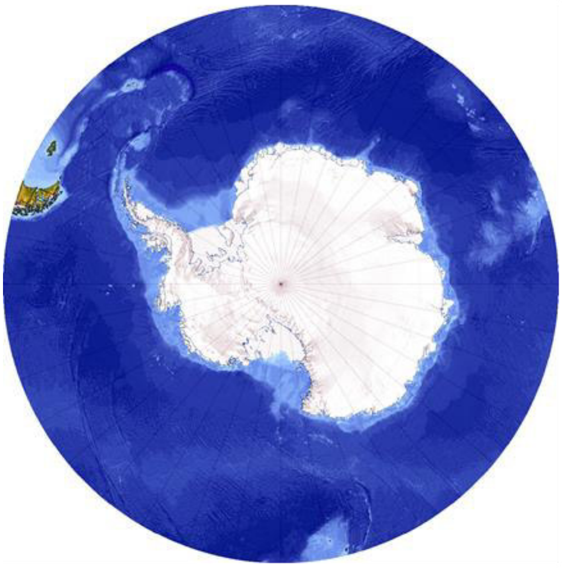
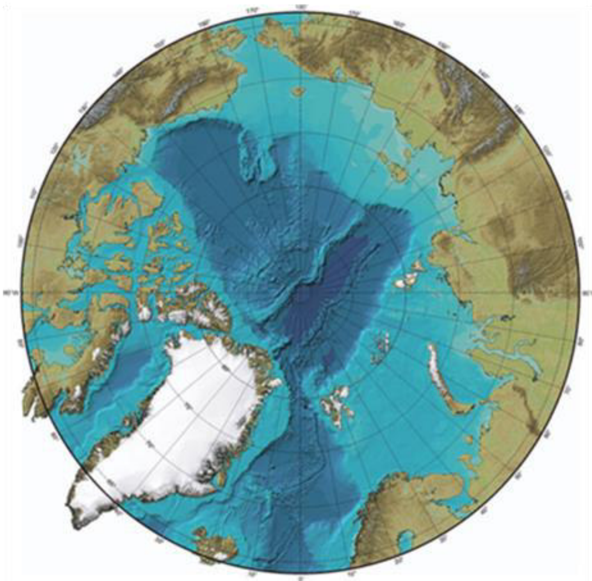
Renewal Proposal

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

October 2016

3 Concept and Goals for the Funding Period of the Renewal (2019 – 2024)

The funding period of the SPP ends on 31st Dec. 2018. Considering the still existing, in many areas even 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 and BGR, we see the compelling necessity to renew the current SPP for six more years, starting on 1st Jan. 2019.

3.1 Overall Conceptual Design

For the current SPP period, the conceptual design was structured around four overarching interdisciplinary research topics. This structure was very successful in the current SPP phase, although some research topics received fewer applications than others. During the next SPP phase, we propose to sharpen the research focus by strengthening three of the most successful interdisciplinary research topics from the previous SPP phase ("Linkages with Lower Latitudes", "Dynamics of Climate System Components" and "Response to Environmental Change") and by introducing a new cross-cutting research topic, "Improved Understanding of Polar Processes and Mechanisms" (**Fig.** 31). This conceptual structure of the next phase of the SPP will strengthen the focus on the most urgent issues in Antarctic sciences and enhance the coordinated interdisciplinary research within the SPP.

A) *"Linkages with Lower Latitudes"*
B) *"Dynamics of Climate System Components"*
C) *"Response to Environmental Change"*
D) *"Improved Understanding of Polar Processes and Mechanisms"*

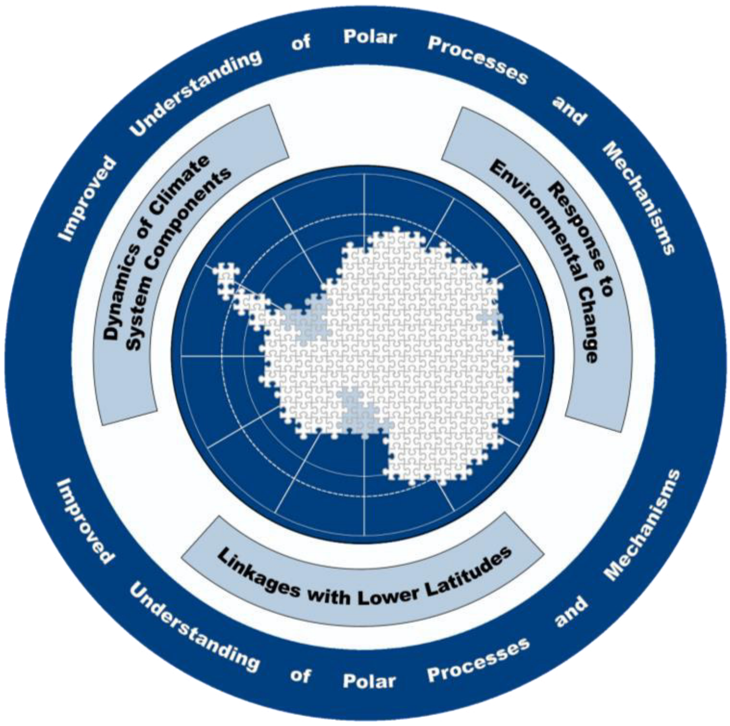

Fig. 31: Overarching interdisciplinary research topics for the next SPP phase 2019-2024 concerning the role of Antarctica in the Earth System.

Within the framework of these four major research topics, we have defined key research priorities and questions (see 3.2. "Scientific Goals") based on the input of the international research community concerned with the Antarctic research and policy. The main research goals of the next SPP phase are aligned with the results of the recent SCAR Antarctic and Southern Ocean Science Horizon Scan, which outlined 80 key questions in all fields of Antarctic research for the next decade on an international scale (Kennicutt & Chown 2015), as well as the research questions identified by the German National SCAR committee. The research priorities within biological sciences and geosciences were fine-tuned based on a recent review article in Frontiers in Marine Sciences (Xavier et al. 2016) and a publication of the working group "Geology and Geophysics of the Polar Regions" of the "German Society of Polar Research" (Melles et al. 2015). This firmly places the proposed new SPP phase in the center of the top research priorities identified by the international scientific community, while taking advantage of the established strong German expertise in Antarctic research. Based on the success stories of the previous SPP phase, we will continue funding the comparative studies of Antarctica and Arctic regions. As indicated in the progress report, most of the German polar research is focused on the Atlantic sector of Antarctica and the Arctic, the main shipping routes of RV “Polarstern”. A review of the atmosphere and ocean research in the SPP in the last decade has been published recently in Ocean Dynamics (Hellmer et al., 2016). We anticipate a similar geographic focus in the next SPP phase (with a strong emphasis on Antarctic research), although fieldwork in other sectors of both Polar regions is possible.

Based on the input of the research community, we also modified the priorities for the geological research in the next phase of the SPP by explicitly restricting it to the younger history of Antarctica (no later than ca. 34 Ma ago), when it became separated from the Australian continent, a circumpolar current established and the Antarctic Ice Sheet developed. The exclusion of the older history of Antarctica was proposed in spring 2016 by the working group "Geology and Geophysics of the Polar Regions" of the "German Society of Polar Research", based on the limited relevance of an Antarctic Gondwana segment prior to 34 Ma for recent climate evolution and the ongoing changes on the continent. This proposal was accepted by the scientific community during an SPP expert meeting on 16th June 2016 in Bremen. This modification allows focusing the available resources on the most urgent current issues in Antarctica.

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

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Xavier JC, Brandt A, Ropert-Coudert Y, Badhe R, Gutt J, Havermans C, Jones C, Costa ES, Lochte K, Schloss IR, Kennicutt MC & Sutherland WJ (2016) Future Challenges in Southern Ocean Ecology Research. Frontiers in Marine Science 3:94.doi: 10.3389/fmars.2016.00094

3.2 Scientific Goals

3.2.A Linkages with Lower Latitudes

The atmospheric and oceanic circulation separates the Antarctic continent from the rest of the Earth system. However, several linkages allow the transport of chemical substances, particles and heat, as well as organisms in and out of the Antarctic continent, Southern Ocean, and Southern atmosphere. In this context, the geological processes that enhance or reduce such linkages must also be considered in order to understand fundamental Earth system processes, driving forces and interconnections, in the present times as well as during the major climate changes in the past. The interlinked influences 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.

3.2.A.1 Opening of Major Oceanic Passage Ways

The isolation of Antarctica is linked to the opening of the Tasman Gateway between Australia and East Antarctica and the Drake Passage/Scotia Sea (separating the Antarctic Peninsula from the southern tip of South America). Closure and opening of the major oceanic passageways and basins played a fundamental role for the exchange of oceanic water masses between the world’s oceans and for the long-term global climate evolution. For instance, the geodynamic evolution of the Southern hemisphere and the opening of the Tasman Gateway and Drake Passage/Scotia Sea led to the re-organization of major oceanic current systems (by initiating the Antarctic Circumpolar Current (ACC)), formation of high escarpments along the newly formed continental margins, reduction of heat transport from lower latitudes to Antarctica, a decrease in atmospheric CO_2 concentrations, and to cooling of the continent and the initiation of a first Antarctic ice sheet at the Eocene-Oligocene transition about 34 Ma. In addition, while many groups of organisms have evolved *in situ* in Antarctica after the breakup of the continent, several taxa have managed to traverse the Polar Front even after the onset of the cooling.
While the timing of deep-water closure of the Tasmanian Gateway is relatively well constrained at about 34 Ma, the dating of the Drake Passage/Scotia Sea deep-water closure is controversial with estimates ranging between 40 and 15 Ma. The exact timing and reconstruction of the associated geodynamics and paleo-geography is of major importance for the fundamental understanding of climate change processes. Narrowing this uncertainty range will be one of the research foci of the next SPP phase. In addition, comparative phylogeography linked with ecological data and molecular clocks could help to understand, which traits allowed organisms to migrate in or out of the Antarctic after the opening of the

major passage ways. The next SPP phase will close these gaps in knowledge by answering the following specific research questions:

1. *How did geodynamics, tectonics, mantle-driven dynamic topography, isostatic adjustment and sedimentation affect the shallow to deep-water opening of the Drake Passage/Scotia Sea?*
2. *How can the timing of the deep-water opening be better constrained?*
3. *What was the role of the oceanic frontal systems in the Antarctic gateways and adjacent ocean basins during interglacial and glacial times (from the Greenhouse to Icehouse world)?*
4. *What are time-scales and relevant ecological traits that allowed several organism groups to traverse the Polar Front after the isolation of the Antarctic continent?*

3.2.A.2 Antarctic Climate Change in the Global Context

Despite the geographical isolation of the continent, Antarctica is significantly influenced by anthropogenic climate change. 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. 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.

To date, little is known about the impact of the changing Antarctic climate on the global climate system. This topic will be one of the research foci in the next SPP phase. Other questions of broad interest to be addressed include the linkage between ENSO and Antarctica, the impact of the changing ozone hole on atmospheric circulation and sea ice, the influence of fresh-water supply from disintegrating ice shelves, and the effects of the changes in polynyas on the formation of Antarctic bottom water and the associated ventilation of the deepest branch of the global Meridional Overturning Circulation (MOC). The aspired SPP phase will provide fundamental new understanding of these phenomena by answering the following specific research questions:

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

3.2.A.3 Rapid Transport Mechanisms and Invasions

Due to its long cold-water history and extreme environmental conditions, Antarctica and the Southern Ocean are home for many endemic species in marine and terrestrial habitats. Antarctic communities are currently challenged by increasing temperature, ocean acidification and by invading biota from temperate regions. The introduction of new taxa into Antarctica are likely related to geological cycles of ice sheet and oceanic front movement and to short-term natural dispersal such as rafting and hitch-hiking on migrants. In recent years, anthropogenic influence has increased, both, directly by transporting organisms (e.g. fouling organisms on tourist vessels) and indirectly by rising water temperature around the Antarctic Peninsula due to climate change, thereby providing better habitat conditions for less cold-adapted biota. Changing climate in Antarctica also leads to changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events as well as to changes in atmospheric circulation patterns.

This affects an important but as yet not well studied aspect of Antarctic transport processes, the transport and dispersal of airborne biota (including microorganisms, spores and other propagules) by atmospheric circulations. The processes of incursion and excursion events of Antarctic biota are poorly understood, and hence will be addressed to provide insights into the biogeographic distribution patterns, dispersal mechanisms, invasions by neobiota and their consequences for native communities. Modern molecular techniques provide new monitoring and identification tools for neobiota, and the newly proposed SPP phase will use these and state-of-the-art tools to answer the following specific research questions:

1. *What is the effect of meteorological conditions on airborne dispersal of biota?*
2. *What influence do airborne microorganisms have on the chemistry and physics of the Antarctic atmosphere?*

3.2.B 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 shapes Antarctica's unique ecosystems, revealing spatial and temporal variability on different scales (seasonal, annual, decadal to millennial). So far it is not fully understood, which of these variabilities are induced by natural or anthropogenic changes and how they influence the present and future Antarctic climate and the polar ecosystems.

3.2.B.1 Atmosphere – Sea ice – Glaciers - Ocean (ASGO) Interactions

The Antarctic climate system is strongly influenced by atmosphere - sea ice – glaciers (see also 3.2.B.2) - ocean (ASGO) interactions and feedback mechanisms. These include transport and exchange of natural and anthropogenic chemical substances (e.g. halogen compounds) and their reactions. Modelling studies highlight the interfaces of the system components as highly sensitive to global climate variability, requiring an interdisciplinary approach to gain better insights into the unique and complex interactions between the different compartments. ASGO interactions 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 but also a large source of high salinity shelf water (HSSW). HSSW plays a major role for the deep and bottom water formation and ocean circulation, and provides a sink for atmospheric trace gases (e.g. anthropogenic CO_2). Some ice shelves (particularly those fringing the west Antarctic ice sheets) are currently exposed to Circumpolar Deep Water with temperatures above 1°C. This warm water cascades from the continental shelf break and provides heat responsible for the acceleration of ice sheet mass loss. Current models indicate that a similar mechanism is at play in other areas, such as the ice shelves of the Weddell Sea that are generally separated from warm water intrusion by the broader shelf. These processes are not yet fully understood and may further change as climate change progresses potentially lead to ice-shelf disintegration and substantial sea-level rise. Furthermore, the ice melt and formation of polynyas affect the light availability in the upper

ocean, with a strong potential impact on marine productivity and the biological carbon pump. Leads and polynyas also strongly modulate methane fluxes, while air and snow chemistry are important for surface ozone and mercury concentrations over inland ice surfaces.
These complex interactions between the changing atmospheric, ocean and ice conditions with the global ocean circulation and CO_2 uptake are not sufficiently understood, and will be addressed in the next SPP phase. Understanding of these interactions requires further analyses of existing and new oceanographic and glaciological data, comparisons of the present processes with those reconstructed for the geological past. An improved quantitative assessment of coupling and feedbacks between the atmosphere and the surface in weather and climate models will be all addressed in the proposed next phase of SPP by answering the following specific research questions:

1. *Why are the properties and volume of Antarctic Bottom Water and other Antarctic water masses changing, and what are the consequences for global ocean circulation and climate?*
2. *How do formation, propagation and variability of leads and polynyas affect the trace gas exchange between the ocean and the atmosphere?*
3. *How can the intrusion of warm water onto the shelf and into ice-shelf-cavities in so far "off-warm-water" shelf areas better described?*

3.2.B.2 Ice Sheet Dynamics and Mass Balance

The Antarctic ice sheet plays a key role for global climate (SCAR Antarctic and Southern Ocean Science Horizon Scan). Changes of the ice sheet such as surface topography, surface characteristics, surface area, and the input of freshwater and sediments have a profound feedback on atmosphere, ocean (through sea level rise and bottom water formation), and Antarctic biomes. The use of different geogenic and glacigenic archives and state-of-the-art ice sheet models is of major importance for the understanding of the history and the reasons for regional differences in the ice-sheet dynamics.
The circum-Antarctic Southern Ocean margins are key regions for the formation of deep and bottom water (namely Antarctic Bottom Water, AABW). Therefore, they are important drivers of the deepest branches of the Meridional Overturning Circulation (MOC). Relatively warm and salty ambient water circulates on the shelves and into cavities below the ice shelves, where it induces basal melting. The extremely cold (basal) glacial melt water (GMW) provides an important constituent to the local formation of AABW.
The evolution and dynamics of the Antarctic ice sheet will be a major research target for the next SPP phase. This includes studies on the changes of the Antarctic ice sheets on 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. In addition, the almost unknown feedback mechanisms should be studied to fully understand the complex interplay between the climate components in the Southern Hemisphere but also to assess the impact of environmental changes in Antarctica on the global atmosphere, ocean and life as well as the relevant time scales. 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.

A major uncertainty for clearly determining the recent evolution and current state of the overall mass balance from various methods, e.g. satellite altimetry and gravimetry, is the densification process. Without further quantitative understanding of how quickly snow turns into firn and into ice, it will not be possible to pin down the density-depth distribution in the firn cover and thus to separate elevation changes caused by densification from mass changes.

Finally, Antarctic (basal) melt water inventories, ice shelf melt rates, and their contribution to the AABW formation, their subsequent circulation and contribution to the MOC and – in particular – their variability in response to environmental and climate change are poorly understood and have not been extensively studied by direct observations. The aspired SPP phase will address these complex scientific gaps in knowledge by answering the following specific research questions:

1. *Is there a temperature threshold that leads to the irreversible loss of parts or even the entire Antarctic ice sheet?*
2. *How is the actual state of ice shelf melting in major drainage outlet basins (e.g. Weddell Sea, Ross Sea) influenced by temporal variability and changing climate conditions?*
3. *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?*
4. *How does the intrusion of the warm (saline) water onto the shelf and into sub-glacial cavities alter basal melting, accelerate grounding line retreat, and destabilize the shelf ice?*
5. *How does firn densification change over time with external forcing and how does this influence current methods to retrieve ice-sheet mass balance?*

3.2.B.3 Sea Ice – Biota Interactions

The sea ice cover in the Southern Ocean represents a major habitat for the organisms living on top, underneath and inside the ice. Sea ice accelerates drifting icebergs, serves as a base for snow accumulation, and has the potential for CO_2 sequestration by fostering biological activity. Ice cover biota includes 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, this zooplankter exclusively feeds on microalgae attached under the seasonal sea ice. The Antarctic Peninsula, a key breeding ground for krill, is one of the fastest warming places in the world. Warming results in a decrease in the winter sea-ice cover and declining stocks of krill with drastic consequences for higher trophic levels such as fish, seabirds and mammals. Sea-ice associated biota such as ice-algae have to cope with large salinity fluctuations, limited gas and nutrient exchange, and strong changes in oxygen conditions.

However, at the ecosystem level, the response and resilience to environmental change is largely unknown for most Antarctic organisms, including krill, which prevents accurate forecasting of potential impacts. Therefore, the physical, chemical, and biological 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 in Antarctic ecosystem functioning. The newly proposed SPP phase will contribute to a better understanding of these processes by answering the following specific research questions:

1. *Can sea-ice associated key organisms adapt to declining sea-ice conditions?*
2. *Which organisms benefit from declining sea ice conditions and what are the ecological and biogeochemical consequences of changing communities?*
3. *How do changes in sea ice extent, seasonality and properties affect Antarctic atmospheric and oceanic circulation?*

3.2.B.4 Southern Ocean Biogeochemistry and Climate-Relevant Trace Gases

The Southern Ocean serves as a major reservoir and conduit for natural and anthropogenic trace gases that play a role in climate change such as methane, dimethyl sulfide, and most importantly, carbon dioxide. Fluxes of these trace gases and the processes they affect 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 and if so, whether this process will continue. Therefore, global and Antarctic climate research needs a better understanding and quantification of the physical and biological mechanisms of the exchange of CO_2 between the Southern Ocean and the atmosphere. Outgassing of water masses with high CO_2 concentration is limited by the sea ice cover, which prevents the physical gas exchange with the atmosphere. 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. The continental shelf of the southern and western Weddell Sea is the prime region for deep-water formation, which spread north across confining ridges and through guiding trenches and ventilate the lower stratum of the World Ocean. Moreover, anthropogenic CO_2 is taken up at the ocean-atmosphere interface by physical and biological processes, and thus partly removed from the atmosphere and eventually transferred to the deeper layers of the (polar) oceans or to the sediment. The efficiency of the "biological pump", a key factor for sequestration of carbon from the atmosphere to the deep sea, is limited by the seasonal availability of light and nutrients. Particularly in the Southern Ocean, micronutrients such as iron, rather than macronutrients such as nitrate or silicate, limit primary productivity. The solubility and bioavailability of these micronutrients is controlled by organic compounds (so-called ligands) in the water. Therefore, the persistence and photo-reactivity of such ligands directly affect productivity and the carbon cycle in the Southern Ocean. Our mechanistic understanding of the role of such compounds (e.g. vitamin B1, B12) within the biogeochemical cycles is very limited, especially in the Southern Ocean.

To distinguish the anthropogenic fraction of CO_2 within the comparatively high CO_2 background is difficult, and thus requires new indirect methods and more observations. So far, little is known about natural and anthropogenic processes of the CO_2 uptake, inventory, and its variability in the Southern Ocean. Other open research topics comprise the changes in processes influencing deep-water formation and thus the ventilation of the deep World Ocean. Natural or anthropogenic processes leave footprints in the atmosphere, in the Southern Ocean water and sediment, in the cryosphere and biosphere, and at their interfaces. These changes span various time scales - from past (paleo) climate changes to recent (anthropogenic). The proposed SPP phase will provide fundamental new understanding by answering the following specific research questions:

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 the physical and the biological pumps interact?*
3. *What is the effect of fresh water supply on the biological and physical pump?*
4. *How are biogeochemical fluxes affected by changes in sea-ice cover and in ocean chemistry?*

3.2.B.5 Climate History of Antarctica Linked to Tectonic and Geodynamic Processes

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 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 the climatic evolution is not completely understood and not quantitatively constrained.

A particular useful tool to study the geological and climate evolution of the past is the sedimentary record, 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”), geophysical measurements (radar, seismics, magnetics, gravimetrics), 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 modelling future changes, and thus will be one of the foci of the next SPP phase. Following specific research questions will be addressed:

1. *What is the consequence of changing Antarctic topography and landscape for the paleo-ice sheet dynamics and global climate?*
2. *How can timing, magnitude and rates of geodynamic and tectonic deformation processes (e.g. mountain uplift or rift formation) be better constrained?*
3. *What is the climate and ice sheet signal in ice-proximal and ice-distal marine as well as subglacial sediments?*
4. *What are the timing and rates of past ice sheet growths and retreats, in particular during past warm times that can be used as analogues for present climate observations and future climate scenarios?*

3.2.C Response to Environmental Change

3.2.C.1 Adaptation of Biota and Ecosystems, Vulnerability and Resilience

Polar Regions are unique and highly prolific ecosystems characterized by extreme environmental gradients. Organisms in marine and terrestrial high latitudes are exposed to lwo temperatures, complete darkness in winter and continuous light and relatively high UV radiation during summer. Extreme habitats are also commonly found in sea ice, the deep-sea, dry valleys, and glacial surfaces. Microbial activity on glacial surfaces has been linked to the biological darkening of so-called cryoconite particles that form as aeolian debris melts into ice surfaces, thereby affecting a significant proportion of the ablation zone. Phototrophic and heterotrophic organisms had to adapt to Antarctic environmental gradients to maintain growth, reproduction, defense and metabolic activity despite environmental conditions that would shut-down cellular processes in most temperate organisms. Understanding the molecular mechanisms of adaptation in Antarctic organisms is a prerequisite for assessing their vulnerability and resilience under climate change scenarios. In addition, polar communities and ecosystems have large inputs into global biogeochemical cycles.
Since only rudimentary data about biological darkening exist for Southern High Latitudes, Antarctic cryoconites will be studied as potential hotspots of biological activity on glaciers and the ice sheet. While knowledge on physiological and biochemical processes to cope with environmental extremes has emerged over the last decade, the genomic basis of adaptation in Antarctica and Southern Ocean organisms is still an open question. Therefore, for the next SPP phase the molecular mechanisms underlying adaptations in polar organisms will be addressed. These include functional studies on genes, proteins and metabolic pathways using state-of-the-art scientific tools including the so-called “omics” techniques. Furthermore, the ecosystem-level studies in the next SPP phase will consider environmental impact on the Antarctic organisms at different trophic levels. Therefore, the most vulnerable food webs and ecosystems in Antarctica and the Southern Ocean will be identified. A key aspect of the physiological, molecular and ecological studies of the Antarctic biota in the new SPP phase will be a focus on interactive effects of multiple environmental stressors to determine their antagonism, synergism or additivity for a more realistic assessment of the current and future states of Antarctic ecosystems in the changing environment. The aspired SPP phase will provide fundamental new understanding by answering the following specific research questions:

1. *Does the biofilm formation on glacial surfaces influence biogeochemical processes and surface albedo of Antarctic glaciers and the ice sheet?*
2. *Are there key genes for adaptation to Antarctic environmental conditions?*
3. *Which food webs and biogeochemical cycles are most vulnerable to multiple stressors in the Antarctic and Southern Ocean?*

3.2.C.2 Temporal Variability and Trends (Detection and Consequences)

The detection and quantification of the environmental changes occurring in Antarctica under the present-day (i.e. known or measurable) boundary conditions are essential for predicting the changes to be expected in the future. Improved remote sensing methods are needed, for example, for monitoring sea ice and polynya characteristics, and measuring the mass balance of glaciers and ice sheets. Monitoring of environmental conditions by long-term in-situ observations is not the focus of the SPP, but is a part of the AWI program at the national level carried out through weather stations, radiosondes and ship cruises.

In the frame of the next SPP phase, the focus will be on improvement and development of new detection methodologies and tools. New possibilities will emerge as new satellite data become available. Changes in oceanic and atmospheric properties need to be analyzed by taking into account new data sources, such as ocean drifters, gliders, ground-based and satellite-based remote sensing units. Analysis of the data obtained from these sources requires support from numerical modelling, while the observations are needed for the verification of numerical models. Regional climate models for the Antarctic or global climate models with a focus on Southern High Latitudes are useful tools for understanding and assessment of trends and variabilities for the past and for future scenarios.

For the detection of changes in Antarctic biology, sites need to be revisited and investigated with comparable, standardized methodologies. New techniques such as remote operating vehicles (ROVs) and permanent sea-floor observatories open new opportunities. To compare the present environmental changes with changes in Earth history, geologists and glaciologists will further develop geological and glaciological proxies for the settings in the past, and improve existing transfer functions for the quantification of environmental and climatic variables. The newly proposed SPP phase will contribute to a better detection and quantification by answering the following specific research questions:

1. *Can we distinguish between natural variability and potential anthropogenic trends in observed changes of the atmosphere-ice-ocean properties and their interactions with biota and biogeochemical processes?*
2. *Which consequences are to be expected from anthropogenically induced trends in Antarctica for communities in and around Antarctica and globally, and for global climate?*

3.2.C.3 Anthropogenic Impacts

The terrestrial and marine environment of Antarctica is particularly sensitive to the effects of anthropogenic pollution as this region is pristine. Despite the remote and isolated position of Antarctica, atmospheric and marine organic and inorganic contaminants, black carbon, nano particles, marine litter and microplastics, as well as emerging infectious diseases find their way to Antarctica from lower latitudes. As Antarctica is one of the least polluted places on Earth, it is an ideal location for measuring the spread of global pollutants. Traces of man-made chemicals used in other parts of the world can be detected in the atmosphere, in the snow, on ice and in the water column. They become concentrated through the food webs particularly in the vertebrates. The contaminants are mainly transported over long distances by means of the circulation in the atmosphere and the ocean currents, or are directly related to human activities in Antarctica such as the research stations and increasing tourism industry (e.g. oil spills). Another ecological problem in Antarctica waters is the decrease of the pH as a consequence of rising global carbon dioxide levels (called “ocean acidification”). Compared with temperate regions, the Southern Ocean will be impacted early by acidification since colder water stores more CO_2.

Since only rudimentary data about anthropogenic pollution exist for Antarctica, contaminants will be studied as stress factor for biota. Although it is assumed that the decrease in pH will become an increasingly important stressor, affecting Southern Ocean food webs (particularly calcifying organisms), comprehensive data are lacking. Therefore, the aspired SPP phase will provide fundamental new understanding by answering the following specific research questions:

1. *What is the exposure and response of Antarctic organisms to contaminants?*
2. *What are effects of multiple anthropogenic stressors on Antarctic and Southern Ocean biota?*
3. *Which species and communities are most threatened by the decrease of the pH ("ocean acidification") in the Southern Ocean?*

3.2.C.4 The Function of Sea Surface Microlayers

The sea surface microlayer (SSM) constitutes the uppermost 10-300 µm of the surface of the ocean, which is in direct contact with the atmosphere, and has physico-chemical and biological properties that are distinct and separated from the underlying water column. Therefore, this layer represents a biologically active boundary interface between the Southern Ocean and the atmosphere, particularly during sea ice-free periods. Boundaries tend to take on emergent properties that neither of the bordering region possesses, and might modulate transfer of materials and energy from one side to the other. Many biogeochemical functions of biologically active boundary layers are related to trapping, transmission, transformation and/or loss of materials across the atmosphere-sea interface. While transmissive boundary characteristics allow a vertical passage of a chemically unaltered material from one into another compartment, transformative boundary behaviors chemically change a material from one in another form during the passage. Due to their biological activity temperate, SSM communities typically exhibit a high degree of transformative boundary features. The SSM is involved in numerous biogeochemically and ecologically important processes, including the synthesis, transformation and cycling of organic material, and the air–sea exchange of gases, particles and aerosols.
However, SSM microorganisms, the organic composition of aerosols, the processes underlying the transport of organic 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. Therefore, during the next SPP phase the following specific research questions will be for the first time answered:

1. *What microorganisms inhabit the sea surface layer (SSM) in the Southern Ocean?*
2. *How important is the biogeochemical role of the SSM in the Southern Ocean?*
3. *Does the SSM in the Southern Ocean act as trap for pollutants?*

3.2.D Improved Understanding of Polar Processes and Mechanisms

As shown in the research topics **A** (**Linkages with Lower Latitudes**), **B** (**Dynamics of Climate System Components**), and **C** (**Response to Environmental Change**), 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 the basic processes and linkages is still limited. An improved understanding is a prerequisite to answer the relevant research questions summarized under A, B, C.
New and interdisciplinary approaches comprising the biological, chemical, physical and geological Antarctic system and their interactions will be applied in the new phase of the SPP 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 A-C.

3.2.D.1 Atmosphere – Ice – Ocean Interaction

Model studies and rare observations emphasize the complex interaction of the unique Antarctic climate system components (atmosphere – sea ice – ice shelves – land ice - ocean) and their sensitivity to changing environmental conditions and response to climate change. The interfaces between these components are highly sensitive to climate variability on various time scales. Through their metabolic activities, Antarctic organisms are also involved in all major biogeochemical processes between the compartments seawater, atmosphere, sea ice and sediment.

However, the basic underlying mechanisms and possible feedbacks are not well understood. Therefore, comprehensive in situ observations, remote sensing, and model approaches are required to improve our qualitative and quantitative understanding of the Antarctic climate system. A broader knowledge of these basic (physical) mechanisms and a wider understanding of the individual interacting components is the most important pre-requisite to allow realistic predictions for the future evolution of the entire Antarctic climate component system (including better bathymetric data). This knowledge is also essential to enable predictions at different time scales (from annual and decadal to millennial) and spatial scales (from local to the continent-wide). The newly proposed SPP phase will contribute to a better understanding and prediction by addressing the following specific research questions:

1. *What are the relevant processes for the interaction between ocean, atmosphere and cryosphere in the Southern Ocean?*
2. *What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice?*
3. *How can coupling and feedbacks between the atmosphere, ice and ocean be better represented in weather and climate models?*
4. *What happens if one of the system components is enhanced / reduced or mechanisms are accelerating / declining?*
5. *Are there stabilizing or de-stabilizing feedbacks between the components, e.g. between bottom water formation, glaciers, sea ice formation and extent?*

3.2.D.2 Biodiversity and Ecosystem Services

Biodiversity, beyond species numbers and distribution, is concerned with the genetic diversity within species, as well as with the diversity of specific and complex ecological processes that are the basis for numerous ecosystem services, such as carbon dioxide capture and sequestration by phytoplankton. Studies on the genetic diversity and phenotypic plasticity with species include, for example, population genetics, the dietary plasticity, functional genomics and the plasticity of physiological responses to environmental conditions. The biodiversity of the Antarctic is to a large extend the result of natural selection through geological time, driven by adaptations to marine cold water environments and extremely seasonal terrestrial, aquatic and marine environments. Seasonality (see 3.2.C.1- *Adaptation of Biota and Ecosystems, Vulnerability and Resilience*) includes, for example, ice and snow cover, food supply and the availability of open water on land and sea.

Although efforts to study biodiversity have strongly increased over the last decade, we still know little about the biodiversity of many important groups of polar organisms, for example, from the deep parts of the Southern Ocean. In addition, Antarctic food webs are considerably more complex than previously thought, and a much better understanding of Antarctic ecosystems, including food webs and interactions under different conditions (e.g. during winter, or in relation to oceanographic cycles like Southern Annular Mode (SAM)) is needed. Consequently, in the next SPP phase the following specific research questions will be addressed:

1. *How do Antarctic food webs change seasonally and in relation to oceanographic cycles?*
2. *How is the genetic diversity of Antarctic organisms linked to their phenotypic plasticity?*
3. *What is the role of Antarctic ecosystems for ecosystem services such as carbon dioxide capture and sequestration by phytoplankton and seaweeds?*

3.2.D.3 Keystone and Indicator Species in Antarctic Ecosystems

Antarctic ecosystems are characterized by smaller numbers of taxa compared to other biomes. While terrestrial ecosystems are primarily determined and limited by solar energy and water availability, nutrient availability is a key factor in the polar oceans. 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 image analysis or automated molecular identification (e.g. DNA metabarcoding). Recent changes 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’). On the other hand, rare or locally endemic species are an important consideration, as they contribute a large proportion of global biodiversity levels.
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 about other indicator species in pelagic marine 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 (see 3.2.C.3 - *Anthropogenic Impacts*) on Antarctic biodiversity and ecosystem processes should be determined. The newly proposed SPP phase will contribute to the determination of indicator species by answering the following specific research questions:

1. *Which new methods and indicator species are particularly suitable for monitoring ecosystem health and disturbances terrestrial, aquatic, benthic and pelagic marine environments?*
2. *How will changes in keystone species impact upon the population sizes of other species?*
3. *What is the state of rare or locally endemic species and threatened species in the Antarctic?*

3.2.D.4 Ice Sheet Dynamics from Sedimentary Records and Lithospheric Processes

Glacial cycles produce not only erosional and depositional pattern that are used for reconstructions of past ice sheet advances and retreats, but also interact with the lithosphere in their Glacial Isostatic Adjustment (GIA) response. 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 crust and lithosphere.

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 potential for an improved prediction of ice sheet behavior in a future climate. Consequently, in the next SPP phase the following specific research questions will be addressed:

1. *What is the relationship between the development of the West Antarctic Rift System and the evolution of West Antarctic Ice Sheet?*
2. *Can presently observed high GIA rates in some regions be linked to active mantle processes (e.g. mantle upwelling)? What is the relationship to past crustal uplift as observed from thermo-chronology?*
3. *How has glacial erosion changed the Antarctic landscape, and how have these changes affected past ice sheet dynamics?*