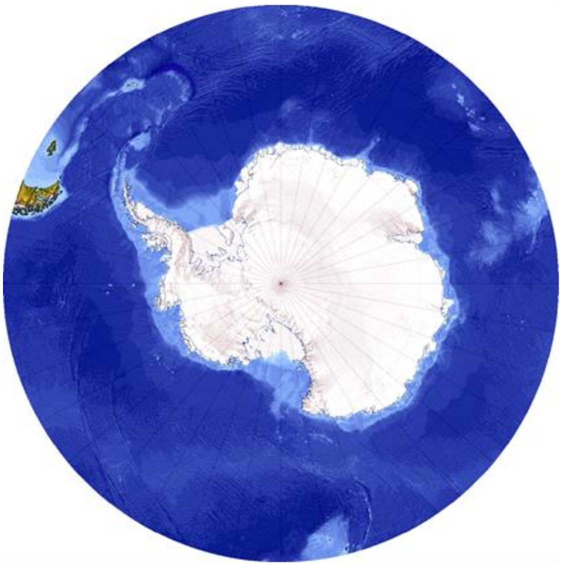
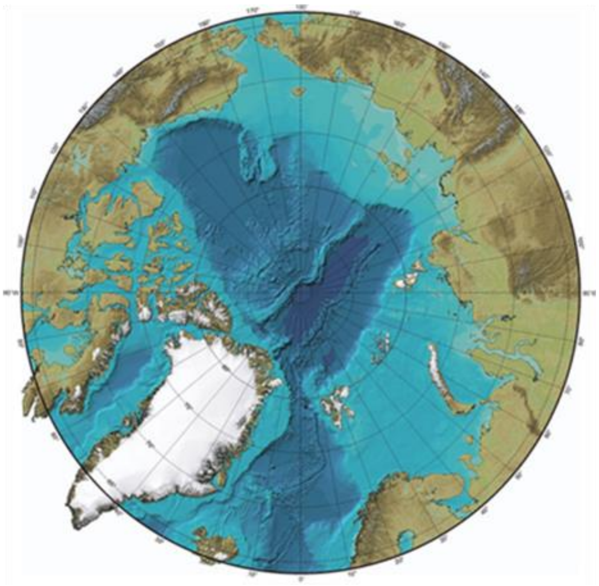
Renewal Proposal 2025-2030

Infrastructure Priority Program of the German Research Foundation
(DFG SPP 1158)

"Antarctic Research with Comparative Investigations in Glaciated Areas of the Arctic"





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DFG-SCHWERPUNKTPROGRAMM 1158
ANTARKTIS FORSCHUNG
mit vergleichenden Untersuchungen in arktischen Eisgebieten

March 2023

3 Concept and Goals for the Funding Period of the SPP Renewal (2025 – 2030)

The funding period of the SPP 1158 ends on 31st Dec. 2024. Considering the still existing and often increasing demand by German university and non-university groups to carry out polar research, and its special and unique dependency on a coordinated approach with utilization of the excellent logistics provided by AWI, BGR and DLR, we see the compelling necessity to renew the current SPP for six more years, starting on 1st Jan. 2025.

The Antarctic research strategy of the SPP renewal proposal is closely aligned to the research questions and national priorities outlined in the BMBF Mare:N Research Agenda “POLARREGIONEN IM WANDEL” published in 2021, and the DFG Polar Research Agenda 2030 published in 2017, both of which have been compiled with strong SPP community member input. The main agenda for the future SPP Antarctic research program is based on the international science community strategy outlined by SCAR, where many SPP community members participate, lead working groups or act as expert referees. For this renewal proposal, we based the assessment of our focal themes and contributions to the international community on foresight processes around “The 80 most important scientific questions as identified by the 1st SCAR Antarctic and Southern Ocean Science Horizon Scan”; the “Antarctic Climate Change and the Environment – a Decadal Synopsis and Recommendations for Action”; and the “SCAR Strategic Plan 2023–2028: Antarctic and Southern Ocean Science and Policy Advice – communicating Urgent Messages from the South”, which are central to the UN (“United Nations Decade of Ocean Science for Sustainable Development: Southern Ocean Action Plan”). Furthermore, our research foci are aligned with the WCRP (World Climate Research Program) Strategy (2019–2028) and the identified tasks in the climate assessment reports of the UN Intergovernmental Panel on Climate Change (IPCC).

In 2022, the SPP coordinators distributed a questionnaire among the SPP community to identify important research questions in the coming decade. Finally, all external and internal research questions for the SPP renewal proposal have been discussed and prioritized during three expert workshops in Bremen (1st Dec. 2022, 6th and 7th Feb. 2023). The scientific focus thus defined is not exclusive, and the program is open to additional Antarctic research questions.

The research topics chosen for the new SPP phase are of utmost importance to advance our understanding of the role of Antarctica in the Earth System. The research questions outlined in this proposal are designed to expand the current Antarctic expertise in the German scientific community, to attract established and new university and non-university scientists to realize research in the polar regions, and to foster innovative interdisciplinary methods for the next decade of research activities. We expect that the new SPP phase will result in significant, internationally visible and excellent contributions to top Antarctic research priorities, and will further strengthen the position of German polar science in the international research community.

3.1 Overall Conceptual Design

In the current SPP period, the conceptual design is structured around four overarching transdisciplinary research questions which can be regarded as highly successful. For the next SPP phase we propose to focus the research by strengthening two of the most successful transdisciplinary research topics from the current SPP phase (“Dynamics of Climate System Components”, “Response to Environmental Change”) along with the crosscutting research topic “Improved Understanding of Polar Processes and Mechanisms” (**Fig. 3.1**). The overarching topic “Linkages with Lower Latitudes” will be replaced by “Connectivity and Exchange in Polar Systems”.

- ***I) “Dynamics of Climate System Components”***
- ***II) “Response to Environmental Change”***
- ***III) “Connectivity and Exchange in Polar Systems”***
- ***IV) “Improved Understanding of Polar Processes and Mechanisms”***

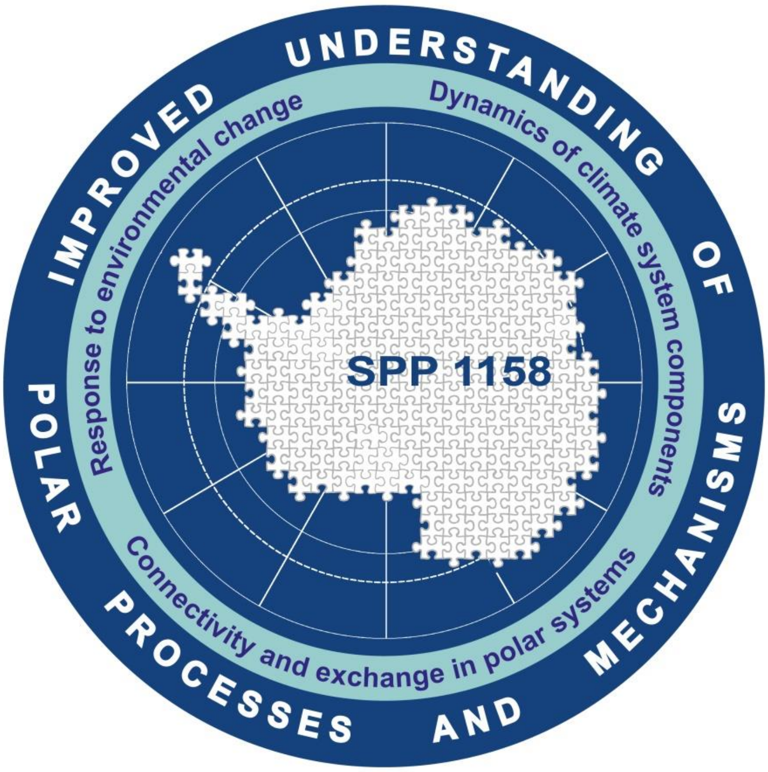

Fig. 3.1: New SPP logo with the overarching transdisciplinary research topics for the next SPP phase 2025-2030 concerning the role of Antarctica in the Earth System.

The SPP also addresses research questions related to the geological evolution of the Antarctic continent since the time (~34 Ma) when it became completely isolated from other continents, a circumpolar current established and the Antarctic Ice Sheet began to develop. Hereby, geological processes and structures that provide a boundary condition or feedback to the evolution of the ice sheet will be studied.

3.2 Scientific Goals

3.2.I Dynamics of Climate System Components

The Earth climate system, and particularly that of Antarctica, is not in steady state, as observations and model results clearly show. The dynamics of the Antarctic climate system shape Antarctica’s unique ecosystems, revealing spatial and temporal variability on different scales (seasonal, annual, decadal to millennial). So far it is still not fully understood, which of the variations are induced by natural or anthropogenic changes and how they influence the present and future Antarctic climate and the polar ecosystems. In the last decades the extent of Antarctic sea ice did not change much, but now, in the austral summer 2023, unexpectedly a massive decrease was observed (https://www.tagesschau.de/ausland/amerika/klimaantarktis-wissenschaft-101.html), which could impact the availability of krill as the main food source in polar ecosystems.

The state of stability of the Antarctic Ice Sheet is one of the largest uncertainties both in past climate reconstructions as well as in projections (IPCC 2021). Recent studies summarize multiple climate tipping points when global warming exceeds 1.5°. The West Antarctic Ice Sheet and the Greenland Ice Sheet are already retreating and partly collapsing while the East Antarctic Ice Sheet and some marine-based parts of the East Antarctic Ice Sheet are expected to destabilize when global warming exceeds 3 to 4°. Warming of the Antarctic realm is expected to have multiple effects on the ice sheet: an increase in snow precipitation, surface melt and oceanic heat triggering changes in ice shelves that are buttressing the ice sheet. However, the underlying physical processes are not yet fully understood and may further change as warming progresses, potentially leading to enhanced ice-shelf disintegration and substantial sea-level rise.

Therefore, one aim of the new SPP phase is to quantify past, present, and future dynamics of the Antarctic ice sheet to better understand its contribution to sea-level rise, by identifying the key drivers and by improving the underlying processes by observations and models.

3.2.I.1 Atmosphere - Cryosphere - Ocean Interactions

Current knowledge and research gaps

The physical and chemical interactions between atmosphere, cryosphere, and ocean and their feedback mechanisms are in a fine-tuned balance on regional scale. Yet, modeling studies identify the interfaces of these system components as highly sensitive to global climate variability, thus requiring an interdisciplinary approach to better understand the unique and complex interactions between the different compartments which are triggered by synoptic weather systems and mesoscale weather phenomena such as katabatic winds. Open water and thin sea ice areas, associated with winter polynyas in the coastal areas, represent a significant energy source for the atmosphere and foster the formation of saline water masses (High Salinity Shelf Water, HSSW). HSSW is responsible for circulation, melting and dissolution processes underneath ice shelves, thereby transforming HSSW into Ice Shelf Water (ISW). Both HSSW and ISW are precursors of Antarctic Bottom Water (AABW) which is exported into the world oceans. AABW is a major component of the Meridional Overturning Circulation (MOC). Thus, it directly links the sea ice formation on the Antarctic continental shelves to the global ocean as well as to the carbon and other important biogeochemical cycles. AABW has already become older and has warmed in the last decades, but most likely not by near-surface processes but by entraining warmer and older Circumpolar Deep water when descending at the Antarctic continental shelf to the bottom. The sensitive balance between atmospheric forcing and a continuing freshening of the ocean’s surface can significantly impact the AABW production with direct global consequences. Important factors are enhanced sea ice- and ice shelf meltwater, changing ocean currents, and transport by mesoscale eddies, all impacting physical, chemical and biological characteristics in Antarctica.

Another poorly understood process in Antarctica is the aerosol – cloud – climate interaction, as it is one of the most difficult components to model, due to difficulties in obtaining sufficient accurate measurements. Therefore, more knowledge on the quality and quantity of ice nucleating particles and cloud condensation nuclei is required, because they influence cloud formation and their radiation properties, with consequences for the energy budget of Antarctica. The chemical composition of aerosols, the processes underlying the transport of marine organic/inorganic compounds from the Southern Ocean into aerosols and the degree to which these processes are climate-relevant or are affected by climate change have not yet been studied in Antarctica.

Key research questions for the new SPP funding phase

1) *How do formation, propagation, and variability of leads and polynyas affect the trace gas and particle exchange between the ocean and the atmosphere?*
2) *Why and how are the properties and volumes of Antarctic Bottom Water and other Antarctic water masses changing, and what are the consequences for global ocean circulation and climate?*
3) *How can the interaction between ice-shelf cavities and warm water better understood and parameterized in models?*
4) *What are the sources, sinks, and vertical distribution of aerosol particles initiating condensation and freezing processes in the atmosphere and how does the aerosol abundance and spatio-temporal distribution change in a changing Antarctica?*
5) *How do changing cloud and precipitation properties impact the radiative budget, the coupled ocean-atmosphere system, the cryosphere, and Antarctic ecosystems?*
6) *Will there be a release of greenhouse gases stored in Antarctic and Southern Ocean clathrates, sediments, soils, and permafrost as climate changes?*

3.2.I.2 Ice Sheet Dynamics and Mass Balance

Current knowledge and research gaps

The Antarctic Peninsula ice shelves are thinning, retreating, losing volume, and suffer collapse, as reflected in the calving of A68, a 5,800 km^2 iceberg that shed in July 2017 from the Larsen C Ice Shelf. Despite the significant impacts such events have on glaciology, physical oceanography, biogeochemistry, and the structure and function of surrounding ecosystems, significant knowledge gaps still limit our understanding of ice-shelf systems and dynamics, and of processes leading to ice-shelf demise.

The mass loss of the Antarctic Ice Sheet is a major source of current sea-level rise and is accelerating rapidly. Yet, its future sea-level contribution is the most uncertain element in global sea-level projections. This is due to the lack of understanding of the underlying processes, in particular of ice-flow dynamics associated to ice-ocean interaction but also of surface mass balance and its interaction with flow dynamics. The use of different geogenic and glaciogenic archives and state-of-the-art ice-sheet models is of major importance for the understanding of the history and causes of regional differences in ice-sheet dynamics.

During and after the collapse of ice shelves, scientific studies typically are delayed by years owing to variable sea ice conditions, logistical and infrastructural issues, and not least funding delays. Warm water penetrating onto the continental shelf break carries heat that accelerates ice-sheet mass loss at the Antarctic Peninsula. Current models indicate that similar mechanisms are at play in other areas of Antarctica. So far, this warm water intrusion onto the shelves towards the ice shelves can be blocked by dense water formation on polynyas (dense HSSW formation) and by basal glacial melting (dense ISW production), as documented, for example, for the Filchner-Ronne Ice Shelf (FRIS) in the southern Weddell Sea (‘dense shelf regime’). A comparison of the 2018 conditions with those surveyed earlier since the 1980s indicated that, in spite of climate change and in contrast to other Antarctic regions, the water masses on the southern Weddell Sea shelf remained relatively stable overall. Most of the stations near the Filchner Ice Shelf edge were dominated by cold ISW, which forms when water masses (mainly HSSW) interact with the underside of the shelf ice. However, HSSW-formation depends on surface forcing and on sea surface properties impacting stratification. Local changes in sea ice formation or glacial melt distribution can be expected under continued warming, and this might negatively impact the dense water production on the southern Weddell Sea continental shelf and thus weaken the oceanic protection of the FRIS.

The development and dynamics of the Antarctic Ice Sheet will be a major research target for the next SPP phase. This includes geological time-scales over the last 34 Ma that are archived in sediment deposits on land, in periglacial lakes, on shelves and the deep-sea of the Southern Ocean. Such knowledge is necessary for predictions of the future climate. It is still not clear how small-scale morphology in subglacial and continental shelf bathymetry affect the Antarctic Ice Sheet response to changing environmental conditions. Furthermore, the processes and properties that control the shape and flow of the Antarctic Ice Sheet have to be studied. This includes geothermal heat flux, sediment distribution and change in topography/morphology in subglacial and continental shelf bathymetry.

Finally, Antarctic (basal) meltwater inventories, ice shelf melt rates, and their contribution to the AABW formation, their subsequent circulation and contribution to the meridional overturning ciculation, and – in particular – their variability in response to environmental and climate change are poorly understood and have not been extensively studied by direct observations.

Key research questions for the new SPP funding phase

1) *How will basal melting of Antarctica’s ice shelves develop under changing circulation and variability of water masses on the shelves and vice versa?*
2) *Is there a temperature threshold that leads to the irreversible loss of parts or even the entire Antarctic ice sheet?*
3) *What is the present-day ice mass balance, and how can observations contribute to fundamentally improve accuracy, resolution, and duration?*
4) *How does sub-glacial and ocean-bottom topography affect the response of the Antarctic ice sheet to changing environmental conditions?*

3.2.I.3 Southern Ocean as a Carbon Sink

Current knowledge and research gaps

The Southern Ocean serves as a major reservoir and conduit for natural and anthropogenic trace gases that play a crucial role in climate change, such as methane, and most importantly, carbon dioxide. Fluxes of these trace gases are very variable in space and time. With regard to the carbon cycle, the debate is ongoing whether the sink for atmospheric CO_2 is diminishing due to climate change (e.g. by changing or zonally shifting wind fields, changing sea ice cover etc.) and if so, whether this process will continue. Up to now, the physical pump is responsible of the oceanic uptake of anthropogenic CO_2, but the role of the biological pump may contribute significantly under global warming. Therefore, global and Antarctic climate research needs a better understanding and quantification of the physical, chemical and biological mechanisms of the exchange of CO_2 between the Antarctic Ocean and the atmosphere. Ocean-atmosphere gas exchange is limited by the (variable or even shrinking) sea ice cover. Carbon export by deep and bottom water formation, particularly at the ocean margins ('breathing windows' of the deep sea), and Antarctic Intermediate Water (AAIW) formation in the Antarctic Circumpolar Current (ACC) is crucial for the CO_2 and nutrient budgets of the Southern Ocean.

For the carbon cycle, the efficiency of the "biological pump" is a key factor for sequestration of carbon from the atmosphere to the sea floor. As a result of Southern Ocean warming a transition of large unicellular diatoms to smaller phytoplankton (flagellates) is predicted, with unknown consequences for carbon sequestration. In addition, micronutrients (e.g. iron), ice cover, and light regime critically influence plankton species dynamics, thereby affecting carbon and nutrient vertical export. The far-reaching consequences for primary production, interactions between key species and the food web structure as well as for biogeochemical cycles and ecosystem services must be explored on different spatial and temporal scales.

Besides research on key species, a wide multi-disciplinary community analysis is needed to adequately evaluate the current and previous community composition and biodiversity. Key species might shift, mass occurrences or an invasion of new and potentially harmful species with consequences for trophic interactions might happen. Also all vertical habitats, such as the sea ice, the upper water column, the pelagic and benthic realm should be considered.

The origins, properties, ecological functions and distributions of organic molecules in Antarctic water masses, as well as processes affecting their transformation at the intersections with sediments, the cryosphere and the atmosphere, are poorly recorded and understood. We lack fundamental knowledge of such molecules as biogeochemical proxies and mediators of biotic interactions. This knowledge is crucial, especially in a changing Southern Ocean. Today, this region is a strong carbon sink, particularly in summer. However, in contrast to previous belief, the biological carbon pump is not "switched off" in winter, enhancing the role of the Southern Ocean on the global carbon cycle.

Increased knowledge and understanding of chemo-ecological species interactions rendering the efficiency and magnitude of primary production is of very high relevance, namely among planktonic eukaryotes and prokaryotes. As primary production is tightly linked to carbon flux, we urgently need better understanding how climatic change in the Southern Ocean affects the efficiency of the biological pump and thus organic carbon flux to the sea floor (marine snow). To assess, evaluate and model the sensitivity of the biological pump in the Southern Ocean to climate change, improved simulation models for three-dimensional circulation of CO_2 on various spatial scales are required. Since physiological, ecological, and biogeochemical relationships and feedback loops are not well understood and covered in polar-ocean models, additional research is needed with regard to pelagic and benthic primary production and to the processes that determine the fate of this biologically bound (blue) carbon in Southern Ocean food webs, as well as to finally evaluate how much carbon reaches and is stored in the deep ocean. This requires a methodological array of field observations and reconstructions on seasonal to geological time scales, experiments with Antarctic key species under controlled conditions, as well as synthesis of individual studies and modeling. Such multi-disciplinary approaches will improve our understanding as well as to better predict the influence of physical and biogeochemical processes on CO_2 uptake, its change under increasing warming scenarios, and its integration into Earth system models.

<u>Key research questions for the new SPP funding phase</u>

1) *How much CO_2 (particularly anthropogenic CO_2) is taken up by the Southern Ocean (past, present, future) and which processes and interactions are the most relevant?*
2) *How do physical and biogeochemical processes interact with the biological pump?*
3) *What are the effects of changed Southern Ocean dynamics on the biodiversity, primary and secondary production?*
4) *What are the positive and negative feedbacks caused by environmental shifts in terms of carbon sequestration, nutrient fluxes, and energy flow?*
5) *Will changes in the organic particle flux to the sea floor affect pelagic and benthic biotas?*

3.2.I.4 Sea Ice – Biota Interactions and Associated Biogeochemical Cycles

Current knowledge and research gaps

The sea ice cover in the Southern Ocean represents a major habitat for all biotas living on top, underneath and inside the ice. Sea ice accelerates drifting icebergs, serves as a base for snow accumulation, has the potential for CO_2 sequestration by fostering biological activity and is involved in many biogeochemical processes. Sympagic biota (organisms that are living associated with the sea ice for at least a part of their life cycle) include all components of the food web, ranging from bacteria to mammals. The key organism in the Southern Ocean ecosystem is the crustacean krill, which forms massive swarms. In winter, they feed mainly on ice algae attached to the bottom of the seasonal sea ice. The Antarctic Peninsula, a key breeding ground for krill, is one of the fastest warming places worldwide. Warming results in a decrease in the winter sea ice cover and declining krill stocks with drastic consequences for higher trophic levels such as fish, seabirds, and mammals. Early developmental stages of krill require the rough sea ice bottom layer to evade predators and to feed on nutritional-rich diatoms (ice algae). In the years of low sea ice conditions krill tend to be replaced by free-floating filter feeding salps, which expanded their biogeographic distribution and abundance.

However, at the ecosystem level, the response and resilience to environmental change is largely unknown for most Antarctic organisms, which prevents accurate forecasting of potential impacts. Therefore, the physical and biogeochemical processes associated with sea ice and snow cover, and their variability through historical and geological times, need to be further investigated in order to better understand and quantify the role of polar sea ice in the global climate system as well as for atmospheric conditions and in Antarctic ecosystem functioning.

Key research questions for the new SPP funding phase:

1) *Which species are winners or losers of declining sea ice conditions and what are the ecological and biogeochemical consequences of changing communities?*
2) *How do changes in sea ice extent, seasonality and properties affect biogeochemical processes?*
3) *Which are the important chemical “currencies” and chemo-ecological processes involved in reciprocal interactions of sea ice primary producers and their associated organisms (bacteria, fungi, viruses)?*
4) *How does the presence and absence of sea ice influence particle production, thereby affecting atmospheric conditions, radiative budget and precipitation patterns?*
5) *Which aerosol particles are produced by biogeochemical and physical processes in ice-free and ice-covered ocean and are they relevant for cloud processes?*

3.2.II Response to Environmental Change

Climate change is significantly altering the polar regions, which are estimated to diminish by at least 16% in 2099 according to the latest IPCC assessment report. As a consequence massive changes to biodiversity and ecosystem functioning are expected. Biodiversity plays a vital role in many climate-relevant processes in the polar regions (e.g. fixation/release of carbon). Therefore changes in the communities and their ecological functions can affect the climate system, although the underlying mechanisms are not yet well understood. In addition, the biodiversity of many organism groups is not fully explored (e.g. fungi, protists), hence, the respective baseline communities are often not defined, which is a prerequisite for documenting any change in structure and function. Therefore, also further findings of integrative taxonomical approaches are needed.

The most severe threats to Antarctic biodiversity and ecosystem functioning are “stressors”, such as warming, pollution, habitat loss and invasive species. These stressors often interact in complex and unexpected ways, hence, multiple-stressor research is required to understand and predict interactions between individual stressors. The combined effect of two or more stressors is frequently more than synergistic or less antagonistic than expected based on their individual effects. Advancing our understanding of the cumulative ecological impacts of multiple stressors is critical for the evaluation of biodiversity and ecosystem processes.

For an improved assessment of future changes, a precise knowledge of natural climate variations and the responsible processes from geological time periods are necessary in which the influence by humans did not play a role. To understand future climate, research primarily requires information on the duration, speed, frequency, and regional patterns of long- and short-term climate variability. Such information is stored in sedimentary deposits and ice sheets, among others, and their interpretation using numerical modeling contributes to the understanding of the relevant physical and biological processes, and is thus important for improved forecasts of future climate developments.

3.2.II.1 Biodiversity, Acclimation and Adaptation to Environmental Change

Current knowledge and research gaps

Antarctic organisms are already responding to the changing climate, yet the underlying genetic, physiological, and biochemical mechanisms are not well understood. In the marine realm, benthic and pelagic communities exhibit complex responses to thinning sea ice, collapsing ice shelves and calving icebergs. The concept of synchronicity in food requirement and food availability, and the subsequent impacts on energetics, survival, and reproduction, is cast in the match–mismatch hypothesis. Collapsing ice shelves and calving icebergs influence a complex framework of temporal and spatial overlaps that establish the upper limits of matching and consumer-food interactions. Although specific predator-prey interactions are governed by this temporal and spatial dependency, overall productivity at the ecosystem level is determined by matches and mismatches among all trophic levels. Food abundance, food quality, condition of the food source, and thermal tolerances can offset synchronicity in a warming environment as documented for the Antarctic Peninsula. Plasticity and phenology/life cycle traits are also involved in this process, and genetic variability and age structure, migration, and larval dispersal can also be affected. This all can weaken synchronization between food availability and food requirements, affecting predator-prey dependencies and consequently Antarctic marine ecosystem structure and function.

To better understand plasticity for all domains of life, ecological and evolutionary processes have to be considered, as both are strongly interdependent. Without ecology it is difficult to really understand natural selection; and without evolution it is even more difficult to understand the organisms’ traits and their interactions with the environment. Therefore, ecology and evolutionary biology play a crucial role in facing the grand challenges in the polar regions. This includes the development of realistic plans for coping with the implications of global change, for stopping the alarming biodiversity loss, and for designing evolutionarily stable strategies. To better understand ongoing evolutionary processes in Antarctica, it is crucial to compare past and current genetic diversity and population structure.

In the terrestrial realm, biological responses are also multifaceted. Terrestrial ecosystems in Antarctica are unique because of the dominance of nonvascular poikilohydric vegetation like lichens, bryophytes, eukaryotic algae, and cyanobacteria. Additionally, cryotolerant terrestrial algae in Antarctica have encystment phases, which enable them to remain dormant under harsh conditions. Therefore, the physiological state of nonvascular vegetation reflects their immediate environmental conditions. As a result, the distribution, biomass and biodiversity of nonvascular vegetation in conjunction with their microbiomes in Antarctica can be interpreted as a direct reflection of the habitats' climatic conditions.

In addition, the terrestrial vegetation but also microorganisms and their adaptive potential are strongly linked to permafrost and pedogenesis. Consequently, the so far almost unstudied influence of the coupling of biogeochemical and hydrological cycles, plant-soil-microorganism interactions and stabilization of soil organic matter to the current and future net greenhouse gas balance must be urgently researched in Antarctica.

Key research questions for the new SPP funding phase:

1) *What are the underlying physiological, biochemical and genetic processes and mechanisms of species adaptation to a changing Antarctic climate?*
2) *What are the physiological and phenotypic boundaries of polar organisms to survive under changing environmental conditions?*
3) *Are diverse communities more resilient to environmental change than communities of less diversity?*
4) *How did organisms evolve through changing climatic conditions in the past and how did this past climate change influence genetic diversity and population structure?*
5) *What is the impact of climate change on Antarctic permafrost and future greenhouse gas emissions, and what are the consequences for terrestrial organisms' interactions and ecosystem functions?*

6)

3.2.II.2 Anthropogenic Pressures on Antarctica and the Southern Ocean

Current knowledge and research gaps

Besides warming other anthropogenic pressures such as increasing contamination affect Antarctica and the Southern Ocean. Since the discovery of the pesticide Dichlorodiphenyltrichloroethane (DDT) in Antarctic crabeater seal and Adélie penguins, many pollutants including micro plastics have been regularly reported in various biotic and abiotic matrices from Antarctica and the Southern Ocean. Contaminants reach Antarctica either directly, through the increasing tourism and fishery activities, or in case of e.g. persistent organic pollutants (POPs), across the broad barrier of water and air masses encircling Antarctica via long-range atmospheric transport. Therewith volatile and semi-volatile chemical compounds emitted across the southern hemisphere reach Antarctica together with air masses moving along a temperature gradient. Since this process depends on temperature, the transport of contaminants to the Antarctic will likely increase. The overall levels of pollutants in Antarctica are, however, generally lower than in other regions in the world due to less industry and farming in the Southern Hemisphere, which applies to the atmosphere, water column, sediments and organisms. Because the pollutant problem has so far not been regarded as significant in Antarctica, systematic monitoring programs for pollutants are mainly missing, although some European activities exist for selected contaminants (e.g. mercury) such as the Integrated Global Observing Systems for Persistent Pollutants (www.igosp.eu). However, pollutants reaching Antarctica encounter organisms which are eminently vulnerable to effects of exposure: they take much longer for their development than similar temperate species and are characterized by long life spans due to slower metabolic activity. It has also been proposed that evolutionary isolation leads to underdeveloped detoxification systems. In addition, Antarctic trophic webs are relatively simple and characterized by a short food chain indicating that the top of the food chain depends on only few key-species, such as krill and Antarctic cod thereby increasing the potential of biomagnification of pollutants. Thus, even small initial concentrations of pollution present in abiotic matrices of Antarctica may finally constitute a significant hazard for individuals, populations and ecosystems.

In addition, pollutants degrade very slowly, due to the extreme cold climate and long winter darkness, disturbing the chemical communication of species via infochemicals which plays a pivotal role in marine biotic and ecological interactions and food-web functioning. Another problem is related to the fate and behavior of degradation products of contaminants in the ecosystem, which might be even more toxic than the target compounds. Besides micro pollutants, micro plastics often act as vectors for pathogenic bacteria; hence, these anthropogenic particles might spread microorganisms in the Southern Ocean. Many pollutants and their degradation products require improved chemical analytics and polar biological model systems for ecotoxicological assays. Therefore, such gaps of knowledge will be closed, at least partially, in the coming SPP funding phase.

Key research questions for the new SPP funding phase:

1) *What is the exposure and response of Antarctic biota and the structure of the Antarctic food chain to contaminants and environmental pollution (e.g., black carbon, persistent organic pollutants (POPs), mercury, fine dust, micro plastics etc.)?*
2) *What influence do polar conditions have on the degradation of micro pollutants and the effect of the degradation products on the biota?*
3) *How will the source and distribution of these contaminants change?*
4) *What is the potential for bioaccumulation of pollutants in key compartments of the Antarctic food web?*
5) *Are there suitable biomarkers to evaluate ecotoxicological impacts on Antarctic biota?*

3.2.II.3 Climate History and What to Learn for Predictions of Future Developments

Current knowledge and research gaps

Antarctica once formed the keystone of the supercontinent Gondwana. The break-up of Gondwana led to the formation and isolation of the Antarctic continent, the establishment of the circumpolar current and the uplift of the Transantarctic Mountains and high-standing continental margins. These processes, directly and indirectly, triggered the formation of a continental-scale ice sheet and the change from a warm greenhouse to a cold ice-house world beginning at the Eocene-Oligocene transition. Exhumation and uplift of mountains exert climate control in various respects: they change air and oceanic currents, modify gradients between surface and stratosphere temperatures, diversify the CO_2 balance, and feed ice sheets and glacial drainage systems. Main episodes of continental rifting and mountain building in high latitudes (for example in the Transantarctic Mountains) may have substantially contributed to the permanent glaciation of Antarctica, especially to the formation and preservation of the East Antarctic Ice Sheet, while recent and neotectonic activities in the Antarctic appear of major importance for dynamics and fluctuations of the West and East Antarctic ice sheets. Nevertheless, the influence of the Transantarctic Mountains and other Antarctic mountain chains and continental rifts (e.g., West Antarctic Rift System) on climatic evolution needs to be better understood and quantitatively constrained. Sedimentary records form a particularly useful tool to study the geological and climate evolution of the past, but continuous sedimentary rock sequences are lacking or not accessible in Antarctica.

Therefore, geoscientific reconstructions mostly rely on indirect evidence such as sedimentary drill cores from the circum-Antarctic offshore basins or shelf regions (e.g., ANDRILL (Antarctic Geological Drilling Program), IODP (Integrated Ocean Drilling Program), seabed drills such as MeBo (“Meeresboden-Bohrgerät”, underwater drill rig), geophysical measurements (radar, seismics, magnetometry, gravimetry), or exhumation and exposition studies from basement rocks via thermochronological and isotopic data. The Quaternary climatic evolution of Antarctica can be reconstructed from young sediments (e.g., from periglacial lakes) and ice cores from the center and margins of the ice sheets. It is fundamental for understanding and modeling future changes and thus will be one of the foci of the next SPP phase.

Key research questions for the new SPP funding phase:

1) *How do continental breakup processes and ocean gateway formation interact with the long-term climatic evolution of Antarctica?*
2) *How does volcanism affect the evolution of the Antarctic lithosphere, ice sheet dynamics, and global climate?*
3) *What are and have been the rates of geomorphic change in different Antarctic regions, and what are the ages of preserved landscapes?*
4) *What can we learn from past amplified warming of Antarctica for future climate change and its effect on the ice sheet?*
5) *Which proxies can aid quantitative climate reconstruction?*

3.2.III Connectivity and Exchange in Polar Systems

The atmospheric and oceanic circulations separate Antarctica from the other continents. However, several linkages allow the transport and exchange of chemical substances, particles and energy as well as of organisms in and out of the Antarctic continent, Southern Ocean, and Southern atmosphere. In this context, the geological processes that enhance or reduce such connectivity must also be considered in order to understand fundamental Earth system processes, driving forces and interconnections, in present time as well as during the major climate changes in the past. The interlinked influences and interfaces of the physical, chemical, geological and biological parameters on the climate system need to be better understood to allow improved predictions of future climate scenarios.

There exist very distinct teleconnections between Antarctic and lower latitude climates, particularly over the South Pacific and South Atlantic with the West Antarctic/Antarctic Peninsula regions, but these are not fully explored. So-called atmospheric wave trains, for example, exhibit spatial and temporal (seasonal, interannual) variations in both regions, with consequences for the tropical-Antarctic relationship between climate and sea ice extent. Other linkages between ENSO and Antarctica are also not well understood, as well as the impact of the changing ozone hole on atmospheric circulation and sea ice.

3.2.III.1 Antarctic Climate Change in the Global Context

Current knowledge and research gaps

Despite the geographical isolation of the continent, Antarctica is significantly influenced by anthropogenic climate change, since the polar regions are connected with the mid-latitudes via large-scale atmospheric circulations. Comparisons of ice core records from Greenland and Antarctica in conjunction with recent modeling indicate that the strong Arctic surface warming coincides with broad cooling over much of Antarctica’s continent and the Southern Ocean. The near-surface temperature change pattern of the East Antarctic cooling and a warming at the Antarctic Peninsula during the last decades is generally attributed to atmospheric circulation changes associated with the ozone hole. One reason for the lack of ability to reliably assess ozone-climate couplings and to predict future developments is related to the quality of most current Earth system models, which do not depict the feedback effects between the ozone layer and the climate system. Longer global surface temperature observations suggest that this contrasting pole-to-pole change could be a manifestation of a multi-decadal interhemispheric or bipolar seesaw pattern, which is well correlated with the North Atlantic Sea surface temperature variability, and thus generally hypothesized to originate from oscillations of the Atlantic meridional overturning circulation. The interaction of these processes with each other and with other components of the climate system poses a great challenge to both observation and modeling.

Key research questions for the new SPP funding phase:

1) *Which processes connect Antarctic climate change and variability to mid and lower latitudes?*
2) *How do Antarctic processes affect mid-latitude climate, weather, extreme events and sea level rise?*
3) *How will the expected recovery of the ozone hole affect regional and global atmospheric circulation, climate and ecosystems?*

3.2.III.2 Neobiota and Invasive Species

Current knowledge and research gaps

The Southern Ocean and Antarctica have so far been unaffected by invasive species because of various environmental barriers, such as extreme cold temperatures, the physical barrier created by the ACC and its associated polar fronts, and the deep oceanic basins around Antarctica. The Antarctic region also receives far less shipping traffic than other regions of the world, thereby limiting the propagule pressure exerted in the Southern Ocean. However, as warming and human presence increase in Antarctica, the barriers to invasion are breaking down or being bypassed.

The introductions of new taxa into Antarctica are likely related to geological cycles of ice sheet and oceanic front movement when considering long temporal scales. In contrast, short-term natural dispersal such as rafting and hitch-hiking on migrants, or hull fouling organisms on tourist boats has been documented, and hence led in recent years to increased introductions. Particularly rising water temperature around the Antarctic Peninsula provide better habitat conditions for less cold-adapted biota. While terrestrial invasions in the subantarctic region are relatively well documented and researched, the Antarctic region, and particularly the marine realm, has remained understudied to date. A better understanding of the present day and future threat of invasive species that could affect this region is required.

Environmental change, primarily warming, leads to adjustment or avoidance responses of the affected biotas. It is expected that mobile species extend their biogeographic ranges poleward to cooler regions, as far as this is possible due to geographic barriers. Such regional shift was already observed, for example, in the Antarctic krill (with simultaneous population decline), but also in certain seabirds and marine mammals. Antarctic krill populations declined in the West Antarctic Peninsula region, and salps expanded their distribution and abundance. Salps produce 4-fold more fecal pellet-fixed carbon than krill. While most krill fecal pellets are exported to 300 m, that of salps are retained in the mixed layer due to fragmentation. Thus, declining krill abundances could lead to decreased carbon flux, indicating that the Antarctic Peninsula might become a less efficient carbon sink for anthropogenic CO_2 in future.

Besides warming the atmospheric transport of particulate material, such as micro plastics, black carbon and other atmospheric particles, will gain increasing importance as dispersal vectors for microorganisms.

In terms of terrestrial habitats, a rise in neophytes, and especially associated mycorrhizal traits, is likely to change biogeochemical cycles in Antarctic tundra, as it would alter biogenic weathering and root priming. The expected consequences for coastal and shallow water communities are unstudied.

The disappearance or migration of key species and their associated changes in the composition of communities and food webs can affect important ecosystem functions and services in the polar regions as already documented in the Arctic. A quantification of such changes is still largely pending.

Key research questions for the new SPP funding phase:

1) *How do invasive species affect biodiversity and ecosystem functions of Antarctic and Southern Ocean ecosystems?*
2) *How will mechanisms of dispersal of propagules in and around Antarctica and the Southern Ocean change in the future?*
3) *How will the increasing ice-free zone impact biodiversity, biotic interactions and invasions?*

3.2.III.3 Ice–Bedrock and Ice-Bedrock-Ocean Interfaces (Sub-glacial Topography)

Current knowledge and research gaps

Changes of ice flow dynamics, as the major cause of current and past rapid ice sheet change, are sensitive to and interact with conditions below the ice and the shelf seas. These conditions include quantities like subglacial and ocean-bottom topography and morphology, sediment distribution, and geothermal heat flux, down to small spatial scales. However, these conditions are not known in the required detail, and their interactions with ice-sheet changes are not sufficiently understood. Ice-ocean interactions are modulated by bedrock motion. On time scales from decades to millennia, glacial-isostatic adjustment (GIA) is the dominant process. However, GIA forward-modeling results are equivocal due to their sensitivity to ice-load history and solid Earth rheology, which both are not sufficiently known and spatially variable. Improved constraints of GIA are urgently needed to understand its feedback with ice mass change as well as with solid Earth properties.

Key research questions for the new SPP funding phase:

1) *What is the Earth rheology in Antarctica and the Southern Ocean, and how does it affect bedrock motion due to glacial isostatic adjustment?*
2) *How do tectonics, topography, ice-load history, and isostatic adjustment affect the spatio-temporal pattern of sea-level change on all scales?*
3) *How can processes and conditions, and specifically sub-ice geology and geothermal heat flux, at the ice-bedrock interface be quantified, and what is their impact on ice-sheet development?*
4) *How do paleo-landscapes, landform assemblages and sedimentary archives on Antarctic continental margins relate to previous ice dynamics, and what can they tell us about future ice-sheet evolution?*

3.2.IV Improved Understanding of Polar Processes and Mechanisms

As shown in the research topics **I** (*Dynamics of Climate System Components*), **II** (*Response to Environmental Change*), and **III** (*Connectivity and Exchange in Polar Systems*), Antarctica and the Southern Ocean reveal a complex relationship between physical, chemical, biological, and geological phenomena and processes, which are so far poorly understood. Due to the continent’s remoteness and difficulties for *in situ* observations, our knowledge of fundamental processes and principles is still limited. An improved understanding is prerequisite to answer the relevant research questions summarized under **I**, **II**, and **III**.

New and interdisciplinary approaches comprising the biological, chemical, physical and geological Antarctic system and their interactions will be applied in the new SPP phase by developing conceptual or numerical models and their validation in the field. Such models can help to improve our deep understanding of complex fundamental processes in the Antarctic system beyond the currently known isolated phenomena, and hence is pivotal for understanding the changes and linkages outlined in **I** to **III**.

3.2.IV.1 Sea Ice Dynamics

Current knowledge and research gaps

Compared to the amplification of global warming in the Arctic and its massive sea-ice loss, the direct radiative warming effect of rising greenhouse gas concentrations is much weaker in Antarctica. Except for the Antarctic Peninsula, where many changes in meteorological, glaciological, physical, chemical and biological parameters have been documented, the Antarctic climate has remained relatively stable over the last decades. No changes in Antarctic Circumpolar Current transport or meridional position have been observed, thereby protecting Antarctica from southern bound heat flux. This phenomenon causes the so-called “Antarctic sea ice paradox”. Despite global warming, the Antarctic sea-ice extent has not declined based on long-term observational data, while climate model simulations tend to exhibit strong negative sea ice trends. This discrepancy between observations and modeling needs to be remedied by more realistic ocean circulation models, and in particular simulating Southern Ocean eddies, that increase the equatorward heat transport response to global warming. As a result, the ocean becomes more resilient at moderating the anthropogenic warming around Antarctica and hence at delaying sea-ice decline. Nevertheless, in February 2022, Antarctic sea ice shrank to below 2 million km^2, the lowest minimum extent ever recorded, and very recent data from 13th February 2023 (www.meereisportal.de) indicate an even stronger decline to <1.9 million km^2. In such a situation much of the Antarctic coast is ice free, exposing the ice shelves that fringe the ice sheet to wave action and warmer conditions, with unforeseen consequences for physical, chemical, biological and geological processes. To what extent this new phenomenon can be ascribed to natural variability or indeed first indications of imminent change is under current scientific debate.

The recent low summer sea ice extent in Antarctica raises questions about the contributions of dynamic and thermodynamic atmospheric and oceanic energy fluxes. Accurate measurements of snow cover, superimposed ice, and snow ice are particularly important, as they are sensitive indicators of changes in atmospheric forcing and could trigger snow–albedo feedbacks and accelerate ice melt. However, extensive snow depth and ice thickness measurements and sea-ice core analyses in the northwestern Weddell Sea indicated similar sea-ice properties compared to those found in the very few previous studies from the 1980s and 1990s. These results indicate that atmospheric processes such as thermodynamic effects (advection by winds and currents, increased air temperatures, turbulent fluxes, longwave radiation, etc.) probably play a less important role, whereas the effect of dynamic oceanic processes and their interaction with the atmosphere (e.g. increased ocean heat transport, sea ice formation in polynyas and sea ice leads) seems underestimated and needs to be addressed in future studies.

Therefore, one aim of the new SPP phase is to quantify past, present, and future dynamics of the Antarctic sea ice to better understand its quality as a complex, multiphase and multicomponent system, by identifying the key drivers and by improving the underlying processes by observations and models. These include also interactions with ocean and atmosphere, as well as ecological consequences.

Key research questions for the new SPP funding phase:

1) *What processes and feedbacks drive changes in the mass, properties, and distribution of Antarctic sea ice?*
2) *Will Antarctic sea ice massively decline and what will be the causes and consequences for all interlinked processes?*
3) *How can climate model simulations be improved to better reflect realistic sea ice changes?*

3.2.IV.2 Ice Sheet Dynamics

Current knowledge and research gaps

Apart from ice-flow dynamics (cf. 3.2.I.2), the current surface mass balance and its change under a warming climate are uncertain components of present-day and future ice sheet development. Surface mass balance fluctuations and long-term changes affect the structure and thickness of the firn layer and are a major cause of surface elevation changes over most parts of the ice sheet. However, uncertainties in firn processes such as compaction make it challenging to infer surface mass balance trends from trends in surface elevation.

Glacial cycles produce not only erosional and depositional patterns that are used for reconstructions of past ice sheet advances and retreats but also interact with the lithosphere through GIA. The geological record of past ice sheet dynamics provides important constraints for understanding the processes controlling ice retreat mechanisms, their timing and rates. On the other hand, current GIA models for Antarctica show large uncertainties, which is partly due to unknown physical properties (e.g. rheology) of the regional Earth lithosphere and mantle (see also 3.2.III.3).

The global importance of the Antarctic Ice Sheet underlines the need for more *in situ* observations at the ice-sheet surface, at ice-free regions of the continent, from subglacial interfaces as well as from moorings on the shelf and underneath, complemented with autonomous platforms such as floats and gliders. Such detailed observations are necessary to monitor potential changes and to advance the process understanding in order to improve numerical models and reduce their uncertainties in projecting future sea-level rise.

Constraints on the tectonic architecture and development, crustal uplift/subsidence processes, geodynamic processes of the lithosphere, landscape evolution and improved GIA rates will – combined with sedimentary records of past ice-sheet dynamics – lead to an integrated understanding of past and present ice-sheet dynamics with the potential for an improved prediction of ice-sheet behavior in a future climate.

Key research questions for the new SPP funding phase:

1) *How much does increased surface mass balance counteract changes of ice-flow dynamics?*
2) *What was the role of ice-sheet melting driven oceanographic processes and atmospheric warming in the past ice-sheet retreats/collapses, and what can be learned from these past processes for future scenarios and sea-level predictions?*
3) *How has glacial erosion changed the Antarctic landscape, and how have these changes affected past ice-sheet dynamics?*

3.2.IV.3 Antarctic environmental chemistry

Current knowledge and research gaps

With the global oceans’ highest macronutrient concentrations, Southern Ocean primary production is strongly (co)limited by micronutrients, trace metals and essential bacteria-mediated growth factors, such as vitamins and iron shuttles (i.e. ligands). The solubility and bioavailability of trace metals are strongly governed by organic ligands, which directly affect Southern Ocean primary productivity. Yet, the origin and distributions of facilitatory organic molecules, such as ligands and possibly many others, in Antarctic water masses, as well as molecular characteristics lending these molecules properties to be efficient under cold temperatures and low light, is poorly recorded and understood.

We thus lack fundamental chemical understanding of whether cold-adapted, chemically-mediated abiotic and biotic processes, let alone the physicochemical properties of molecules to function under Antarctic conditions, are comparable to our knowledge of chemical thermodynamics ruling chemically mediated interactions under temperate conditions. Therefore, increased knowledge of cold-adapted bio/chemical processes and key molecules governing Antarctic life and primary production and related processes are urgently sought.

The new SPP phase aims to increase our understanding of “cold-adapted” chemical knowledge to mechanistically address the biochemical and biogeochemical principles that explain the key role of the Southern Ocean in our global climate.

Key research questions for the new SPP funding phase:

1) How do environmental changes influence the chemical composition of dissolved and particulate organic matter and the transition of the organic matter size continuum?

2) Are the physicochemical properties of molecules facilitating Antarctic a/biotic processes similar or unique to our knowledge of temperate principles of chemical thermodynamics?

3) Are the key chemical “currencies” and chemo-ecological processes involved in reciprocal interactions of primary producers (algae, bacteria, fungi, viruses) at different trophic levels similar in temperate and Antarctic biomes?

4) How are biogeochemical processes and fluxes affected by changes in ocean physics and chemistry?

3.2.IV.4 Integrative Biotic Modeling Approaches

Current knowledge and research gaps

Experimental and field studies on the effects of environmental change on polar ecosystems are essential to evaluate adaptation mechanisms and strategies of organisms to the various stress factors and their multiple effects and risks, and to understand the associated ecological, physiological and genetic processes. These changes in communities, food webs, energy fluxes, and their causes must be documented and understood, and modelled with realistic approaches that enable reliable predictions of future developments in different climate scenarios and for ecological forecasting. In addition, habitat modelling predicts the distribution of a species across geographic space and time as function of changing environmental data. All models need to be ground-truthed based on in-situ knowledge of ecosystem functionality, community distribution, and ecological changes on decadal time and spatial scales. Additionally, investigations on connectivity and exchange processes between polar ecosystems and low latitudes as well as to land-ocean interactions for a conceptual overall understanding are required. Together with colleagues from other SPP disciplines the improved coupling of biological models with those in polar physics and biogeochemistry will be addressed, supported by a planned SPP Topic Workshop on integrative modeling.

Key research questions for the new SPP funding phase:

1) *How will threshold transitions vary over different spatial and temporal scales, and how will they impact ecosystem functioning under future environmental conditions?*
2) *How can changes in the form and frequency of extreme events be used to improve biological understanding and forecasting?*
3) *How can habitat modelling be coupled with biogeochemical models to forecast effects of biodiversity changes on ocean biogeochemistry?*

3.2.IV.5 Keystone and Indicator Species in Antarctic Ecosystems

Current knowledge and research gaps

Knowledge of polar biodiversity is still extremely limited, especially for polar microbes including phototrophic and heterotrophic protists, which represent most of the diversity in Antarctic ecosystems, and which drive polar biogeochemical cycles and food-webs. In addition, the potential of these organisms to adapt to environmental change is almost unexplored, and hence there exist not much data on the resilience of polar food webs. Studies of eukaryotic responses to changing environments using state-of-the-art experimental approaches (e.g. omics techniques) are restricted to a handful of polar (model) species such as the marine diatom *Fragilariopsis cylindrus*, whose number is too low to provide generalized insights given the heterogeneous nature of different polar habitats (e.g. sea ice, permafrost, melt ponds, cryoconite holes, ice-free ocean, snow and glaciers), which likely drives local adaptation and therefore potentially speciation.

Therefore, and in order to detect changes in polar ecosystems and their consequences, it is important to develop and apply standardized methods of monitoring and quantification based on indicator species such as automated molecular identification (e.g. environmental DNA metabarcoding). Recent declines in top predators such as penguins have shown that changes in keystone species can impact the population sizes of other species in the ecosystem, potentially leading to further species loss (‘cascade effect’).

While Antarctic krill has been determined as a keystone species in pelagic ecosystems, less is known about keystone species in terrestrial and marine benthic ecosystems as well as sympagic environments. These species need to be identified based on ease of observation and their indicator value for the conditions of the ecosystem. Based on this, the influence of increasing anthropogenic impacts, specifically multiple stressors on Antarctic biodiversity and ecosystem processes should be determined. To identify the unifying biological concepts responsible for life in polar ecosystems, much more polar model systems have to be established. Their genomes, transcriptomes, proteomes, and physiology should be comprehensively addressed to fundamentally understand how life in the cold evolved and to determine how and which genes contribute to adaptation and acclimation.

Key research questions for the new SPP funding phase:

1) *Which new approaches and indicator species are particularly suitable for monitoring ecosystem health and disturbances in Antarctic terrestrial, aquatic, benthic, and pelagic marine environments?*
2) *How will changes in keystone species trigger cascade effects in other species and related biotic interactions?*
3) *Can the loss of keystone species be compensated by other taxa and what are the consequences for ecosystem functions?*