development, historical sciences, glacier monitoring, environmental history, permafrost, palaeontology, social science, natural hazards and risks, water resources

5 PSI
Paul Scherrer Institute
Villigen (AG)

Ice coring, glaciology, climate, atmospheric composition, aerosol, snow and firn

6 UniBas
University of Basel
Basel (BS)

Biology, biodiversity, atmospheric composition, oceanography, marine mammals, pathology, environmental pollution, ecotoxicology, fish biology

7 UniBe
University of Bern
Bern (BE)

Ice coring, glaciology, climate, permafrost, biogeochemistry, oceanography, atmospheric composition, (marine) geology

8 UniNe
University of Neuchâtel
Neuchâtel (NE)

Biodiversity, ecosystem functioning, ethnography

9 EPFL
Swiss Federal Institute of Technology in Lausanne
Lausanne (VD)

Snow and firn, meteorology, limnology, microbiology, remote sensing, space, technology development, international law and governance, biodiversity, ecosystem function and biogeochemistry

10 UniL
University of Lausanne
Lausanne (VD)

Glaciology, climate, microbiology, geology, remote sensing, permafrost, rock glaciers

11 UniGe
University of Geneva
Geneva (GE)

Oceanography, biochemistry, ecosystem functioning, biodiversity, history of science, political sciences

12 UniFr
University of Fribourg
Fribourg (FR)

Glaciology, rock glaciers, permafrost, surface-atmosphere interaction, snow and firn, climate, microbiology

13 WSL
Swiss Federal Institute for Forest, Snow and Landscape Research
Birmensdorf (ZH), headquarters + Davos Dorf (GR)

Snow and firn, glaciology, permafrost, surface-atmosphere interaction, meteorology, biodiversity, ecosystem functioning

STRENGTH 1

Snow, glaciers and ice sheets

Switzerland has a long-standing tradition of research on snow and ice. Starting with 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 their stability and dynamical behaviour, mechanisms of ice flow and iceberg calving, and mechanical and thermal conditions within and beneath the ice sheets. Swiss researchers extensively use ice cores from glaciers and ice sheets as one of the most important climate archives.

GLACIER AND ICE SHEET DYNAMICS AND 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 and the ice dynamical response of all three to global warming. Switzerland has acquired outstanding expertise in this area, which is now of high societal relevance. Indeed, the combined ice masses in high-altitude glaciers and polar ice sheets represent the largest freshwater reservoir on Earth. The size of this reservoir is not constant but changes over time in response to climate variations and is linked to substantial sea-level variations. Current and future increases in atmospheric temperature 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 ice flow dynamics at the west coast of Greenland. Swiss researchers also conduct leading research on Alpine and high-altitude glaciers. While these glaciers store much less ice and thus have a limited effect on sea level in the long run, their response time is much faster and their geographical position means any change will be of immediate societal relevance with regard to water and energy supply for high-altitude regions in the coming decades. The World Glacier Monitoring Service (WGMS) of the Global Climate Observing System is located in Switzerland and is in charge of the compilation of standardised information on glacier changes in length, area, volume and mass.

POLAR ICE SHEETS AND GLACIERS 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 continue to improve our understanding of the response of glacier mass to climate change by observations, forecasting of future ice loss through modelling, reconstruction of past climate and atmospheric composition through ice cores, and by quantifying variations of glacier extent in response to past climate variations.

A major new advance in this field is expected from the "Beyond EPICA – Oldest Ice Core" European project with strong Swiss participation. The project will extend the ice core climate record in Antarctica over the Mid Pleistocene Transition, i.e. the last 1.5 million years.

SNOW AND FIRN

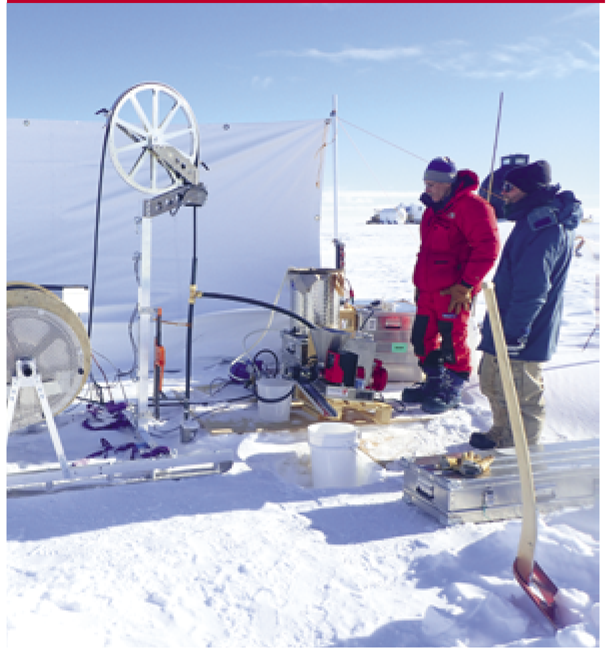
Research on snow and firn is also a trademark of the Swiss research landscape. In this field, Swiss competence is extremely high, with a wide range of techniques and a deep understanding of the physics of snow. Current Swiss research on snow in Antarctica and Greenland includes the mechanisms of snow 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. A detailed understanding of snow properties and structures is essential in order to comprehend mass balance changes of ice 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.

Finally, snow amount, structural properties and spatio-temporal distribution also have major impacts on biological processes through snow reflectance, insulating capacity and mechanical resistance. Swiss expertise is very welcome at an international level for improving measurement protocols and capacities, and predicting 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.

Beyond EPICA

There was a drastic change in climate dynamics during the Mid Pleistocene Transition about 1 million years ago. Clear 40,000-year glacial / interglacial cycles gave way to much stronger and longer glaciations, with interglacials occurring only about every 100,000 years and maximum glacial sea level lowering by up to 130 m. The reason for this change is still a matter of debate. Only an Antarctic ice core covering the last 1.5 million years can provide the direct climate forcing record over this time interval and the information on Antarctic ice sheet size and temperature needed to address this issue. The University of Bern is a partner in the Horizon 2020 project "Beyond EPICA – Oldest Ice", with the goal to retrieve such an ice core in the coming years.

The new RADIX miniature drilling technique developed by the University of Bern makes it possible to drill down to bedrock and log the borehole in 1-2 weeks. © Barbara Seth



STRENGTH 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 modelling. 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 the Jungfraujoch, as well as the long time series of observations in Greenland and analysis of ice core archives. Finally, the sophisticated modelling 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. The cycle involves processes that occur on both very small scales (e.g. the formation and growth of snow crystals) and very 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 vapour and surface precipitation, runoff and snow accumulation samples, while 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 modelling techniques. This provides a unique opportunity to develop comprehensive research on the hydrological cycle in polar regions, in order to link the timescale of individual weather systems to the longer-term processes that determine the variability of ice core signals.

ENERGY FLUXES AS DRIVERS 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 Baseline Surface Radiation Network experiment since 2000, in order to detect changes in the radiation at the Earth's surface that may be coupled to climate changes.

For vegetated and soil surfaces in polar areas, energy fluxes are 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 for the thermal state of permafrost soils and their carbon content. Vegetation / energy flux 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. Moreover, comparative studies on high-altitude permafrost changes are performed within PERMOS, the Swiss permafrost monitoring network. Thus, the Swiss science community is currently well positioned to improve our understanding of feedback mechanisms 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. In the present-day ocean, the Southern Ocean forms the most important hub of this kind, regulating ocean-atmosphere exchange of CO_2 and also playing a dominant role in the biogeochemical cycles of both major nutrients (nitrate, phosphate, silicate) and trace metal micronutrients (e.g. iron, zinc, cadmium). As microorganisms depend but also significantly alter the pool of carbon and nutrients, this complex feedback needs to be investigated. Process studies, including the characterisation of biodiversity and functional maps from genomic analysis, are used to study this complex feedback and help us to understand ecosystem functioning.

Swiss Camp in Greenland

Researchers from the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, in collaboration with the Swiss Federal Institute of Technology in Zurich and the University of Colorado Boulder (USA), have been taking measurements in a long-term programme at the "Swiss Camp" station in Greenland since 1990. They have noted an increase in the melting of ice. The station, located in the western part of the ice sheet, has recorded a warming of 3°C since the beginning of the measurements and an inland shift of the equilibrium line (the point at which ablation is equal to accumulation) by 50 km. Swiss Camp is also a reference for 18 automatic weather stations, which are spread over the entire ice sheet and together form the Greenland Climate Network. The network is the basis for climate information, weather forecasts, and the validation of satellite sensors and process studies as well as regional climate models.

The Swiss Camp at the equilibrium line altitude on the western slope of the Greenland ice sheet. © Konrad Steffen

Tundra in the rain

Tundra ecosystems occur under cold and dry climatic conditions. The long-term "International Tundra Experiment", with 46 locations spread across all three poles (including the Val Bercla site in the Swiss Alps), has shown increasing vegetation height and plant compositional changes with elevated temperatures. It is less well known how the permafrost environment will develop with increasing precipitation, especially increased rainfall. At the north-eastern Siberian Kytalyk research site, the Spatial Ecology & Remote Sensing Group at the University of Zurich test the effects of soil temperature, moisture and nutrient availability on plant strategies, community composition and energy fluxes. The Kytalyk site is located on extensive lowland plains that border the Arctic Ocean. It is a region with major soil carbon stocks locked in the permafrost, where an increase in precipitation by 55% is predicted by the end of the 21st century.

The north-eastern Siberian Kytalyk research site © Gabriela Schaepman-Strub

Regarding the past ocean, the Southern Ocean has been shown on the one hand to provide the dominant control on long-term changes in carbon storage in the abyss via iron fertilisation 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 and hence N_2O 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 for the past and for the future.

Swiss polar scientists are closely involved in investigating the role of polar oceans in the modern marine biogeochemical cycles of major and trace nutrients through observational and modelling studies. They are also reconstructing and modelling past / future 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. While 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 humans. Polar or high-altitude observatories remote from direct anthropogenic emissions are particularly important for monitoring global pollution levels.

There has been a long tradition of monitoring air components in the Alps, especially associated with the Jungfraujoch Sphinx Observatory. It is the highest observatory 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 also been deployed to the polar regions, for example recent measurements of anaesthetic gases with climate change implications and persistent organic pollutants (PCBs), which have been transported up to Svalbard. This combination of accurate trace gas and aerosol measurements and modelling of transport by air masses has proven to be invaluable in understanding the origin of many pollutants in the Arctic.

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

Swiss scientists have gained extensive expertise in microplastic research by investigating microplastic occurrence in Swiss waters and sediments, microplastic sources, and the uptake and effects on aquatic organisms. This knowledge is currently being applied in polar regions and can answer questions regarding the extent of the microplastic pollution, its sources and sinks, and uptake in the polar food web.

In addition to monitoring strategies, more in-depth process understanding is needed to better assess pollution pathways and to predict how polar pollution will evolve under climate change. The cycling and human exposure to pollutants such as mercury or PCBs in polar regions may be affected by sea-ice loss, permafrost melt or changes in food-web structure.

STRENGTH 3

Polar oceans and sea ice

POLAR OCEANS AS KEY COMPONENTS OF THE CLIMATE SYSTEM

The polar oceans are key components of the climate system and home to unique ecosystems. As a consequence of these two factors, they also play an overproportional role in the global-scale marine biogeochemical cycles of major and trace nutrients. Anthropogenic climate change affects polar oceans and their ecosystems 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. Together with melting permafrost on land, this constitutes a perturbation of the polar area that is unprecedented over many millennia. The warming of the oceans will have global consequences through the acceleration of the melting around the boundaries of the ice sheets in Greenland and Antarctica, and as a consequence, their destabilisation and large contribution to sea level rise. The acidification will strongly stress marine calcifying organisms and hence disturb biodiversity, the microbial loop, viral shunt and 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.

Photo on page 18

The research vessel Akademik Tryoshnikov at the Mertz Glacier in East Antarctica, named after the Swiss explorer Xavier Mertz (1882-1913).

The science community of Switzerland is well positioned to make significant and substantive scientific contributions towards a better understanding in the following areas:

- Observational, data analysis and modelling studies into the role of the polar oceans in governing the marine biogeochemical cycles of major nutrients and metal micronutrients, since polar ocean processes strongly influence the global cycle of these nutrients;
- Paleoclimatic studies on marine sediment cores from the Southern Ocean to 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;
- Simulations using a hierarchy of ocean-carbon cycle models to provide a quantitative understanding of past changes and the current uptake of carbon and heat under anthropogenic climate change. Such knowledge is crucial for climate change projections and, more generally, for a better quantification of climate sensitivity.

The Antarctic Circumnavigation Expedition (ACE)

ACE was the first project carried out by the Swiss Polar Institute. From December 2016 to March 2017, 22 scientific teams from all over the world took part in this ground-breaking expedition aboard the Russian research vessel "Akademik Tryoshnikov". From biology to climatology to oceanography, the researchers worked in a number of interrelated fields as they sought to expand our understanding of the White Continent. In November 2016, during the Akademik Tryoshnikov's pre-expedition voyage from Bremerhaven in Germany to Cape Town in South Africa, ACE's starting point, the ship hosted the ACE Maritime University, under the auspices of the Russian Geographical Society. During this voyage, some 50 up-and-coming scientists attended onboard lectures and engaged in oceanographic work.

SEA ICE REDUCTION AND ITS IMPACT

Anthropogenic climate change has led to substantial loss of sea ice cover particularly in the Arctic, while in the Southern Ocean, sea ice is as yet comparatively little affected. Sea ice loss has far-reaching effects on polar marine ecology, productivity, species distribution and biogeochemistry. In the Arctic, large reductions of summer sea ice and a persistent loss of multi-year ice are observed. This opening of the Arctic in summer will increase the pressure through enhanced human activities in the region, such as commercial shipping, exploration, mining and geostrategic activities. In the area of sea ice research, Swiss scientists have contributed to internationally well-recognised research, primarily on the snow layer and its processes in the Arctic but also in the Southern Ocean around Antarctica. The snow layer on the sea ice cover determines the energy balance and therefore the dynamics of this component.

Photo on page 21

Work on invasive species on Possession Island in the Crozet Archipelago.

STRENGTH 4

Biodiversity and ecosystem functioning under climate change

Polar terrestrial and aquatic ecosystems are experiencing rapid changes in biodiversity and function, primarily as a consequence of amplified climate warming. The related increased precipitation, sea ice loss, permafrost degradation and natural hazards such as river flooding or receding coastlines, are expected to change landscapes and the marine system at a high rate across vast areas. Increasing human activities at the poles, including tourism, shipping and industrial infrastructure, will further induce disturbance and disruption to these vulnerable ecosystems. Changes in biodiversity and ecosystem structure have consequences for ecosystem functioning, with direct relevance to local societies, such as through fisheries and subsistence species for polar Indigenous communities.

The world beyond the poles will also be affected, through ecological teleconnections such as related to migratory species and through physical oceanographic teleconnections such as changes in low trophic level polar planktonic communities, which can have a major impact on the global marine nutrient cycling. Microbes and viruses play a profound role in the fate and biogeochemistry of carbon and nutrients, due to their high abundance and rapid turnover, yet the extent of their influence remains mostly unknown. The magnitude of the feedbacks from polar ecosystems on 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 address the above uncertainties through quantification of feedbacks between climate, vegetation, microorganisms and permafrost, by linking existing process understanding with predictions of biota 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 identification of areas for conservation of the unique polar biodiversity. These 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:

- 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.
- Prediction of species distributions and ecosystem functions in polar regions, based on statistical and process-based modelling.
- The relationship of phytoplankton, microbes and viruses to the biogeochemical cycling of micronutrients, such as iron and zinc, and the main nutrients, nitrate and phosphate, in the Southern Ocean.
- Response and adaptation of fish to extreme polar conditions and to the threat of climate change and pollution.

STRENGTH 5

Critical enablers

Beyond the thematic fields of excellence outlined above, Swiss polar science can count on the following crucial cross-cutting expertise, acquired through the experience of working in high-altitude environments:

TECHNOLOGY DEVELOPMENT

The high-latitude environment is a challenge for any measurement system as well as for general infrastructure and represents therefore an opportunity but also a necessity for technology development. Given the fact that environmental observations in polar areas are sparse, improved technology is a key ingredient for scientific progress. Two important areas for development are energetically self-sufficient infrastructure and measurement installations, and automated measurement systems that 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.

The Swiss science community in collaboration with industry is well placed 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 laboratory analytical techniques, as pioneered at Swiss research institutions, could be the single most important input to the 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, aeroplanes and drones provide access to remote areas and data of continuous spatial coverage across a variety of scales, and have, for example, revolutionised 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 choice for research on mass change and balance of the ice sheets and glaciers, 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 not only for 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 strong expertise in various fields, acquired to a large extent within the context of high mountain research. This is particularly true for fields such as architecture, material sciences, 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, infrastructure developments for high latitudes could benefit highly from close collaborations between academia and the private sector.

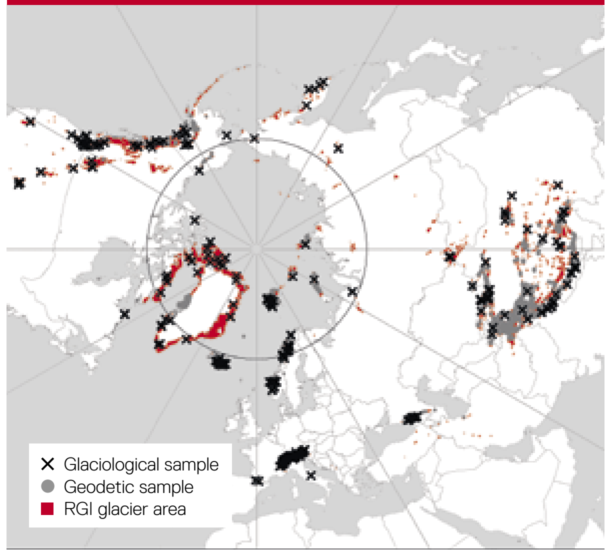
DATA MANAGEMENT AND MODELLING

The strong modelling and time series competence present in the Swiss science landscape coupled with a focus on data science benefits the Swiss polar community and should not be underestimated. Investigations of often complex, interdisciplinary and multi-dimensional datasets related to scientific activities in the field are already benefiting from a partnership with the Swiss Data Science Center (SDSC), using data from the Antarctic Circumnavigation Expedition as a case study. Furthermore, Swiss activities of the WGMS and Copernicus programme are both collecting and managing data from polar regions. 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. Climate observations are realisations of partly stochastic processes that have subtle and complex properties. Careful statistical analysis of these data, addressing the underlying stochasticity, is therefore needed for knowledge building.

World Glacier Monitoring Service

125 years of internationally coordinated glacier monitoring under Swiss leadership: The World Glacier Monitoring Service (WGMS), hosted at the University of Zurich, compiles and disseminates standardised data on glacier changes from in situ and remotely sensed observations through a worldwide scientific collaborative network. Currently, the WGMS database contains times series of more than 19,000 glaciers. Of these, about 20% are located above the polar circles. Glaciers distinct from the two ice sheets have lost more than 9000 billion tonnes of ice since 1961, raising sea levels by 27 mm. This loss corresponds to an ice cube with the area of Switzerland and a thickness of 30 m. The WGMS exemplifies the high international standing of Swiss expertise in glaciology and the ability to coordinate international monitoring efforts.

Locations of glaciological and geodetic data samples from the WGMS database and glacier areas in the Randolph Glacier Inventory (RGI). © WGMS



STRENGTH 6

Socio-cultural issues and socio-ecological systems

The pace of change experienced by Indigenous communities throughout the Circumpolar North, unprecedented over the past century, has even accelerated in recent decades. This can be linked to several combined influences, such as climate change, rapidly increasing economic exploitation, changes in governance, and the opening up to the global world. Many communities suffer from an array of difficulties and risks, ranging from health issues, food security, economic viability, poverty and unemployment to culture preservation, language maintenance and gender imbalance. To tackle such problems in a relevant manner, Indigenous people, who were previously seen exclusively as objects of study, increasingly play an active and often leading role at all stages of the research, starting from the identification of the research questions.

Photo on page 26

Sled dogs are a traditional form of transport in Greenland.

The recognition of the fact that social and ecological systems are inextricably linked has fostered new approaches involving natural and social sciences in inter- or trans-disciplinary research, often centred on the concept of resilience. This type of research, which represents a positive departure from the study of the human dimensions of rapid climate and environmental change, figures prominently on the agenda of social scientific research. In order for it to have proper relevance for communities in the Arctic, it must be placed into historical and societal context and perspective, putting people first.

Non-indigenous residents of the Circumpolar North are also affected by rapid change, and in some regions are in a state of demographic flux between the Arctic and more temperate regions. The immigration of transient workers needed to develop economic projects (e.g. dam construction) challenges local social equilibria, which should be taken into account in impact studies.

Social sciences and humanities (SSH) disciplines play an important role in the integration of natural science disciplines and as an interface between stakeholders, among them local communities. Outreach to the Arctic communities is essential to ensure that the findings of science are accepted and have an impact on policy. As such, the SSH may play an increasingly indispensable role in research, even when the main focus is on natural phenomena.

Social topics must also be approached from broader, global perspectives, ranging from developments in governance and security, including that of the Arctic Ocean (political science, law), to studies of the impacts of economic development, in particular the exploitation of non-renewable resources. The model of governance of Antarctica is not immutable either, and its evolution must be monitored and anticipated.

Correlates with contemporary social issues in Alpine regions are relatively few, as settled areas of the European mountains are situated at maximum altitudes that barely compare with the extreme environments of the Far North. Nonetheless, comparisons today may include topics such as dealing with the consequences of melting permafrost, above-average rate of warming, and viability of remote communities in the face of outmigration and rising costs of infrastructure maintenance. The mountain research community can contribute to and benefit from inter- and trans-disciplinary co-design and collaborations on the topic of human adaptation in extreme environmental settings, and further develop this expertise and experience also for Switzerland.

Through archaeological and anthropological studies of long-term human adaptation, a few Swiss researchers have distinguished themselves internationally throughout the 20th and now at the beginning of the 21st century. Switzerland, as a global economic player, as an Observer in the Arctic Council and as a signatory of the Antarctic Treaty, has a strategic interest in better understanding the developments in the Arctic and in the Southern Ocean and Antarctica from social scientific perspectives. Through the international engagement of researchers in projects involving Indigenous participants and communities, and Swiss representation on the International Whaling Commission (IWC), as well as through the contacts of Swiss museums with Arctic artists and communities, Switzerland has generated goodwill among Indigenous governance bodies, including the Permanent Participants of the Arctic Council. This precious capital should be maintained and developed.

Photo on page 29
© François Bernard

Mertz Glacier in East Antarctica, visited during the ACE expedition in 2016-2017.

3

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, and high-altitude extreme environments. While the immediate emphasis is on polar science questions and their impacts on polar communities, comparative studies in high-altitude areas in support of polar science questions are also an important strand of a Swiss polar science strategy.

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 that enable Swiss polar science to play a leading role in international research efforts.

The Swiss polar community proposes four thematic "Flagship Topics" in which to launch its own scientific initiatives, and strengthen participation in international programmes and networks up to 2025 and beyond.

To increase its impact and contribute decisively to tackling global scientific challenges relating to extreme environments, the Swiss polar community proposes four thematic "Flagship Topics" in which to launch its own scientific initiatives, and strengthen participation in international programmes and networks up to 2025 and beyond.

In these Flagship Topics, SPI could play a crucial role by supporting logistics and coordinating research initiatives or expeditions, and by funding research programmes in a complementary way to the Swiss National Science Foundation or other funders.

This would help to raise the profile of the Swiss polar community internationally, and make a difference in major current and upcoming scientific questions.

FLAGSHIP TOPIC 1

Cryosphere through time – Processes, feedbacks and responses

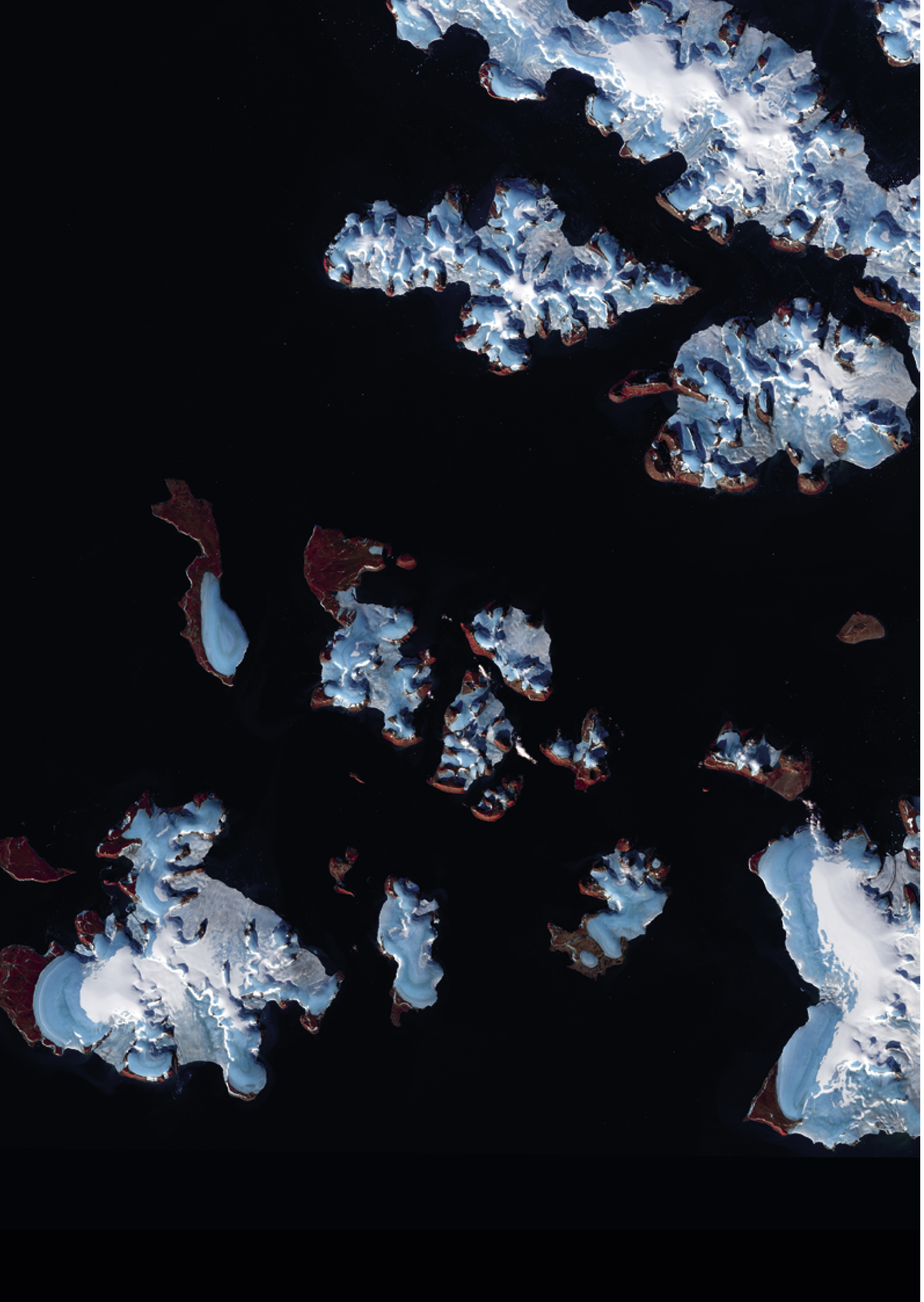
Ice sheets, polar and high mountain glaciers, the snowpack and permafrost respond sensitively to the on-going global warming. Albedo changes related to snow, sea ice and glacier retreat as well as dynamical responses of ice sheets, ice shelves and glaciers are some of the most important feedback processes 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 CO_2 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 already very likely to occur 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 require an answer:

- **What are the short- and long-term responses and the controlling processes of glacier, ice sheet and ice shelf changes to warmer climate boundary conditions, and is there a threshold for ice sheet disintegration that can be avoided by mitigation measures of anthropogenic global warming?**
- **Can we improve the estimate of the Earth system sensitivity using novel polar and high-altitude climate archives that extend our record towards warmer climate intervals than today (e.g. with higher CO_2) and by using improved quantitative climate proxy information from these archives?**
- **What is the coupling and interaction of land ice, ocean circulation and atmospheric CO_2 on decadal to multi-millennial time scales and, in particular, what natural greenhouse gas cycle feedbacks (e.g. 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-altitude ice cores (see also chapter *Snow, glaciers and ice sheets* on page 12), major progress in answering these questions can be accomplished within the coming 5-10 years. This could notably include the following research activities by the Swiss community:

- **Providing observation-based process understanding of glacier and ice sheet mass balance changes, including 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 should be achieved by integration of field studies in Greenland and Antarctica with the comprehensive Swiss expertise in climate and glacier modelling and remote sensing.**
- **Better constraining Earth system sensitivity and the natural climate / greenhouse gas coupling by extending the paleo record from polar ice cores up to the last 1.5 million years. This will provide unrivalled 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 influence the mass balance and energy exchange between glacier and ice sheet surfaces and the atmosphere.**
- **Securing precious ice core material from high-altitude glaciers that are highly endangered by global warming and glacier melt, and 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 for successfully achieving 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 provided by the SPI on a case-by-case basis, thus avoiding the high costs of SPI becoming an independent polar logistics provider.



FLAGSHIP TOPIC 2

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 future anthropogenically influenced climate changes. These cycles link the Earth system compartments, i.e. the biosphere, land, ocean, ice and atmosphere. While there are important research questions 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:

- How important are Southern Ocean freshwater fluxes for ocean stratification and circulation, (micro)nutrient budgets and uptake of heat and CO_2?
- How relevant is long-range atmospheric transport for Arctic clouds and air pollution?
- Can comprehensive Earth system models help assess the relevant processes that drive the past, present and future evolution of the carbon, nitrogen and water cycles?

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

- A Southern Ocean campaign to study the role of freshwater fluxes for CO_2 uptake and (micro)nutrient inventories 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 processes involved can be studied with a dense network of ARGO floats in the Ross or Weddell Seas, combined with a ship campaign with supply ships from the USA and New Zealand, and mesoscale ocean-atmosphere-ice modelling. Such an initiative would strongly profit from the development of novel sensor techniques.

Photo on page 34
© WGMS

Melting glaciers in Russia's Arctic territory. This image, recorded by the Sentinel-2 satellite on 12 September 2017, shows the blue glaciers on the reddish-brown Franz Josef Land archipelago north of the 80th parallel in the Arctic Ocean (black). The glaciers (blue) are covered with little or no snow (white), which is a clear indicator of significant loss of mass. Source: Copernicus Sentinel data 2017.

- Dedicated field experiments to investigate the role of long-range atmospheric transport for polar 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 field campaign with aircraft and ships, strongly supported by the Swiss polar research community and its expertise in atmospheric transport, cloud microphysics, aerosol-cloud interactions, radiative effects and biogeochemistry, would be a rewarding step forward in specifically addressing the importance of long-range transport from densely populated areas to remote polar regions.

- Development of a coupled Earth system model to study the long-term evolution of CO_2, N_2O, 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 utilise the high-quality numerical modelling 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 modelling activity would include:

- A strong link to the ice core community.
- The efficient implementation of high-resolution modelling options in collaboration with the Swiss National Supercomputing Centre.
- 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 realise these challenging research ideas. Swiss researchers could for instance contribute to major international initiatives that aim at modelling a complete glacial cycle with comprehensive Earth system models (PALMOD), or at understanding and advancing our ability to predict the frequency of occurrence and intensity of environmental extremes (ExtremeEarth). 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 proposed activities.

Photo on page 37

Benthic organisms of the Southern Ocean play an important role in carbon cycling processes and hence as climate regulators.

FLAGSHIP TOPIC 3

Biodiversity and ecosystem functions

Triggered by climate warming, alpine, Arctic, and Antarctic biodiversity has experienced rapid changes over the past decades. These changes impact resources used by 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:

- **What is the legacy of past climatic fluctuations on current biodiversity and the related constraints on future ecosystem responses?**
- **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?**
- **What are the consequences of polar biodiversity and functional ecosystem 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 and freshwater and marine systems (see also chapter *Biodiversity and ecosystem functioning under climate change* on page 22).

A breakthrough in the prediction of biodiversity and ecosystem functions can be made in the coming 5-10 years by integrating this expertise in the development of a spatial process-based ecosystem model. This model will consider 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 areas of research and related outcomes:

- **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 the main present-day drivers of biodiversity and ecosystem change, and quantify effects on fluxes of energy, water, carbon and other biogeochemicals across the terrestrial, freshwater and marine domains.**
- **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 aspects form a major contribution to the international science and policy agendas of polar regions (IASC and SCAR) but also globally (IPCC, UN Convention on Biological Diversity, Group on Earth Observations Biodiversity Observation Network, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IWC).

The 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. fieldwork, databases and expensive measurements, such as metagenomics, tracers and drones), 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.

FLAGSHIP TOPIC 4

Technology in extreme environments

Both polar and high-altitude regions still contain unexplored environments whose scientific and practical importance has yet to be determined. The extreme polar and high-altitude environments are a challenge for any measurement system, as well as for general infrastructure, and offer therefore an opportunity for technology development (see also chapter *Critical enablers* on page 24). Given the fact that environmental observations in polar regions are sparse, improved technology is key for scientific progress. Two important areas requiring development are firstly, energetically self-sufficient infrastructure and measurement installations, and secondly, automated measurement systems that will work in remote regions with extreme environments. In both fields, Switzerland has strong expertise as exemplified by 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 extreme environments. Some key challenges include:

- **Technologies for analysing subglacial environments without contamination.**
- **New sensor development to shrink labs onto a chip the size of a small coin. Complementary metal-oxide-semiconductor, electrochemical, field effect transistor, radiofrequency, mechanical and optical sensors have been integrated with lab-on-a-chip devices for on-chip sensing.**
- **Novel technologies for extracting core samples (e.g. from ice sheets and glaciers, lake sediments, deep permafrost sediments).**
- **Autonomous measurement platforms for atmospheric research and small-scale meteorological monitoring networks (e.g. miniaturisation of sensors, low power consumption, efficient power storage during polar winter), and remote control of experiments.**
- **Year-round autonomous observational and experimental platforms (e.g. ground-penetration robotic radar vehicle, laser-guided data transfer to satellite).**

REMOTE SENSING, DRONES AND OTHER UNMANNED VEHICLES

Remote sensing observations from satellites and aeroplanes 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 available today in abundance for these remote areas. They need to be merged with the in situ field data for calibration and augmented with high-resolution drone measurements to increase the granularity of geographical coverage. Swiss solar-powered flying platforms have been tested in polar regions by measuring glaciers and are becoming a primary application, as the midnight sun offers ideal conditions for perpetual flights. Miniaturisation of sensors (e.g. 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 study of the causes of Arctic climate change, as they provide an insight into ground-level air layers that are not monitored by measuring stations. Drone imagery acquisition following standardised protocols forms the backbone for upscaling from in situ plot to pan-Arctic scale, in order to assess and understand vegetation development, biodiversity, snow and permafrost dynamics, and the related carbon and energy fluxes of the highly heterogeneous polar terrestrial landscapes and coastal areas. However, satellite technology is improving fast and can deliver high-resolution products. Automatic process chains are already available or on the way. Switzerland is fully involved in these activities (e.g. European Space Agency Climate Change Initiative, Copernicus Sentinel) and continues to be a key player in applying these new technologies.

Future activities in which the Swiss community could have a high impact include the following developments:

- Scalability and limited risks for drones.
- Efficient and cost-effective observation methods.
- Drone flight software for repeat surveillance and monitoring in remote regions.
- Smart drones for field testing new sensors.
- 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 research groups and industry. SPI could play an important role in facilitating this.

MODELLING AND DATA SCIENCE

Simulations with complex computer models are now central to obtaining reliable projections of 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 to explore 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 designing data science tools, could also benefit the Swiss polar community, especially in probing new interdisciplinary questions.

4

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 plan highlights the high degree of international collaboration needed in order to pursue Swiss research in these regions. This is due to the very complex logistics needed to support such research, the difficulty of obtaining access to polar regions as well as the need to share the high costs incurred through the technology and logistics involved.

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

In its "Antarctic and Southern Ocean Science Horizon Scan", SCAR used a worldwide consultation and an international panel to identify 80 key questions covering all aspects of science. IASC undertook a similar exercise for the Arctic, resulting in a report entitled "Integrating Arctic Research – a Roadmap for the Future", with a much greater emphasis on linkages of the physical and biological systems with society.

On the one hand, the development of new international research programmes by both SCAR and IASC, centred on 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 large existing overlap of the SCAR and IASC science plans 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 Swiss 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.

The Swiss priorities outlined above align almost perfectly with the international agenda and key topics identified for both poles.

Switzerland is currently playing a constructive collaborative role in international initiatives. Support by the SPI notably enables Swiss groups to be present in significant international initiatives, for example Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC; 2019-2020) or Ice Memory.

As yet, no attempt has been made to consolidate the relevant questions for high-altitude areas globally. With no single international organisation taking responsibility for the high-altitude 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.

5

Looking to the future

Making a difference for the Swiss polar community

SPI has an important role to play in supporting the diverse polar research community in Switzerland, in strengthening Swiss polar science and in promoting synergies. To complement the scientific strategies outlined above, the following goals and initiatives have been identified as priorities up to 2025 and beyond.

- Build a strong and cohesive community as well as support scientific exchange and outreach on polar-related topics (including conferences, teaching programmes, dedicated scientific workshops, support of visiting lecturers at Swiss universities, exchange with international polar organisations and structures supporting young polar researchers, such as the Association of Polar Early Career Scientists).
- Offer training and logistical support for the organisation of research expeditions and fieldwork in extreme environments (including health and safety training and support, checklists, coaching and advice).
- 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 SDSC.
- Fund fieldwork, logistics, technological developments and short-term opportunities for Swiss polar researchers in all fields of research, with a particular emphasis on early career researchers, to complement science funding from sources such as the Swiss National Science Foundation and the EU Framework Programmes.
- Launch and manage medium- to large-scale research expeditions (notably by funding the project management, logistics and coordination) and contribute to large-scale international programmes and initiatives related to the Flagship Topics 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 Swiss research about and in polar regions, the founders of the SPI are working towards establishing the SPI as an institution co-funded by the Swiss Confederation for the period 2021-2024. Such anchoring would not only enable SPI to offer sustainable support to researchers all over Switzerland but also to launch initiatives and expeditions for and by the Swiss research community.

The founders of the SPI are working towards establishing the SPI as an institution co-funded by the Swiss Confederation for the period 2021-2024.

This Science Plan will remain a living document to match the evolution of the Swiss polar community. In the short term however, this document will play 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 Swiss Polar Institute – Supporting the Swiss polar science landscape

The Swiss polar science landscape is very diverse, with scientific activities spread over more than 13 academic institutions (see map on page 10) and covering 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 government on matters related to polar issues.

The SPI was founded in 2016 in order to offer new opportunities and funding to all researchers based in Switzerland who work in the polar regions.

SPI works very closely with the SKPH, which is responsible for sending Swiss representatives to SCAR and IASC and their scientific working groups. Furthermore, since Switzerland received Observer status in the Arctic Council in 2017, the Swiss research community is also encouraged to contribute and strengthen expert knowledge at the level of the Arctic Council's Working Groups, Task Forces and Expert Groups. However, in contrast to many other countries, Switzerland has traditionally had no central polar research institute or logistics provider, limiting the activities of excellent Swiss scientists to the remote and inaccessible polar areas.

The SPI was founded in 2016 in order to offer new opportunities and funding to all researchers based in Switzerland who work in the polar regions. It works to support the bottom-up nature of polar science performed in Switzerland and the multi-institutional approach covering many polar research areas.

The SPI is currently funded by its founding members: Swiss Federal Institute of Technology in Lausanne (EPFL), Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Swiss Federal Institute of Technology in Zurich (ETHZ), University of Bern, and the Editions Paulsen. The SPI Secretariat is in charge of daily work and implementation. The SPI 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.

SPI has successfully generated a new dynamic within the Swiss Polar community.

SPI activities and calls are open to the entire Swiss research community. The SPI has launched dedicated funding calls to complement existing opportunities and to fill gaps linked to the specific needs of polar science. The Polar Access Fund offers funding for young researchers 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 polar research projects. 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 the SPI mission. In 2016-2017, SPI organised the Antarctic Circumnavigation Expedition (ACE), which took 22 international scientific projects on a three-month expedition to collect samples and data (oceanographic, terrestrial, atmospheric and cryospheric) from the Southern Ocean, sub-Antarctic islands and the Antarctic continent. A similar SPI circumnavigation expedition around Greenland is planned for the near future. Other expeditions as well as the logistical and financial support of Swiss scientists to lead or contribute to major international research expeditions at the three poles (the Antarctic, the Arctic and high-altitude regions worldwide) are foreseen, depending on future funding of SPI.

SPI has successfully generated 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 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.

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